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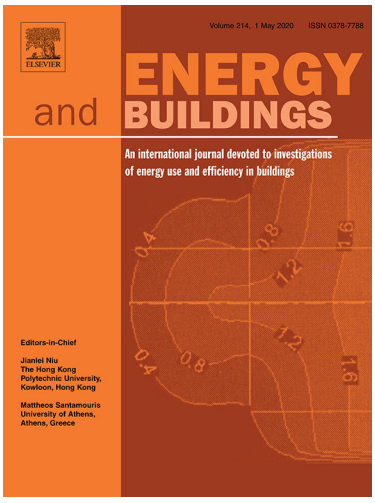

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Demand response potential of district heating in a swimming hall in Finland

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Abstract

In this paper, the demand response of district heating for swimming pools and pool space air is proposed and applied in a swimming hall in Finland. Swimming halls have significant heat demands e.g., domestic hot water supply, space heating and pool water heating, and thus have much large heat storage capacity for the realization of district-heat based demand response. A dynamic building simulation tool IDA ICE was used to simulate whole swimming hall including pools and HVAC systems. In addition, a rule-based demand response algorithm which utilized dynamic district heat price was proposed and applied in the district heating control of the studied swimming hall. The results show that the large storing capacity of pool water promises the large amount of charged and discharged heat energy, and ensure the application of demand response of district heating in swimming hall. The application of demand response of district heating can increase the average pool water temperature from the normal setpoint of 26.5 °C to 27.3 °C. In addition, demand-response district heating control for the swimming pool water and pool space air decreases the total district heat costs of the swimming hall by 1.1%. During the repayment periods of 7 and 15 years, the energy cost savings and maximum cost of profitable investment for the demand response control are between 10 000 € and 20 000 €.

Keywords: Swimming hall; Demand response; District heating; Rule-based algorithm; Profitable investment cost

1. Introduction

According to European Commission 2017, building sectors consume over 40% of the total final energy in Europe Union (EU), which results in approximate 35% of the EU total CO_2 emissions [1]. The energy demand for both commercial and residential buildings is growing dramatically, and more than 50% of this energy is used for Heating, Ventilation, Air-conditioning (HVAC) systems [2-3]. The significant building energy demand along with its continuous upward trend emphasizes the importance of sustainable building technologies to reduce the building energy use and mitigate its related environmental impacts, e.g., global warming [4]. Demand response is one of the promising building energy side management and saving technologies, which gains much attention in recent years [5-6], while electricity and district heat use in HVAC systems are main contributors for the realize of demand response in both residential and commercial buildings [7-8].

Demand response (DR) is defined as ‘‘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” [9], which is one of the energy optimization solutions based on demand side management (DSM), conducting the effort from the demand side to meet the grid requirements, e.g. dynamic electricity & heat price and reliability information [10]. In recent years, demand response is considered as an effective method to keep the energy balance between demand and supply sides, which increasingly becomes a more promising method achieving energy cost saving and CO_2 emission reduction in electricity market [11, 12]. Thus, the current research focus of the demand response is mainly on the electricity [13], and demand response of electricity has been widely investigated in all aspects of buildings.

However, according to the Finnish energy 2018 [14], the energy demand of district heating is the most significant for residential and service buildings in Finland, accounting for the largest share (46.1%) of Finnish energy market followed by the electricity of 18.2% in 2015. In addition, the market share of district heating in European Union (EU) accounts for approximate 12% of heat demands in the residential and service sectors [15]. Thus, the effective energy saving method in district heating is significant in this kind of buildings, and it seems the demand side management of district heating has significant potential of achieving energy and energy cost saving and CO_2 emission reduction. Demand response of district heating is also feasible, but has been investigated by only few researchers in recent

years. In 2017, according to Martin [16], the control algorithm based on the dynamic district heat prices are used to achieve the temperature setpoints adjustment of space heating and ventilation supply air in an energy simulation software. The results show that 6% annual heating costs can be reduced based on demand response with decentralized heating control. In the following year, Mäki [17] used model predictive control to apply demand response of space heating in an office building and tapped the potential of district heating demand response in energy flexibility and saving and thermal comfort within office buildings. The results show that 4.7% annual heating costs can be saved in the case building with demand response of space heating.

In 2019, Sweetnam et al. [18] applied demand shifting response based on district heating networks to improve the load factor of the participating households and the attractiveness of district heating, and found that the energy demand increased by approximate 3%, but estimated cost saving from district heating networks exceeds this value and capital costs are reduced considering reduction of pipework sizes and required boiler capacity. Then, Salo et al. [19] investigated the impacts of optimal demand response control strategies on the district heating system, and found the maximum energy cost saving can be decreased only by 0.7%. However, the energy cost saving can be doubled (1.4%) by applying hot water thermal storage in the system, and the thermal energy storage can balance the peak loads of district heating for long-term. In 2020, Ala-Kotila et al. [20] experimentally analysed a developed demand response of district heating in existing student apartment buildings. The results show that demand response of district heating can decrease the peak load by 14-15% on average, while applying it in eight buildings can achieve 11% normalized energy saving, and corresponding 9% reduction of energy cost and CO_2 emission. The above researches have validated the feasibility of the application of demand response of district heating in building energy systems; However, the researches on the demand response of district heating in building energy systems are still few, and worth further investigation.

Swimming halls also belong to building sectors, which are special building types considering indoor air conditions and high energy consumption [21]. According to Hemmilä and Laitinen [22], swimming halls altogether with ice halls account for 1.2% of altogether annual Finnish building energy consumption, of which swimming halls account for about half. Thus, energy-saving technologies should be applied in the swimming halls to achieve high energy efficiency and energy cost saving. Kampel et al. [23] analysed approximate 100 datasets of facilities in 41 Norwegian swimming pools,

and they found the energy use of all existing facilities can be reduced by 28% per year by the collected data. In addition, Zuccari et al. [24] used their own developed ad-hoc algorithm to calculate potential savings of non-renewable primary energy in swimming pools, which can be achieved by energy-efficiency actions, e.g., heating, filtration and water replacement. While Lam and Chan [25] investigated and evaluated the effects of heat pumps application on the thermal performance and life cycle energy cost in hotel swimming pools. They concluded that the application of heat pumps can achieve 39.9-46.3 MWh energy saving during 6.5-month heating seasons compared with conventional boilers, while energy cost saving can reach 36 000 dollars in a life cycle of 10 years for the swimming pool system with heat pumps. Trianti-Stourna et al. [26] reviewed the possible energy conservation strategies for swimming pools, and proposed energy-cost saving solutions (e.g., renewable heating source, multiple boiler arrangements, solar collectors and dehumidification system) for the improvement of energy efficiency, indoor thermal and visual comforts. The significant heat demands in swimming halls, used for domestic hot water (DHW) supply, space heating and pool water heating [21, 27], imply the potential and feasibility of applying demand response of district heat in swimming halls.

Thus, unlike the previous researches focused on demand response of electricity in swimming halls, this paper firstly puts forward applying demand response control of heating in a swimming hall in Finland. This paper is also the first to propose and apply demand-response based control of district heating for swimming pool and pool space air in a swimming hall. The swimming hall model is established by IDA ICE simulation software based on the geometries and equipment parameters of an actual swimming hall in Finland, while a rule-based demand response algorithm was proposed for district heating control of the studied swimming hall and was input into the swimming hall model. Finally, the calculation of the maximum cost of profitable investment, total purchased district heat and energy cost savings was done via post-processing.

2. Methodology

2.1. Structure of the simulation study

The research methods applied in this paper are shown in **Fig. 1**, which are IDA ICE simulations and then post-processing in Excel 2016. There are five main kinds of input data for the swimming hall model, including data from the studied swimming hall in Helsinki [21, 28, 29], assumed model parameters, hourly local weather data [30], hourly district heat prices [19] and algorithm for smart control of its energy system. The total energy cost savings from the investment are calculated based on the total purchased district heat from the simulation and real-time energy prices.

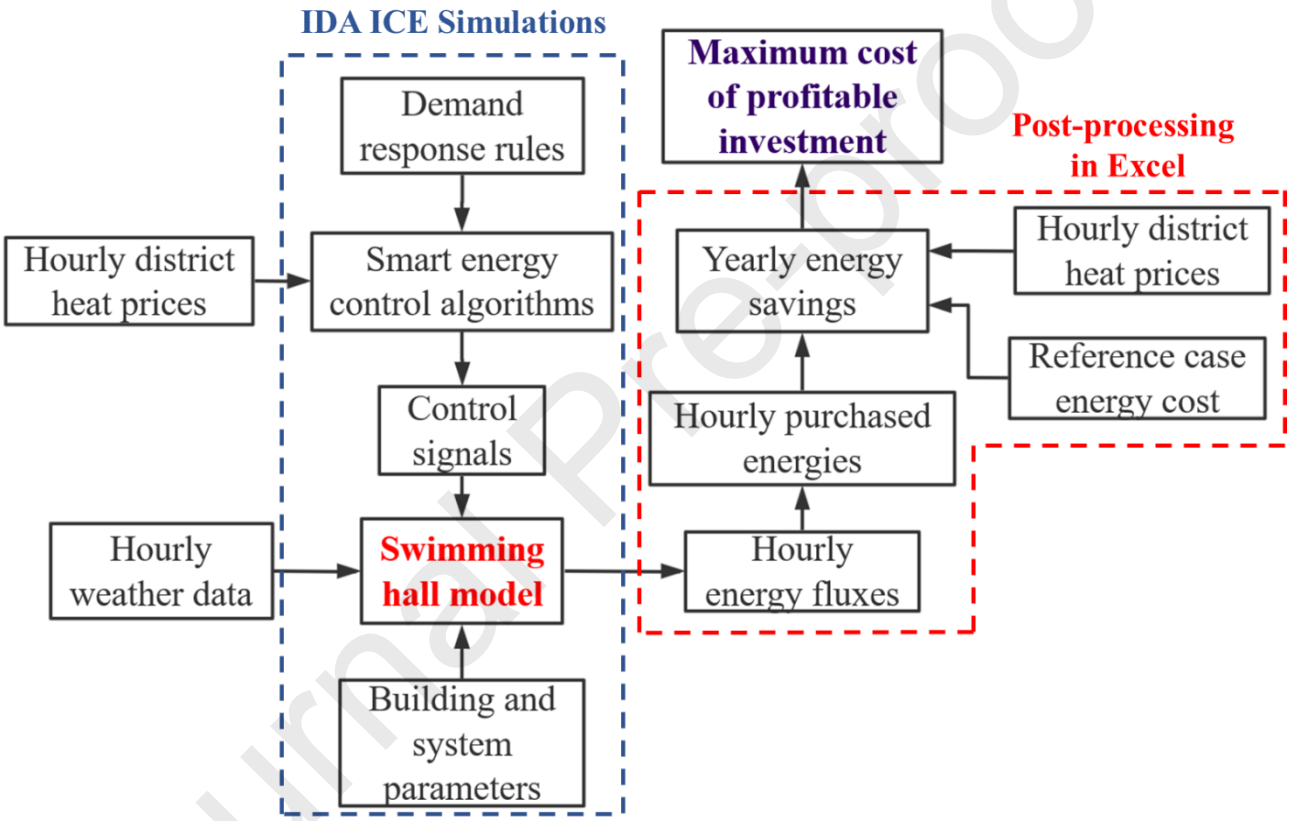

Fig. 1. The logical diagram of method structure.

2.2. IDA ICE building energy simulation tool

IDA Indoor Climate and Energy (ICE), a general-purpose building simulation tool allowing extensive system designs and configurations, was used to establish the swimming hall model [31]. IDA ICE, as a dynamic multi-zone simulation program, is suitable for modelling, e.g. HVAC systems, outdoor climate and internal heat gains, and it can achieve dynamic simulations of mass flows and heat transfer at the same time. The feasibility and reliability of IDA ICE has been validated in multiple

researches successfully, e.g. references [32-34].

The pool extension of IDA-ICE, which allows the modelling of water surface in a zone, was used in the study. The pool model accounts for both mass and heat transfer between a water surface and a zone. Heating demand of the pool water to reach and maintain chosen setpoint temperature is simulated in the extension and the continuous refreshment of pool water is also considered.

2.3. Weather data

A test reference year (TRY), to recreate a typical year in Helsinki based on the historical weather data, is described as the current climatic conditions of southern Finland, and imported into IDA ICE of the swimming hall simulation model [30]. TRY covers but not limits to the temperature, relative humidity, wind speed and direction and solar radiation on both direct normal and diffuse horizontal surfaces in a typical year in Helsinki. As shown in **Fig. 2**, the TRY ranges of temperature and relative humidity are from -20 °C to 30 °C and from 30% and 100%, respectively.

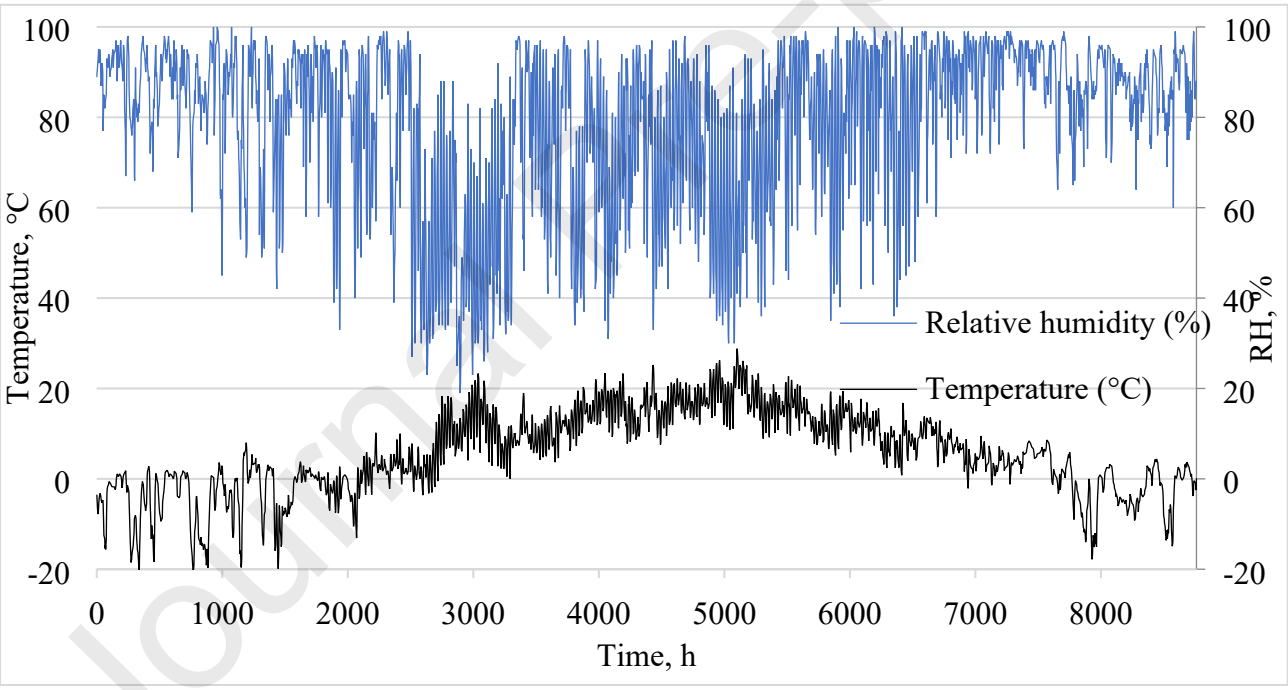

Fig. 2. The temperature and relative humidity for TRY (FMI, 2012).

2.4. Dynamic energy price

Dynamic district heat price was applied in this paper, while the district heat price still typically varies seasonally or monthly in Finland. The dynamic district heat price used in the study represents a price of a Finnish district heat producer, and it contains energy, taxes, and dynamic transfer fee. The

hourly price was determined based on a district heating system consisting of a combined heat and power (CHP) plant and heat-only boiler as described more detailed in [19]. The price was calculated based on the existing hourly fuel price data without intention to predict district heat energy prices in future. **Table 1** shows properties of the dynamic district heat price, while **Fig. 3** shows the comparison of the dynamic price used in the study and a seasonally varying district heat price of a Finnish district heat producer.

Table 1 Properties of the dynamic district heat price.

District heat	Average price [€/MWh]	Standard deviation [€/MWh]	Ratio of standard deviation to average price [%]	Ratio of the price beyond the average [%]
Value	50.63	23.24	46	20%

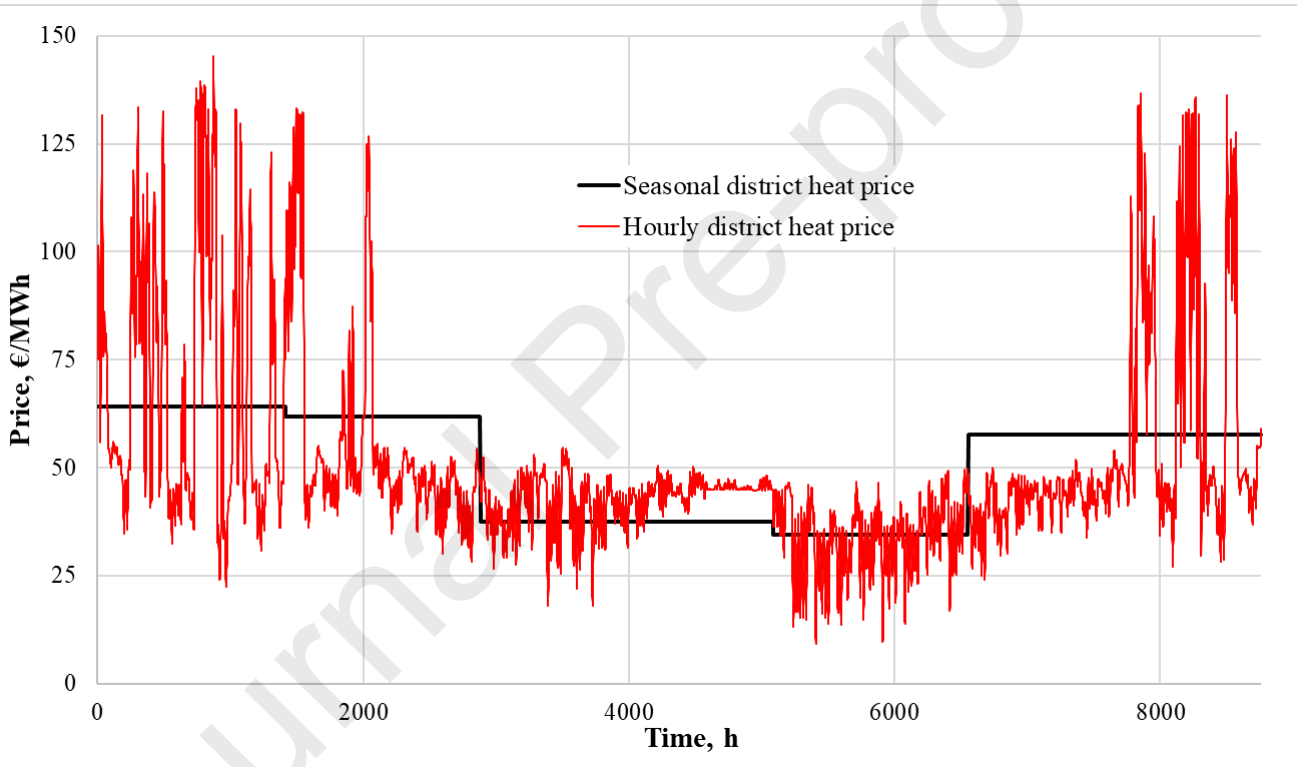

Fig. 3. Hourly district heat price used in the study and seasonal district heat price of a Finnish district heat provider.

2.5. Maximum profitable investment

The calculation of maximum profitable investment is influenced by many factors, while four influencing factors were considered in this study, e.g. energy cost savings, energy prices inflation, nominal interest, and repayment period. **Table 2** shows the calculation method for the maximum cost of profitable investments as well explanation of each variable. The definition of the repayment period

is the assumed minimum lifecycle for the implemented system. The assumed value for annual real interest rate of energy price is 1% and escalation of energy price 2% and three repayment periods, 7, 10 and 15 years were applied in this paper to calculating energy cost savings.

Table 2 The calculation method for maximum cost of profitable investments.

Number	Equation	Result
Eq. 1	$r_e = \frac{i - f_e}{1 + f_e}$	Real interest rate of energy price [35]
Eq. 2	$a_n'' = \frac{1 - (1 + r_e)^{-n}}{r_e}$	Total discount yield [35]
Eq. 3	$S_{inv} = a_n'' \cdot S_{E,a}$	The maximum cost of profitable investments (total energy cost saving)

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

3. Swimming hall description

3.1. Building properties

The studied swimming hall serves as a sports center located in Helsinki, Finland. The geometry and configuration of the studied swimming hall is obtained based on the online data base from the City of Helsinki [36] and team manager of the studied swimming hall. AutoCAD MagiROOM made by Autodesk was used to establish the swimming hall model based on the geometry data. Comprehensive data except of energy consumption of the studied swimming hall are available and applied to build the model. **Table 3** shows the main values of the model geometry of the studied swimming hall, while **Fig. 4** shows the model geometry of the studied swimming hall.

Table 3 Main values of the model geometry of the studied swimming hall.

Area [m^2]		Volume [m^3]	Window to envelope ratio	Envelope area per volume
Net floor	7 982			
Ground	4 047	53 463	8.9%	0.26
Envelope	13 705			

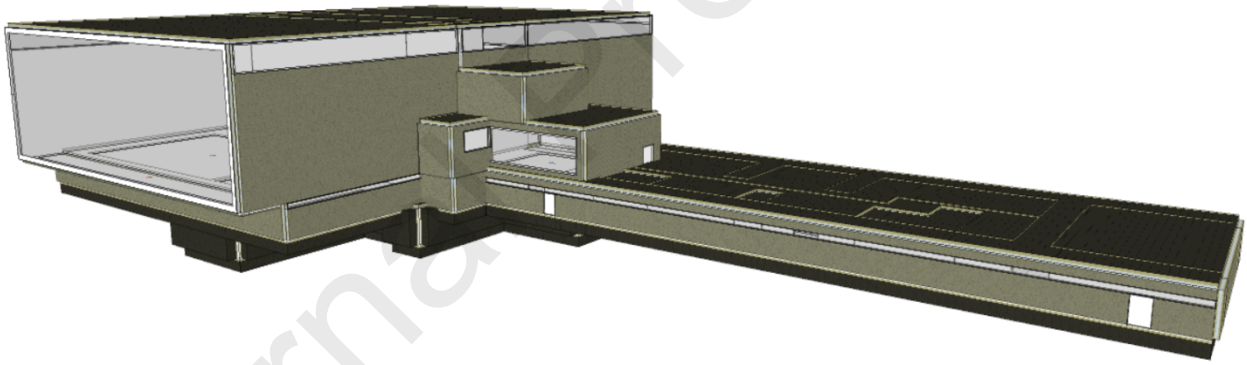

Fig. 4. Model geometry of the studied swimming hall.

The U-values for different structures were set in the swimming hall model according to guidelines Finnish building code [37] (see **Table 4**). Because the proportion of window areas to the envelope is relatively large, the heat losses through the envelope is significantly affected by the U-value of windows. **Table 4** also shows the thermal bridges conductance, air leakage rate (q_{50}) at 50 Pa pressure difference and average infiltration rate used in the simulations.

Table 4 Envelope parameters in the swimming hall model.

Parameter	Value	Location/ Notes
U-value of structure [W/(m^{2}K)] [39]		

-Windows	1.0	All spaces
-Base slab	0.24	All spaces
-Ceiling	0.2	All spaces
-External wall	0.23	All spaces
-Internal wall	0.47	Pool spaces
	0.8	All other spaces
Thermal bridges conductance [W/mK] [29]	0.08	Roof/External wall
	0.24	Base slab/ External wall
	0.06	External wall/External wall
	0.03	External window and door
Air leakage rate q_{50} [m^3/hm^2]	3.3	
Average infiltration rate [1/h] [38]	0.04	Air changes per hour (ACH)

3.2. Technical systems

3.2.1 Pools information

There are three swimming pools in the studied swimming hall, including big pool, children's pool and young-children's pool, while the parameters of these swimming pools, including pool surface areas, average depths and pool water temperatures, are summarized in **Table 5**. The evaporation coefficients used in the simulations for the big pool, children's pool and young-children's pool are 1, 1.5 and 1, respectively, which are selected based on the ASHRAE (2003) [39]. Design heating power of the pool models was 200 W/m^2 per pool surface area, while the design supply water temperature was +37 °C. In addition, the pool water temperatures were set based on the mean temperatures from the latest measurements of the studied swimming hall.

Table 5 The parameters of the swimming pools

Pool	Usage	AHU	Pool surface area [m^2]	Average depth [m]	Pool water temperature [°C]
Big pool	Fitness swimming	Big pools	400	2.8	26.5
Children's pool	Practicing swimming	Big pools	112	1.4	26.5
Young-children's pool	Young Children	Small pool	63	0.75	28

3.2.2 Air handling Units (AHU)

The big pool and the children's pool share the same AHU, while young children's pool use a separate AHU. **Fig. 5** shows the schematic of the two AHU:s serving pool spaces of the studied

swimming hall, which was accurately built in the IDA ICE. The supply airflow rates for both pool spaces are adjusted by own VAV AHU:s and based on respective relative humidity (RH). Recycling of indoor air is used by the AHUs of the pool spaces to increases its RH up to the range between 50% and 57%, while the corresponding supply airflow per net floor area is between 2 $dm^3/s/m^2$ to 4 $dm^3/s/m^2$. The indoor air heating setpoint for the big pool space is +28 °C, whose supply air heating temperature is between +25 °C and +37 °C, while that for the young children pool space is +30 °C. According to Hemmilä and Laitinen [22], the temperature efficiency of heat recovery is 60%.

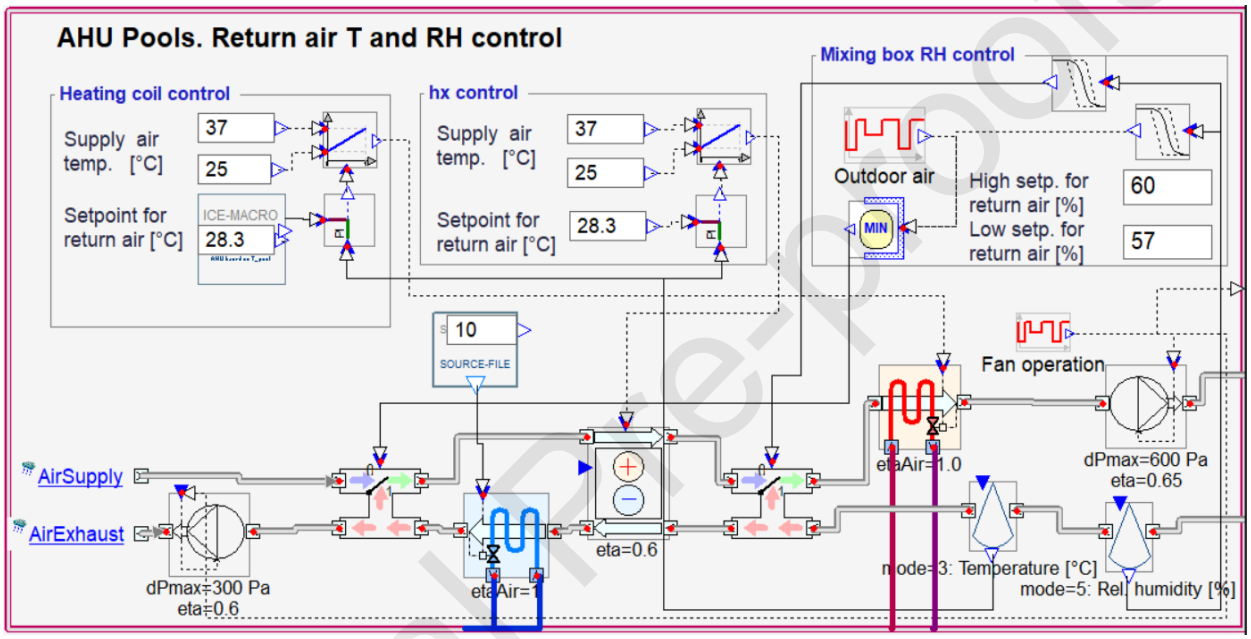

Fig. 5. Schematic of the two AHU:s serving pool spaces of the swimming hall model.

The shower and other warm spaces have own VAV controlled AHU, whose supply air rates are controlled by the CO_2 levels of the spaces. The supply air temperature of the warm space AHU is constant of +16 °C, while that of shower AHU ranges from +13 to +30 °C, affected by the room air temperature. **Table 6** shows the heating set point temperatures and properties of the ventilation system.

Table 6 Heating set point temperatures and properties of the ventilation system.

Space group of AHU	Net surface area [m^2]	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

3.2.3 DHW usage and heating systems

The temperature setpoints for DHW heating and incoming cold water for energy calculation are +55 °C and +8 °C, respectively. The average tap water temperature and average DHW usage are +39 °C and 51 m^3/day based on [22] and [40]. **Table 7** shows the design temperatures and heating powers in the studied swimming hall model. The water radiator heating is supplied in all spaces except showers, while underfloor heating is applied in both pool spaces and showers.

Table 7 The design temperatures and heating powers for heating systems in the swimming hall model.

Heating system	Design temperature [°C]	Design heating power [kW]
Water radiator heating	50/30	Big pool space: 40 Small pool space: 6 Showers: 24
Underfloor heating	34/30	Big pool space: 23 Small pool space: 5
Pool water heating	40/27	400 kW

3.3. Usage schedules

The studied swimming hall annually opens between 14 of July and 31 of May, while the daily opening schedule is from 7.00 A.M to 22.30 P.M. at workdays. The lighting schedule for the swimming hall model is divided into three parts, half power between 7.00 A.M. to 16.00 P.M., full power during other opening period and power off during closing times. **Table 8** shows the weekly schedules for occupancy and DHW usage. The swimming hall spectator stand can accommodate up to a maximum of 300 people, while this happens only once per 2 months from 18 to 21 on Sundays. On the other Sundays between 18 and 21, the spectator stand is occupied by 10%, while the spectator stand is closed during the rest period. The heating system of the saunas is supplied based on the open times of the swimming hall.

Table 8 Weekly schedules for occupancy and DHW usage

Period	Open times	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

4. Smart control of the energy systems

4.1.1. Systems included

In this paper, the smart control of energy systems in the swimming hall refers to demand response control by dynamic district heat prices. The heat capacities of the swimming pools can be utilized via demand response. Adjusting the global temperature is a control strategy used in this study, while the temperature setpoints are adjusted according to the global control signal. The thermal comfort within the swimming halls should be guaranteed to an acceptable level by suitable temperature setpoints. In the studied swimming hall, the water temperature of the main pools (big pool and children's pool) is controlled by demand response of district heat with load-shifting strategy. The temperature setpoints for the main pools are the same, which are 26 ℃, 26.5 ℃ and 30 ℃ for the minimum, normal and maximum values, respectively. **Table 9** shows the heat stored and discharged of pool water temperature changes in big and children pools assuming that the pool water is fully mixed. When the pool water temperature increases from 26.5 to 30 ℃, the maximum heat energy stored is approximate 4 570 and 640 KWh for big and children's pools, respectively. When the pool water temperature decreases from 26.5 to 26 ℃, the maximum heat energy discharged is approximate 640 and 91 KWh for big and children's pools, respectively. Large temperature difference between indoor air and pool water will cause condensation in the space, thus the temperature setpoint for pool water always maintains 2 ℃ lower than that for indoor air. The changeable pool return water temperature will be continuously supervised by temperature sensors so that the air heating temperature can be set based on the water temperature.

Table 9 Heat stored and discharged of pool water temperature changes in big and children pools

Heat energy	Big pool	Children pool	Note
Maximum heat stored [KWh]	4 570	640	Pool water temperature increased from 26.5 to 30 ℃
Maximum heat discharged [KWh]	2 653	91	Pool water temperature decreased from 26.5 to 26 ℃

4.1.2. Control algorithms

The rule-based control algorithm with dynamic district heat prices as parameters is used and responsible for the studied swimming hall energy system. The control algorithms are aimed at giving

the control signal for the energy system and achieve energy consumption reduction or energy cost saving, while the control signals are set to fulfil temperature setpoints adjustment affecting the energy system heating power.

The dynamic district heat prices are used to control the demand response system in this paper. The system temperature setpoints decrease under the circumstance of expensive district heat price and increase in the case of cheap district heat price. Thus, the percentage determination of times for cheap and expensive district heat prices is significant, affecting the system temperature setpoints. **Fig. 7** shows the duration curve for hourly district heat price of whole year, while the dotted lines represent the excluding percentage of 8%, 20% and 30% for both expensive and cheap district heat prices. The selection of the percentages is flexible, whose aim is to divide the district heat prices to three price levels based on the duration curve shapes. **Fig. 6** shows that approximate 20% of the most expensive prices of district heat are apparently higher than that of the rest; thus, 20% was selected as the high price limit (HPL) percentage for swimming pool water heating. The same percentage (20%) was also selected as low price limit (LPL).

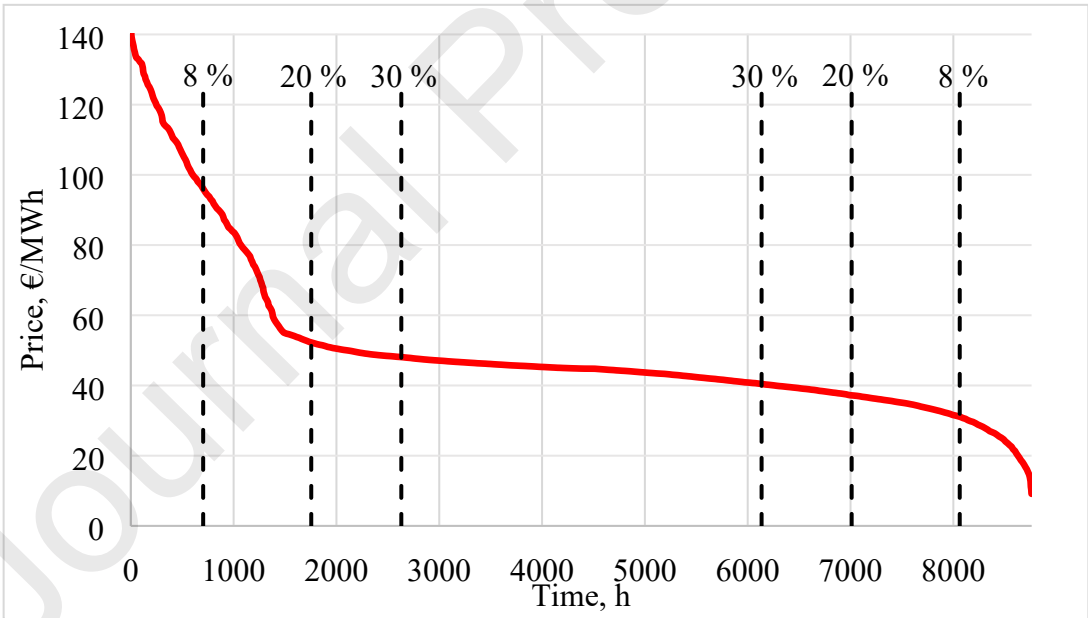

Fig. 6. Duration curve for the hourly district heat price.

The algorithm developed in this paper defines the status of current energy price (CEP), namely current district heat price. The status of CEP is divided into expensive, normal and cheap. **Fig. 7** shows the dynamic energy price algorithm decision making, input data and output data. There are three inputs in the algorithm, selected percentages of 8%, 20% and 30% for the minimum amount of expensive and cheap prices, district heat prices during the last 2 weeks and the district heat prices in the following 12

hours based on the assumption that the prices are known 12 hours in advance. The outputs for the algorithm are control signals of -1, 0 and 1, representing the expensive, normal and cheap status of CEP, respectively. The aim of this algorithm is to classify the corresponding minimum percentages of expensive and cheap district heat prices. There is higher price limit (HPL) and lower price limit (LPL) set for the algorithm, while the price class for the CEP is compared with these limits.

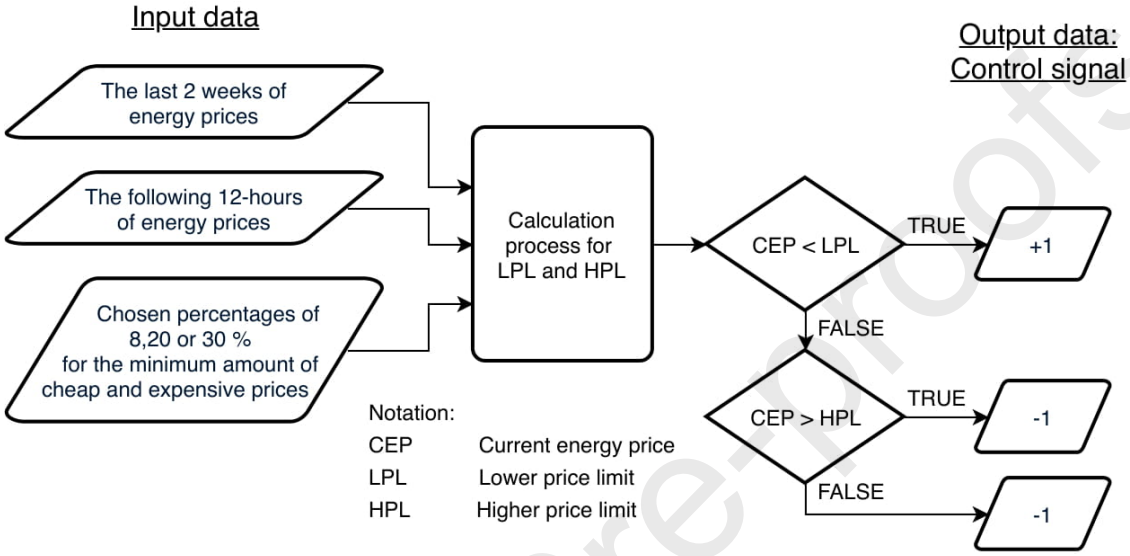

Fig. 7. Decision making, input data and output data of the dynamic energy price algorithm.

Fig. 8 shows the example of dynamic energy prices for the last two weeks, the predicted price data for the following 12-hour, CEP, current HPL and current LPL. The momentary control signal in the example shown in **Fig. 8** is +1 which indicates that CEP at current time is classified as cheap. **Table 9** shows the temperature setpoints based on the control signals and the active percentage of the setpoints during the year.

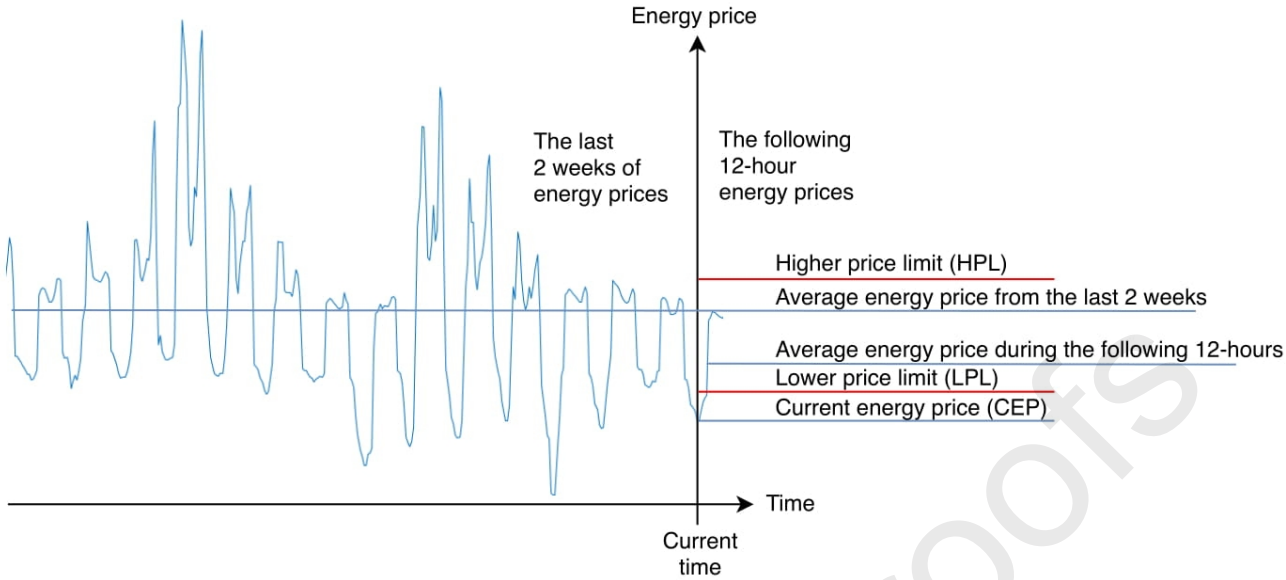

Fig. 8. Example price data of the last two weeks and the following 12-hour, CEP, current HPL and current LPL.

Table 9 Setpoint temperature and the active percentage of the setpoints.

Demand response of district heat in the swimming hall	Conservation -1	Normal 0	Loading +1
Setpoint temperature	+26°C	+26.5°C	+30°C
Percentage	32%	38%	30%

Fig. 9 shows the pool water temperature setpoint based on the district heat demand response in the swimming hall during December (An example period). Due to the unpredictable nature of the dynamic price of district heating, the span of periods is large for an even temperature setpoint, whose difference is from only few hours to a couple of days. Due to the huge heat capacity of the studied swimming hall, it takes a long time to heat the pool temperature to higher temperature setpoint; Therefore, the short periods of higher temperature have little impact on the actual pool temperature, while the pool water temperature reacts to the demand response actions very slowly.

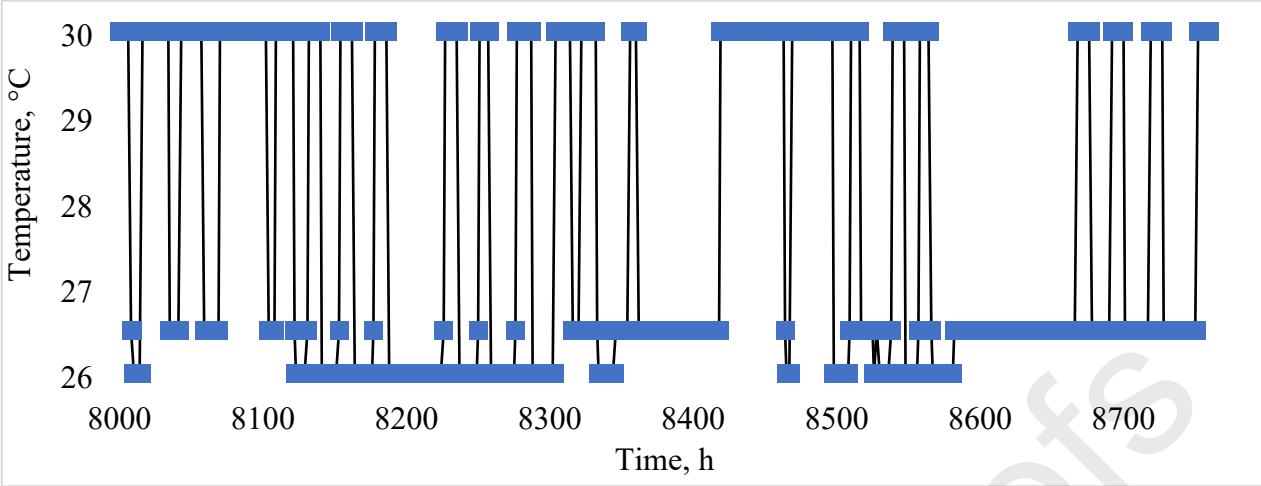

Fig. 9. The pool water temperature setpoint during December.

5. Results

5.1 Case description

The studied swimming hall is open most of the year except of the summer breaks from 1st of June to 13th of July, while the simulation period for the swimming hall is altogether 322 days per year. There are two cases in this paper, e.g. the reference case 1 and the optimal case 2 with demand response. The reference case 1 uses the constant set points of space heating for three pools (Shown in **Table 6**) and the constant normal set points for pool water (Shown in **Table 9**). Compared with the reference case 1, demand-response based control of the district heating in swimming pools and pool space air is applied in case 2. In case 2, the pool water temperature set point ranges from 26 to 30 °C, while the temperature set point for indoor air is controlled to be 2 °C warmer than the pool water temperature in all cases to prevent condensation.

5.2 Effect of demand response on pool water and district heat power

The surface area of the big pool is 4 times larger than that of the children's pool, causing much higher heat demand and heat loss. In addition, the average depth of the big pool is twice that of the children's pool; thus, the thermal capacity per amount of heat loss in the big pool is approximate twice that of the children's pool, causing slower changes in water temperature. The slow reaction to water temperature changes in the big pool increases the potential of demand response. Thus, in this section, big pool is taken as an example to analyse the pool water temperature and total pool water heating power.

Fig. 10 compares the hourly big pool water temperatures between cases 1 and 2 through the whole year with summer breaks. All the pool water temperatures in case 1 hover around the normal setpoint

temperature (26.5 °C), whose deviations do not exceed ± 0.5 °C. However, the pool water temperatures in case 2 are between the range of conservation (26 °C) and loading (30 °C) setpoint temperatures. The average temperature of the big pool water rises from the normal setpoint of 26.5 °C to 27.3 °C. The average temperatures (27.5 °C) during the first half year are higher than that (27.1 °C) during the second half year in case 2. This uneven average temperatures throughout the year is dominated by the district heating trends whose price drops during the first half year and rises during the rest half year. More advanced algorithm could help avoid the long periods of high-water temperature and compensate the effect of uneven average temperatures.

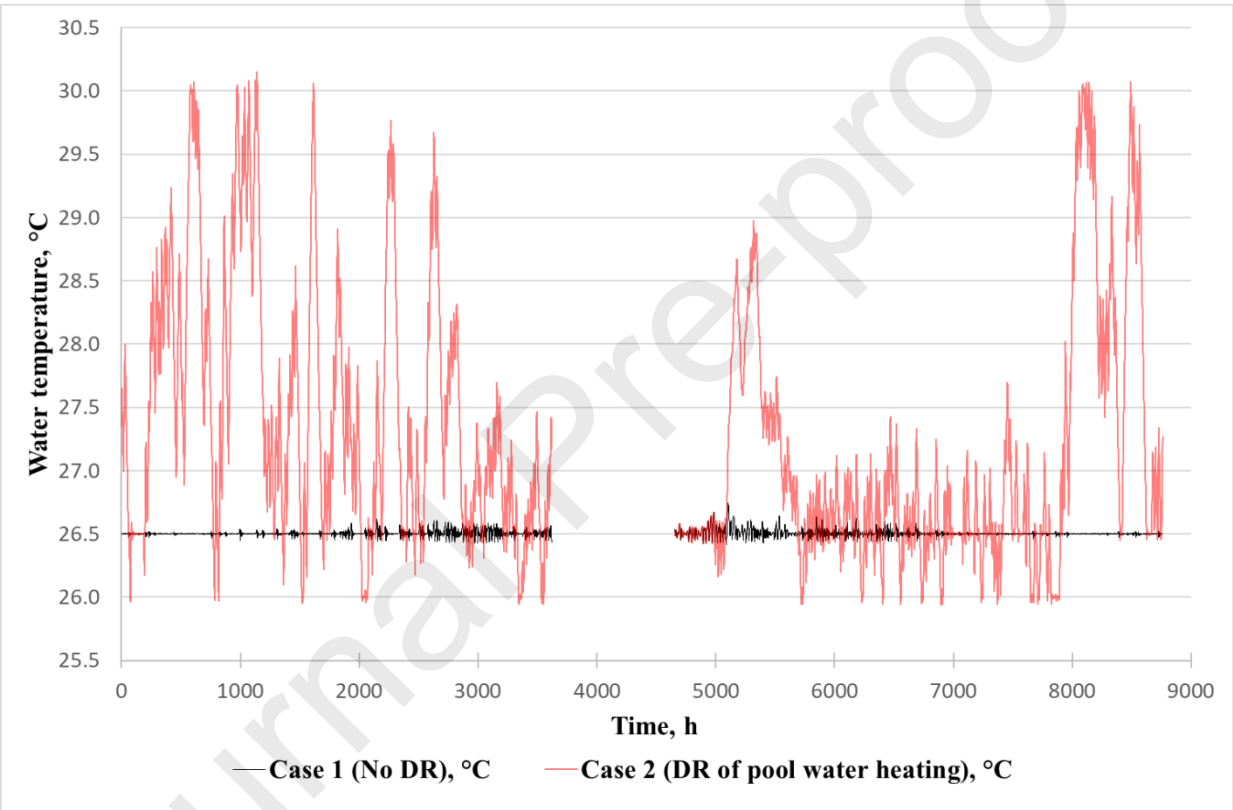

Fig. 10. The comparison of hourly big pool water temperatures between cases 1 and 2.

Fig. 11 compares the duration curve of big pool water temperature between cases 1 and 2. According to **Table 9**, the active percentages of the setpoint are 32%, 38% and 30% for conservation, normal and loading setpoint temperatures, respectively. Approximate 80% of the actual water temperatures are in the range between normal and loading setpoint temperatures, while 20% of them are in the range between conservation and normal setpoint temperatures. Compared with case 1, the heat energy stored in the big pool during the whole simulation period in case 2 is approximate 8 120 MWh, while the heat energy discharged in case 2 is approximate 400 MWh. The large storing capacity

of pool water in swimming hall ensures the large amount of charged and discharged heat energy.

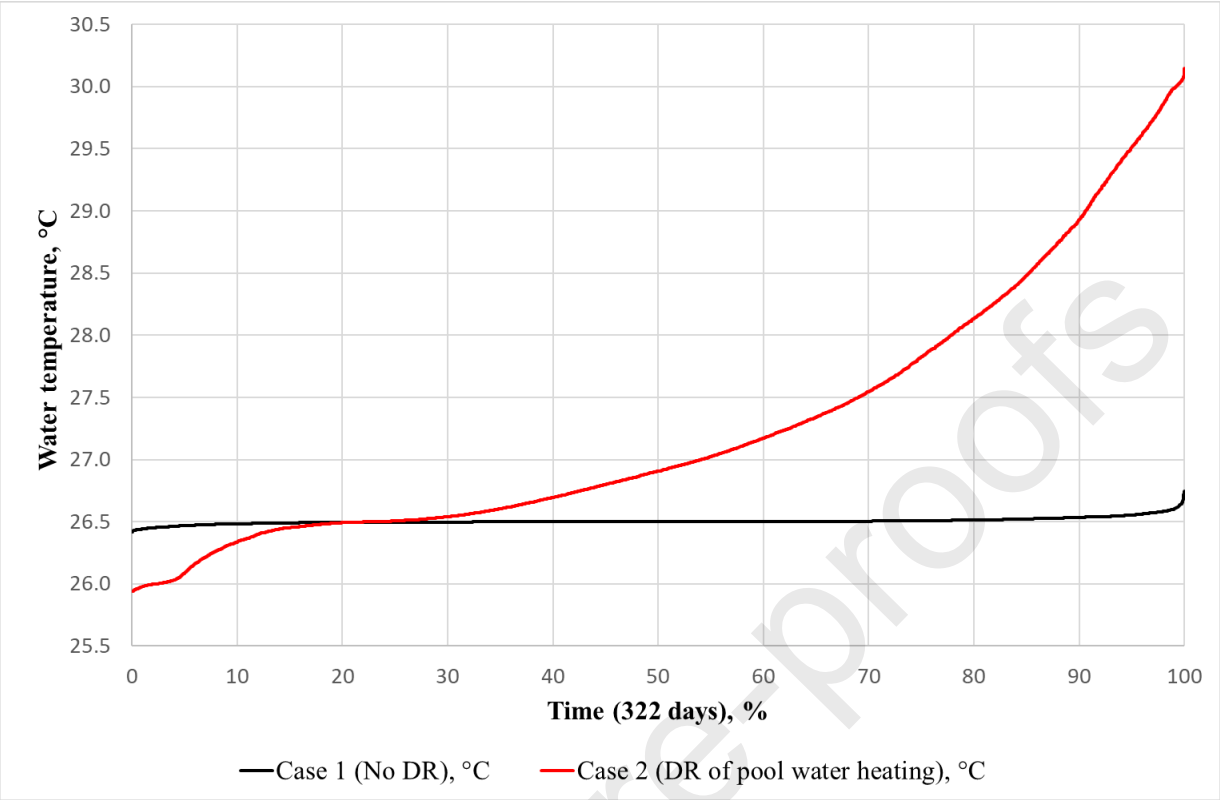

Fig. 11. Comparison of duration curve of big pool water temperature between cases 1 and 2.

Fig. 12 compares hourly district heating power of total pool water heating power between cases 1 and 2. In winter period, the hourly pool water district heating powers in case 2 get a significant variation compared with that in case 1. It should be noted that the variability of district heating power demand of the hall increases because the developed demand response control is used to store and discharge heat when it beneficial based on the price signal defined by the district heating producer. In this way, the swimming hall behaves like an energy storage in the district heat network and the flexibility of network can increase.

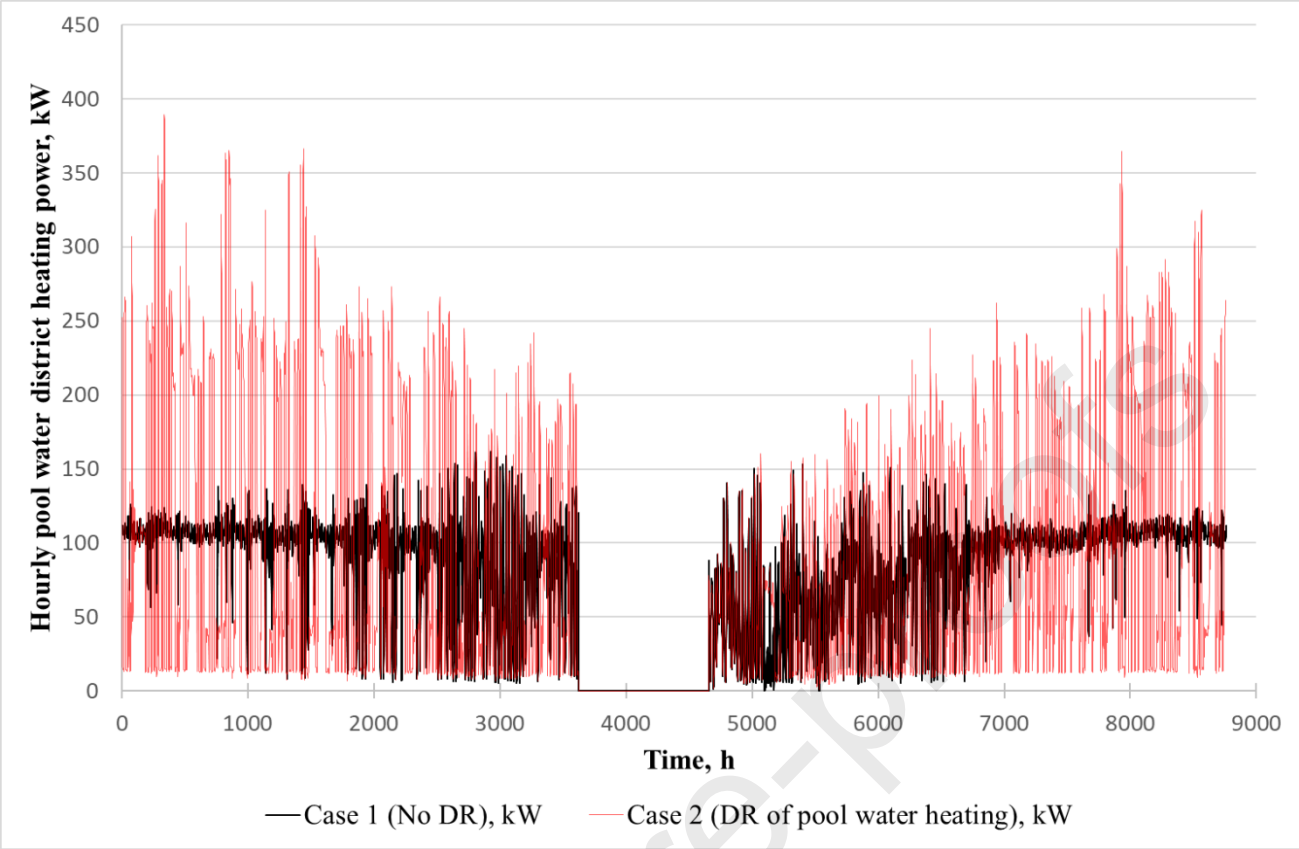

Fig. 12. Comparison of hourly district heating power of total pool water heating power between cases 1 and 2.

Fig. 13 compares the duration curve of total pool water district heating power between cases 1 and 2. The maximum district heating powers of pool water are approximate 160 and 390 kW in cases 1 and 2, respectively. During 64% period of the whole year, the pool water district heating powers in case 1 are larger than that in case 2, while the corresponding differences are all below 80 kW. However, for the rest 36% period of the year, the district heating powers of pool water in case 2 exceed that in case 1, while the maximum difference reaches to around 230 kW. Although the pool water district heating powers in case 2 are smaller than that in case during 64% whole year period, the water temperatures in case 2 can maintain higher than that in case 1 during 80% whole year period (Shown in **Fig. 11**).

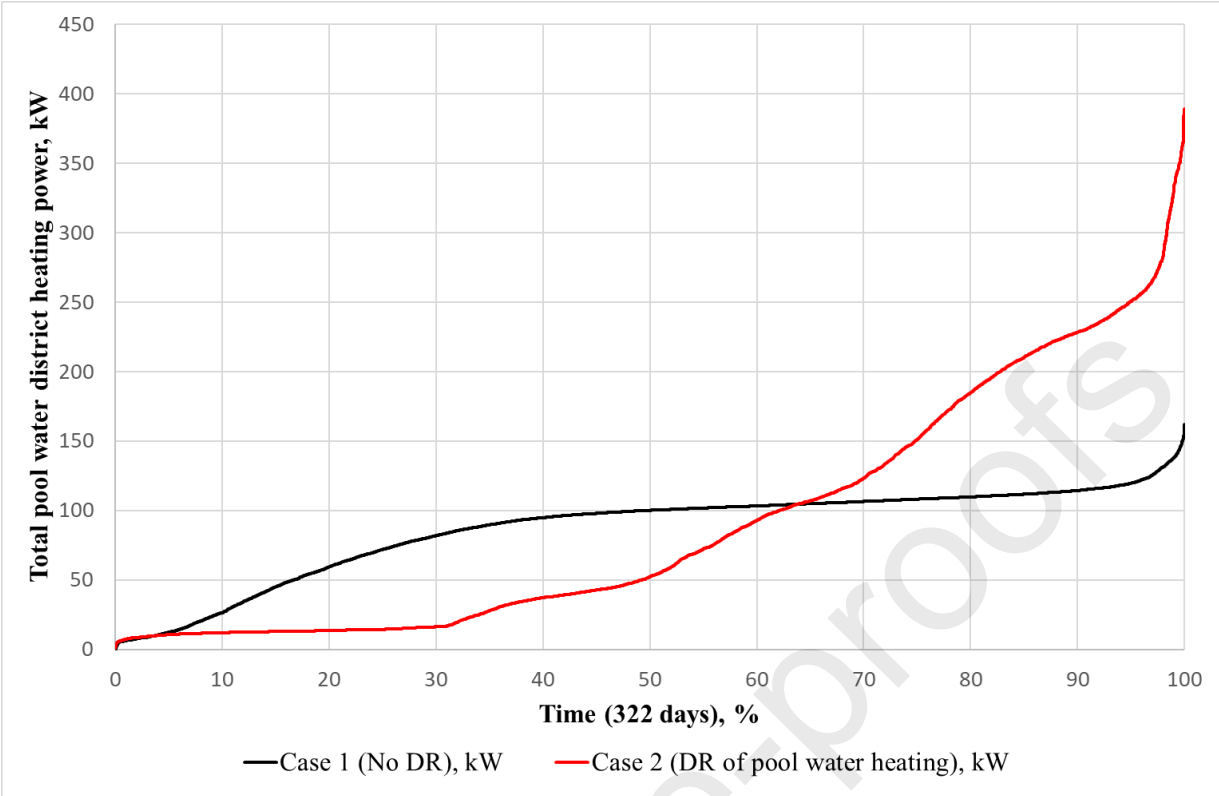

Fig. 13. Comparison of duration curve of total pool water district heating power between cases 1 and 2.

5.3 Breakdown of annual district heat consumption

Table 10 shows the annual district heat energy consumption of separate energy systems of both cases 1 and 2. The purchased district heat is used for space heating, supply air heating, DHW heating and pool water heating, while the largest heat consumer is DHW heating, followed by pool water heating. According to **Table 10**, the total annual purchased district heat in case 1 is 2 717 MWh/a, while that in case 2 is 2 764 MWh/a. In case 2, the temperature setpoint of pool space air is maintained at 2 °C higher than the pool water temperature, increasing the total purchased district heat by 1.7% and pool water heating of 5.5%.

Table 10 Breakdown of the heating energy of systems in both cases

Energy system	District heat [MWh/a]	
	Case 1	Case 2
Supply air heating	614	629
Space heating	458	453
DHW heating	976	976
Pool water heating	669	706
Total	2717	2764

5.4 Energy cost and maximum cost of profitable investment

Table 11 compares the annual energies and energy cost in the reference case (case 1) and the case with demand response (case 2). The annual purchased district heat in case 2 is very close to that in the reference case, slightly increasing from 2 717 to 2 764 MWh/a by +47 MWh/a, while the relative changes between them is only +1.7%. Demand response is not aimed at changing energy mounts in the system but managing the energy use of demand side. The annual cost of purchased district heat includes all the fees and value-added taxes. Compared to the annual cost of purchased district heat in the reference case of 155 000 €, that in the case with demand response is 153 000 €, decreasing by 2 000 € per year. In addition, the energy cost saving rate is about 1.1%.

Table 11 Annual energies and energy cost comparison.

Case	Reference case 1	Demand response case 2
Annual purchased district heat [MWh/a]	2 717	2 764
Absolute changes in annual energies [MWh/a]	--	+47
Relative changes in annual energies [%]	--	+1.7
Annual cost of purchased district heat [€]	155 000	153 000
Absolute changes in annual energy cost [€]	--	-2 000
Relative changes in annual energy cost [%]	--	-1.1

Three repayment periods are set e.g., 7, 10, 15 years to calculate the maximum cost of profitable investments, while the calculation method is presented in Section 3.0. The annual energy cost saving caused by demand response in the swimming hall is 2 000 €. The total energy cost saving for demand response of and the maximum cost of profitable investment in the swimming hall are between 10 000 € (7- and 10-year repayment period) and 20 000 € (15 years repayment period).

6. Discussion

Swimming halls belong to building sectors, which requires good indoor air conditions and consumes much energy [21]. As of 2018, there was 280 swimming halls in Finland, while the average annual growth of swimming halls was 2 in the past 10 years. The growth trend of swimming halls will go on in the future. In addition, many old swimming halls need renovation to meet modern regulations and achieve energy and energy cost savings. The huge new-built and renovation demands of swimming halls in Finland bring the potential of implementing smart and sustainable energy systems for swimming halls.

Recently, demand response has become a promising concept in the electricity market, and has been widely applied in building energy systems to achieve energy cost saving and balance supply and demand sides [41]. The investment cost of demand response system is small in the swimming hall because demand response is realized via specific algorithms to adjust the temperature setpoints. Demand response of district heat is applicable and recommended to the energy system of swimming hall due to its much large heat energy storage capacity. The buildings with heavy concrete structures offer large flexibility potential to energy production side if the demand response control is used. The flexibility potential is significantly larger in swimming halls because they are typically built with heavy building materials like concrete and large heat energy storage capacity of pool water can also be utilized in swimming halls. Because of this, a demand response-controlled swimming hall could operate as an energy storage in a district heating network and decrease the use of CO_2 intensive peak power plants.

It is important to note that the dynamic heat price used in the study was based on the existing hourly fuel price data without taking a value given by flexibility to a district heat producer into account. If a district heat producer gains additional profits because of increased flexibility and the profits are shared with customers, cost savings for a customer may be higher than shown in the study.

The application of demand response in the energy system of swimming hall has never been studied previously; Thus, this research is highly innovative and deserves further and deeper investigations. Since algorithms in this paper were not optimized, the future researches could achieve larger potential energy cost savings compared with that in this study. The recommended focuses of the future research could be optimization of demand response methods and algorithms in the swimming hall or other sports centers, e.g., ice halls and gyms both for a customer's and energy producer's point of views.

Swimming halls have huge potential of demand response of district heat due to the its significant heat demand and capacity. In the future, more accurate smart controls of energy systems in the swimming halls should be proposed and investigated to tap the potential of demand response controls on the energy and cost savings and CO_2 emission reduction. Also, a coupling of demand response control of electricity and district heat in a swimming hall could be studied e.g., when heat pumps are used to supply heat together with district heating.

7. Conclusion

In this paper, demand response is proposed and applied in the energy system of a swimming hall in Finland. The study process is divided into two parts, dynamic simulation with IDA ICE tool and simulation results post-processing with Excel 2016. The inputs for the swimming hall simulation models include data from studied swimming hall, assumed model parameters, hourly local weather data and hourly district heat prices. The focus of this paper is to apply demand response of district heat with a rule-based demand response algorithm in the studied swimming hall, while peak clipping and load-shifting were two demand response concepts studied in this paper. The conclusions are as follows:

1. The large storing capacity of pool water in swimming hall promises the large amount of charged and discharged heat energy and could increase the flexibility of a district heating network.
2. The application of demand response of district heat can increase the average pool water temperature from the normal setpoint of 26.5°C to 27.3 °C throughout the year.
3. The application of developed demand response control of district heating can reduce the average purchased district heat price and total energy cost. In the studied swimming hall with district heat demand response for pool water and pool space air, the corresponding district heat energy cost saving reaches 1.1%.
4. During the repayment periods of 7 and 15 years, the energy cost savings and maximum cost of profitable investment for the demand response control are between 10 000 € and 20 000 €, respectively.

Acknowledgement

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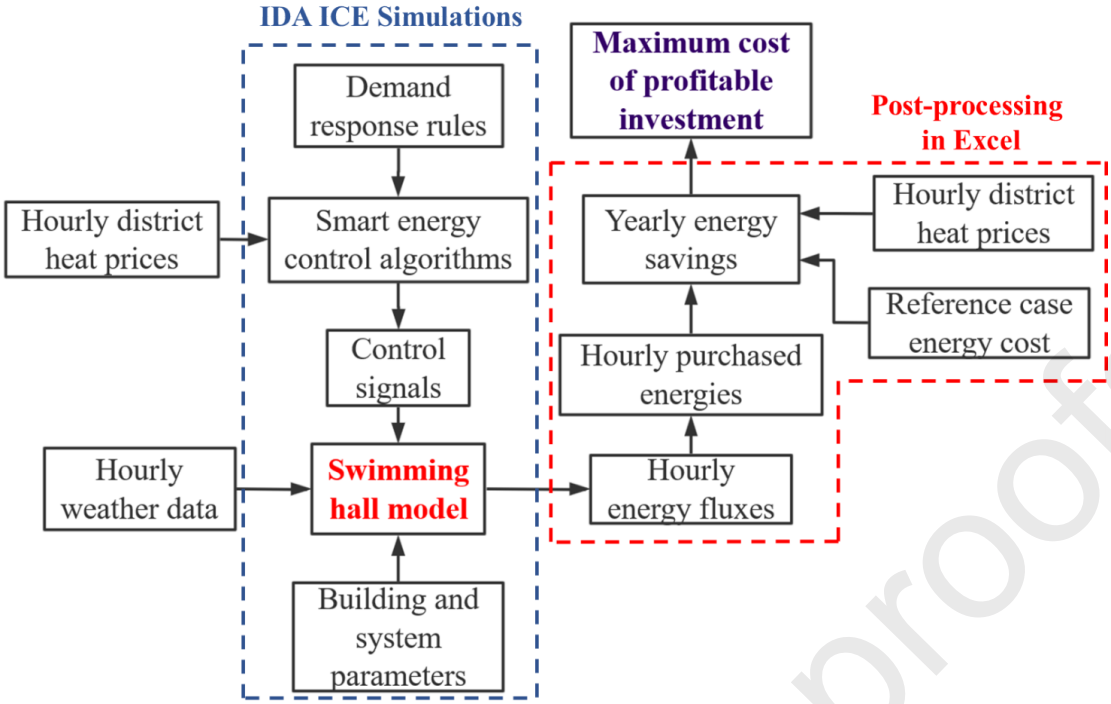
Graphical abstract



The logical diagram of method structure in this paper.