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Feasibility of Grey Water Heat Recovery in Indoor Swimming Pools

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Abstract: Swimming pools are used around the world for recreational, rehabilitation and physical activity. From an energy and environmental standpoint, grey water as a waste thermal potential of swimming pools is a valuable heat source produced continuously in extensive, measurable and large quantities. The main objective of this article is to analyse the feasibility of proposed grey water heat recovery (GWHR) system from the showers and backwater from swimming pool filters for an indoor pool located in recreation centre in Poland. Analysis, calculations and results were obtained and discussions of water and energy consumption were carried out for the mentioned indoor swimming pool on the basis of real measurements case study for water flow rate, water temperature in swimming pools and showers. The results ensure a significant potential of energy savings by using the proposed GWHR system, which allows to reduce the energy demand by 34% up to 67% for pool water preheating and domestic hot water (DHW). The environmental impact of proposed GWHR system was analysed and calculated by using Common Air Quality Index. Environmental results are illustrated and discussed specially for the reduction of CO_2, NO_X, SO_X emissions and dust and ensure a significant reduction of these pollutants in range of 34% to 48%.

Keywords: European regulations for swimming pool; water consumption in swimming pool; heat recovery in indoor swimming pools; CAQI Index; pollutant emission reduction; environmental impact of energy use

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1. Introduction

A recent lifestyle in different countries has a characteristic trend for the vast and intensive use of basins and swimming pools. Swimming pools are used around the world as one of the most popular types of activity, which can be classified as sports, wellness (recreation), rehabilitation, Olympian races, diving, water polo and recreation, water fun and physical activities, sport facilities, etc. [1].

Swimming pool use can be both public and private. Many sport clubs, fitness centres and health clubs have swimming pools used mostly for training or recreation. Many towns and cities provide public pools; even hotels have pools available for their guests to use at their own leisure. High schools, universities and educational facilities sometimes have pools for physical education classes, creational activities and competitive athletics such as swimming teams, which have a significant impact on the public health. Swimming pools can also be found in many private homes or single-family buildings. There are many types of pools for particular user types, for example paddling pools, teaching or learner pools, diving pools, special features such as "flumes" or water slides. Even though named swimming pools, they are often used for a variety of recreational activities, such as SCUBA diving, aqua-aerobics and so on, specialised water sports and physical therapy, as well as for the training of lifeguards, etc. The swimming pools may be heated or unheated, using different active heating technologies, various energy technologies, applications and solutions [1–3].

As such, there is an increase in energy saving and environment conservation terms, including the introduction of alternative swimming pools' heating technologies, based on Renewable Energy Systems (RES), which emerges as an inevitable solution [4].

Figure 1 shows the main categories of swimming pools in Poland. Mainly based on the European weather conditions, which lead to the buildings for swimming facilities, the pools can be divided into the following types [5–8]:

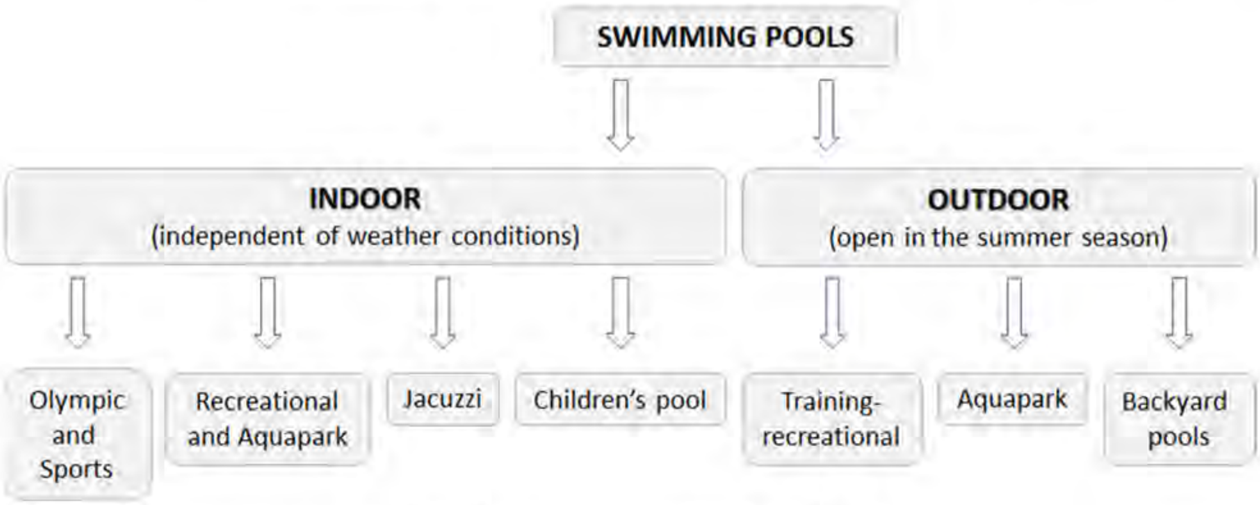

Figure 1. Division of swimming pools in Poland.

A—Indoor swimming pools: This type of swimming pool buildings have a complex structure; in addition to the basin they have an entrance hall, dressing and facilities rooms, sanitary, heating and ventilating halls.

The building envelope must fulfil special requirements according to the special indoor climate in swimming facilities. Indoor swimming facilities have a special indoor climate in the pool hall and shower area. The comfort of users is mainly influenced by air temperature, water temperature, humidity and air velocity [9,10].

Facilities with indoor pools can be a fully integrated combination of indoor and outdoor pools. This combination only makes sense if the indoor and outdoor pools remain open in summer, so the people can move from the outdoor to the indoor pool and vice versa according to weather conditions, so this type of swimming pools can be function generally during the whole seasons of the year.

B—Outdoor swimming pools: In these pools, the swimming basins are located outside the building. The entrance hall, dressing rooms and sanitary facilities as well as dining facilities shall be of lightweight construction which is not heated. So, these pools are open seasonally, in summer. The beginning of bathing season starts in the middle of May and ends mainly in the middle of September. If heating is desired, mainly renewable energy sources, especially solar thermal collectors with means of seasonal energy storage systems, can be used.

C—Sports pools: Sport swimming pools, mostly exist without additional recreational facilities, and are mainly used in school, sports halls and health care centres. Sports swimming pools usually have the same water temperature. The sport swimming pool program includes swimming, diving and swimming lessons and training courses.

D—Recreational pools: This type of pool has a multifunctional range of activities which, in addition to sports, health care and training or teaching school options, also include a recreational aspect like additional fun attractions.

E—The "fun" pools (aquapark): They offer different activities, like fun on and into the water. These pools have characteristic facilities for fun and relaxation, such as various slides, currents, ingenious theme areas, but also a wide range of spa facilities, such as saunas and wellness facilities, and gastronomy.

The data of the main statistical office analysis [8] shows that in the years 2013–2018 the share of outdoor swimming pools in the total number of swimming pools in Poland ranged from 32% to 38% and indoor swimming pools 62–68%.

The total number of swimming pool basins in Poland is 849, which can be divided as follows: 12 Olympic pools, 68 sport pools, 494 communal pools (with dimensions of 25 × 12.5 m) and 275 training and recreational pools as shown in Figure 2 [5].

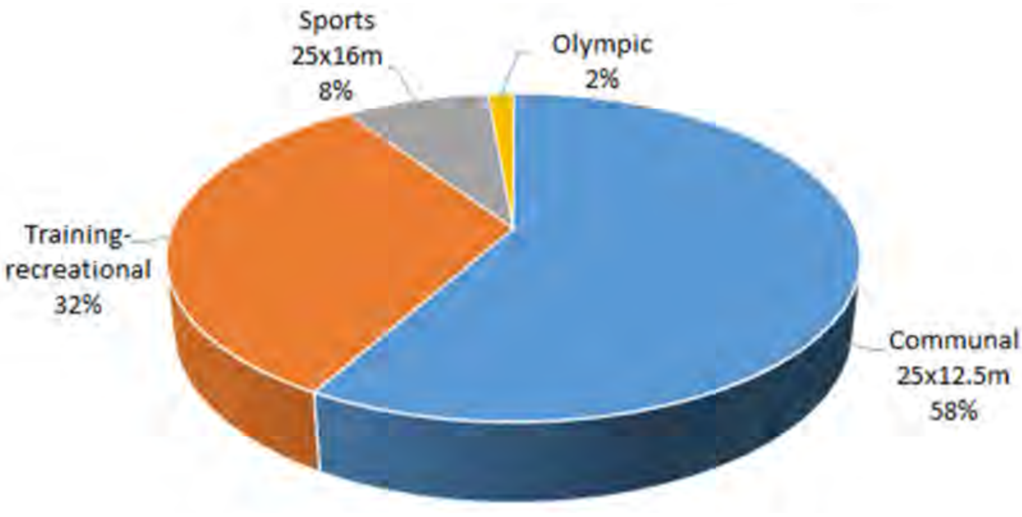

Figure 2. Characterisation of swimming pools based on [5].

Snapshots of swimming pools state in Europe are as follows:

- In Germany, the total number of indoor and outdoor swimming pools is 6006; currently 31 pools are under construction (available on 18 February 2021), outdoor and indoor swimming pools comprise 53% and 47%, respectively [11].
- In Switzerland, most of today's swimming pools which are mainly classical public indoor pools that were built in 1970s without fun and entertainment attractions or teaching pools; most of them need major and fundamental renovation. Currently there are approx. 470 public indoor pools and about 350 school pools, as well as an additional 1000 pools in hotels, hospitals, etc. There are currently around 600 outdoor swimming pools and have similar case [12,13].
- In the UK, the number of swimming pool facilities is 3170, but the total number of the pools is 4559 [14].
- In France, currently there are around 2889 public swimming pools scattered across French cities (this number fluctuates from year to year) [15,16].
- According to the State Health Institute database, there were 957 public swimming pools in Czech Republic in 2014 [17].
- Spain has a large number of public and communal swimming pools: the total swimming pools are of 121,070 facilities, according to data of Piscina & Wellness Barcelona Show and the Spanish Association of Swimming Pool Sector Professionals (ASOFAP) [18]. Additionally, there are plans to enhance this number by 26,000 new swimming pools in the near future [19].

As mentioned above, the bathing and swimming activities are becoming one of the basic needs of people as popular leisure activities; in addition, swimming pools and the concerned technical advanced technologies have become one of the promising fields of scientific investigations and research fields [20,21]. Recently, health and environmental awareness is growing; therefore, the swimming pools must meet the different users' requirements, such as: necessity and quest for relaxation, sport and fitness, games, fun and entertainment, personal health and hygiene. These requirements necessitate essential changes in technical approaches and swimming pool building construction, renovation or extension of existing pools, including energy efficient and environmentally friendly technologies [22].

Recent studies [6,20] indicate that more than 50% of the population has practiced swimming more often than other sport activities. Swimming activity is regularly practiced by 13% of the population, and it is the 4th most frequent, behind cycling/mountain biking, gymnastics and jogging. The swimming activity, after hiking and mountain hiking, is practiced for the longest period in life [6,15,20]. Swimming has been named the sport preferred by most non-sportsmen—4% and therefore has a growth potential of 11%. Swimming has great growth potential, especially among older age groups and women. In addition, more than 60% of the respondents (i.e., for the Swiss population) stressed the importance of indoor swimming pools, and 20% called for the promotion of indoor and outdoor swimming pools [9,20]. The requirements for the swimming pool buildings construction and equipment of swimming pools are contained in the standards and regulations of national swimming associations, which should meet the requirements of International Swimming Federation (FINA) 2017/2021 regulations [7,23–33].

The following sections of this article outline the water consumption characteristics in swimming pools. In addition to water consumption, the next sections focus on the possibilities of reducing energy consumption and energy saving analysis by heat recovery from grey water GW, and pollutant emissions from the used energy for water heating in indoor swimming pools are presented and discussed. Moreover, GWHR system analysis and calculations are performed. The real practical measurements obtained from water and energy consumption as a case study from swimming pool facility in Poland is elaborated, calculated, illustrated and compared. The proposed GWHR system does not take into account the technology details of heat exchanger design, pool water treatment, including the filters, rinsing waters and specific technical solutions of heat recovery. Detailed technical issues as well as the economic evaluation are closely evaluated over the article. For this facility, the water and energy consumption are carefully evaluated and the environmental impact assessment is strictly conducted and calculated especially for CO_2, NO_X, SO_X and dust emissions. The results are illustrated and discussed to focus the water, energy and environment savings potentials of indoor swimming pools.

2. Water Use in Swimming Pools

Swimming pools are a significant user and large consumer of potable water and energy in cities. Water use analyses in general for a swimming pool have not been done with respect to the entire spectrum of climate conditions. Thus, the lack of monitoring requirements produces a lack of guidance for their water consumption [34].

Water consumption is not even included in the aspects addressed during swimming pool inspections [3]. Monitoring water consumption data in swimming pools is important to help the building owners and facility managers to ensure that the building is functioning properly and in an environmentally friendly manner [3,34]. Furthermore, monitoring and consumption data analysis will enable the owners to provide and install low water consumption technologies [3,34,35], which improve the investment and operation cost items and will contribute to social benefits and to reducing the pollution and environmental consequences [3,34–38].

Many detailed indicators and benchmarks were provided by [37,39–41] for water management and consumption, and different units were taken as useable water performance indicators.

In addition, the water consumption for swimming pools in tourism establishments is poorly documented. The indicator for water use efficiency is water consumption per user and water consumption per square meter of pool water surface area.

Monitoring and benchmarking of water and energy consumption is a best practice key measure for pool managers [35,42,43].

Water use in a swimming pool can be categorised into four major components:

1. Initial filling water;

2. Makeup water for maintaining the water level within an operating range;
3. Backwash water for cleaning water filters; and
4. Cleaning water for pool decks and structures.

Some of the above factors can be controlled to reduce the water use by a swimming pool. In order to estimate average and peak water use patterns and water conservation strategies based on long-term perspectives, a continuous simulation model for a swimming pool has been developed. Locally monitored long-term climate data can be applied based on ranges of swimming pool operating strategies [44].

The water consumption in swimming pools depends on many factors such as: the scale of swimming pools, the range of services in pool buildings and needed indoor conditions; the qualification of the equipment of swimming pools; the water requirements for hygiene and sanitary purposes in indoor swimming pools based on regulations and standards and facilities; the time of single circulation (filtering) of water in swimming pools, whose amount depends mainly on the type of pools and the number of people using them; water conservation practices, etc. [45,46].

A number of factors can affect the amount of water used to fill and maintain the desired water level in a swimming pool. These factors for swimming pool water usage can be summarised as follows [35,42,43,45,46]:

- Size of the pool (surface area and depth);
- Local climate: Precipitation, evaporation (air and water temperatures, wind, humidity, shadowiness, etc.);
- Design conditions of the pool: Presence and use of a pool cover, pool water temperature, presence of water aesthetic features like a fountain or waterfall, PH and chemical content of pool water, leakage;
- Individual maintenance trends: Frequency of backwashing, frequency and the method of pool and pool deck cleaning;
- Human behaviour: Splashing-out and swimming habits.

The choice of disinfectant depends upon a number of factors, including safety, size, type and location of the pool, compatibility with the source water, bathing water and the operation of the pool [35,42,43].

As swimming pool water should be of potable water quality, the topic of disinfection is very important from a hygienic point of view. However, due to the scope of this issue, it will not be developed further in this article.

2.1. Pool Water Temperature Requirements

Regardless of the weather conditions, the indoor pool as it is known can be used all year round compared to the outdoor pool. The thermal conditions of the indoor pool such as pool water or indoor air temperature must be constant and the variation in humidity is low. The water in indoor swimming pools is heated to the required temperature, which will ensure comfort temperature for the users. The pool water temperature depends on the purpose of the pool and varies according to national guidelines as follows:

(A) Poland [24]:
  - Water temperature in swimming pools for swimming lessons and jumping pools: 27 °C to 28 °C;
  - Water temperature in children's swimming pools: 30 °C to 32 °C;
  - Temperature in swimming pools of therapeutic type: 32 °C to 36 °C.

(B) International Swimming Federation FINA specified the regulations which are required for swimming pool water temperatures according to the intended use [7]:
  - In swimming pools, also for Olympic games and world championships: 25° to 28 °C;
  - Diving facilities, also for Olympic games and world championships: min. 26 °C;
  - Water polo, as well as for Olympic games and world championships: min. 26 ± 1 °C;

- Artistic swimming, likewise, for Olympic games and world championships: min. 27 ± 1 °C;
- High diving: min. 18 °C in open water venues and preferable min. 26 °C in venues with an artificial pools.

(C) The Swiss Swimming Federation SSCHV [25] and the Swiss Ministry of Sport BASPO [6] adopt the guidelines of the FINA, which sets out the requirements for swimming facilities, water jumping, water ball and synchronous swimming and complements them with recommendations, in particular for systems intended for use by the general public. FINA's rules are reviewed every four years [25]. The water temperature must vary according to the activity [6,25]:

- Sports swimming pool: 25 to 28 °C, but SSCHV recommends min. 26 °C for indoor and 23 °C recommended for outdoor pool;
- Swimming pool for Olympic games and world championships: min. 24 °C, preferably 25 °C to 26 °C;
- Water polo games should be played at water temperatures below 20 °C only with the consent of both teams (in Switzerland, water polo games can be played at water temperatures below 20 °C only with the consent of both teams);
- Artistic swimming, also for Olympic games and world championships: min. 26 ± 1 °C;
- Non-swimming and recreational swimming pools: 28 to 30 °C;
- Swimming pool for small children (paddling pools), play area for children in water: 30 to 32 °C (in the outdoor pool: 23 to 26 °C);
- Aqua-baby pool (6 month to 3 years): 30 to 34 °C;
- Swimming pools for small children who swim with their parents (deep): 32 to 34 °C;
- Play pools: around 30 °C;
- Getting used to the water in the paddling pool and toddler water play pools: 30 to 32 °C (in the outdoor pool 23 to 26 °C);
- Warm outdoor pool with a bathing area in the bathing hall and with benches, massage jets, flow zones and often other attractions: 32 to 34 °C;
- Hot whirlpools: approx. 37 °C;
- Therapeutic gymnastics and physiotherapy: 32 to 34 °C;
- Aqua aerobics, aqua fitness: 27 to 30 °C;
- Aqua jogging: 27 to 28 °C (in the outdoor pool: 23 to 24 °C);
- Swimming pools for swimming lessons: approx. 30 °C (in the outdoor pool: 23 to 26 °C).

(D) The German Swimming Association (DSV) [26–32] defines the water temperature in competitions as 25 to 28 °C, but:

- Temperatures in pools for water polo: min. 21 °C;
- Pools for artistic swimming up to min. 26 ± 1 °C;
- Pools for diving: min. 26 ± 1 °C;
- Pools for open water swimming: min. 16 °C and max. 31 °C;
- Masters competitions in open water swimming may not be held at water temperatures below 18 °C.

The DSV [30] divides pools into four categories A to D depending on the importance of the swimming competition:

- Category A for the highest requirements: international competitions from FINA [47], LEN [48], German championships with Olympic qualification, FINA and LEN competitions;
- Category B for high requirements: national, official competitions of the DSV and its regional associations;
- Category C for medium requirements: further official competitions of the DSV and its regional associations;

- Category D for sub-requirements: regional, official competitions, leisure and popular sports.

2.2. Indoor Thermal Requirements and Comfort Design Conditions in Indoor Swimming Pools

Swimming pools are artificial ecosystems for bathing in which people imitate the conditions of natural waters and indoor controlled variables. These variables like pool water temperature, swimming pool water surface area, air temperature, relative humidity, ventilation, lighting and water pumping must be controlled to create healthier indoor environments for different users (e.g., swimmers, spectators and staff) each of whom wear different types of clothing and engage in various levels of activity. The mentioned variables values can vary based on pool operation throughout the year.

In indoor swimming pools, air temperature and the water temperature need to be balanced to achieve the appropriate humidity, minimise the evaporation of swimming pool water and optimise user comfort.

On the other hand, indoor thermal requirements, as well as the energy demand of swimming pools and indoor aquatic sport centres, depend on the geographical location of the building, the time of year, the sporting activity and the opening time [39,49,50].

Indoor swimming pool facilities are still influenced by age of the building, usable area [51,52], water surface, average water temperature, water usage and swimming pool visitors [49].

For research, the usable area and the water surface area are commonly used [39], because it is difficult to obtain accurate data about the number of visitors and water usage.

The thermal comfort of users depends on many factors and thermal requirements, including: air temperature, temperature of surrounding surfaces, relative humidity, air movement, physical activity of users, etc.

In swimming pool halls, the thermal comfort of users is mainly ensured by the ventilation system. However, there are climatic zones where the radiation space heating facilities must be used. Heaters are mainly used in auxiliary areas such as administrative offices, entrance area, storerooms, etc.

The installation of heaters in the pool hall may be necessary for swimming buildings where exceeded dew point is expected, and in these areas the ventilation system cannot provide adequate ventilation.

Space heating is mainly used for floor and wall surface heating in swimming pool halls and for heating of benches and relaxation zones, e.g., in biological regeneration zones (saunas, steam baths, etc.).

It is recommended to heat the pool floor to a temperature of 28–32 °C; optimally it can be 29 °C. The recommended wall surface temperature ranges in 33–35 °C, and temperature for benches in rest areas ranges in 33–35 °C [24].

The comfort design temperature required for the pool hall should be determined individually for each pool case [6,24]. In [24] it is recommended that the air temperature should be higher by 1–2 °C than the base pool water temperature. In a well-insulated building with little glazing or intensive underfloor heating, it is sufficient to be about 30 °C [6]. With a lot of glazing and no underfloor heating, the temperature ranges between 31 and 32 °C [6]; however, indoor air temperature should not exceed 32 °C in winter [6,24].

The relative humidity may range from 46% to 60% in a pool hall. Depending on air pressure and building location above sea level, it is necessary to avoid the condensation on the inside partitions of the building, e.g., on the window surface, and the humidity must be reduced in winter to avoid the temperature dropping below the dew point temperature [6,24].

Relative humidity in a pool hall, depending on air pressure and location above sea level, may range from 46% to 60%, and absolute air humidity from 14 to 15 g/kg [6,24].

In the summer, the relative humidity can be around 63% in case of external temperatures above 19 °C [6].

2.3. Total Water Consumption in Indoor Swimming Pools

Total water (domestic hot and cold water) in indoor swimming pools is used for the functionality of the swimming pool and for sanitary and hygienic purposes (handbasins, showers, toilets and urinals). The total water use overview for swimming pools is illustrated in Figure 3.

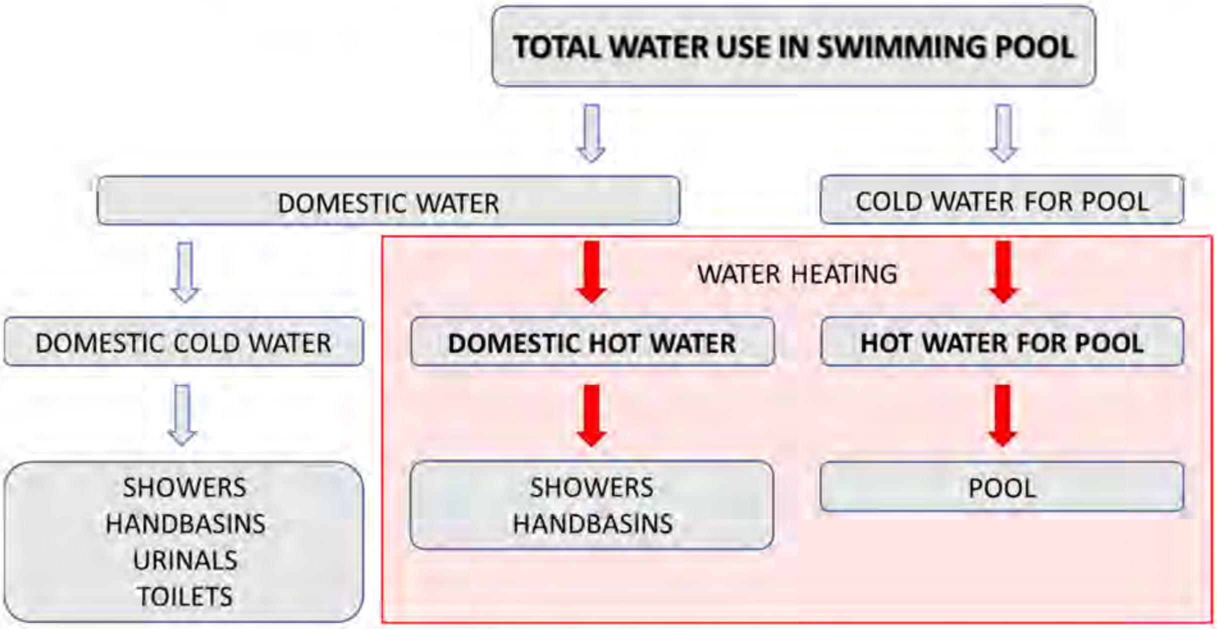

Figure 3. Water use in swimming pools.

Water losses can occur by evaporation and water being dragged out of the pool when swimmers exit the pool, this loss for each exit can amount to 0.75 L per person, so the water in indoor swimming pools is used mainly to replenish pool water losses, for the hygienic and sanitary purposes of people using the bath, and maintaining cleanliness in the facility. The water consumption in an indoor swimming pool according to Polish standard is 160 L/person per day [53], while supplementary water consumption per person in swimming pool according to the German standard DIN 19,643 and sanitary, hygienic requirements is 30 L/person per day of fresh water [23,24]. The water requirements for hygiene and sanitary purposes in indoor swimming pools based on regulations and standards do not take into account new technologies and economical fittings; therefore, they are higher than the actual water consumption rates.

In this section, the authors analyse only the water consumption on the basis of pool water losses, which use the unit of water consumption in L/person per day.

Supplementary pool water is tap water that meets the potable water requirements and is used to recompense the water losses in the pool. The water loss in the pool depends on the type and function of the pool, e.g., an indoor pool only for a sport, a pool with multifunctional adventure, pools for swimming lessons or a recreational purpose, etc. Water losses mainly result from natural evaporation, lifting on the bodies for bathers when moving between pools, and splashing. An important factor influencing the demand for makeup water is the type of technological system, the number of devices installed and their efficiency and effectiveness, e.g., the required volume of water needed to rinse the filter beds. It is necessary to add the water (cold and DHW) for sanitary and hygienic purposes used in handbasins, showers, toilets and urinals.

2.3.1. Total Water Consumption—European Guidelines

The total water consumption in an indoor pool can be grouped as in Table 1, which represents water consumption guideline key values, which are dependent on the technical requirements, available guidelines and user habits [6]. The presented data may change according to individual water consumption rates, technical facilities, swimming habits, e.g., especially for schools, sport clubs and pool users [6]. From Table 1 it can be concluded that the showers are one of the main water consumption sources in indoor pools.

Table 1. Total water consumption in indoor swimming pool [6].

Water Consumption Target	L/Person	Share in %
Filling the pool	5–10	4%
Constant water inflow to the pools adapted to the number of users (at least 30 L/person)	50	28%
Average limits:		
Shower before and after bathing	50–80	37%
Water consumption for toilets, handbasins, dry cleaners, canteens	40–70	31%
Total water consumption	145–210	100%

According to [40,42], the main determined sources of water consumption in a typical community pools are backwashing, showers, evaporative losses and leaks as shown in Figure 4. Water use for amenities (e.g., onsite cafes) may not apply to accommodation pool areas.

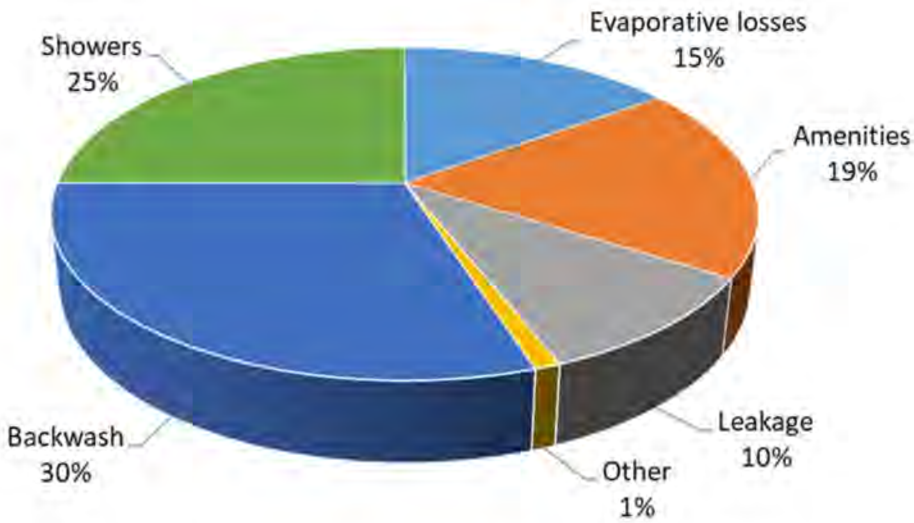

Figure 4. Fields of water consumption in a typical community pool [42].

D. Styles et al. in [42] shows that an indoor heated 25 m (300 m^2) pool located in hotel can lose 21,000 L of water per week by evaporation (water temperature of 28 °C, air temperature of 29 °C and relative humidity of 60%).

The values of total water consumption in pools varies in professional references, they are in range of 150–260 L/person [6,54]. Taking into account the presence of people, the provided average water consumption is 180 L/person [6,54] for recreational and leisure swimming pools in Germany with very large number of users (up to 500,000 users per year), the average total water consumption is 185 L/person, with a rather lower limit for swimming pools with a large number of users and an upper limit for those pools with a smaller number of users. However, the water consumption according to the Polish standard/guidelines for water consumption in indoor swimming pool facilities is 160 L/person and for outdoor swimming pools it is from 200 to 400 L/person as mentioned in Table 2.

Table 2. Total water consumption in a swimming pool in Poland [53].

Water Consumption Target	L/Person
Indoor swimming pool	160
Outdoor swimming pool (a) sports (b) for mass use	 200 400

For sports facilities, the average consumption of DHW by using a shower is 50–70 L/person as mentioned in Table 3 [55]. However, the mentioned values are according to the water temperature 45 °C. According to the same references, DHW consumption for indoor swimming pools alone is 50 L/person in relation to 40 °C as in Table 3.

Table 3. DHW consumption in a swimming pool [55].

Water Consumption Target	L/Person	Temperature in °C
Sports facilities	50–70	45
Indoor swimming pool	50	40

2.3.2. Total Water Consumption in Swimming Pools—Polish Database

An adequate current database review concerns the applied technologies for water consumption in indoor swimming pools on the basis of Polish regulations and standards, which confirm that the hygienic and sanitary facilities in indoor swimming pools do not take into account the procedures of applying water consumption monitoring and measures, advanced applications or implementation of energy saving technologies, as well as economical fittings, etc. Therefore, the water consumption in indoor pools is often is much higher than its actual state or practical water consumption values in Polish swimming pools. This usually leads to an overestimation of the water balance for indoor swimming pools and leads to oversizing of the water consumption limits and increase the investment risks and economic bills [56]. Piechurski [56] analysed two different indoor swimming multifunctional pools in Poland and summarised the results as follows:

Swimming pool A—indoor swimming pool with multifunctional pools with two swimming pool water circulation system in this building:

- The first one treats water for a 25 m × 12.5 m swimming pool;
- The second is for a recreational pool with hydro massage and a slide.

Swimming pool B—Aquapark with multifunctional pools:

This pool consists of six swimming pool water treatment units for several types of swimming pools with different functions and various shapes and water circulating volumes: sports pool, recreation pool, padding pool, whirlpool, outdoor swimming pool, cooling pool.

The research included monthly monitoring of water consumption from the real registered users. Piechurski [56] researched the water consumption calculations on the basis of monthly water consumption and users' numbers as mentioned above. Table 4 presents the calculated average water consumption per person in the given months for the type and characteristic of analysed swimming pools.

Figure 5 shows the calculation results of water consumption for the analysed above-mentioned indoor swimming pools. The results in Figure 5 indicate that the water consumption per person per day in both A and B pools is much lower than the estimated values in regulation and adapted standards.

Table 4. Characteristics of the analysed pools [56].

	Pool Type	Pool Basin Size in m	Water Surface Area in m^2
A	Sports pool + Recreation pool	25 × 12.5 -	in both pools 372.5
B	Sports pool	25 × 12.5	312.5
	Recreation pool	irregular	520
	Paddling pools	irregular	70
	Whirlpool 1 piece	round	1.3
	Whirlpool 2 piece	round	2.6
	Outdoor	-	626
	Cooling pool	-	11

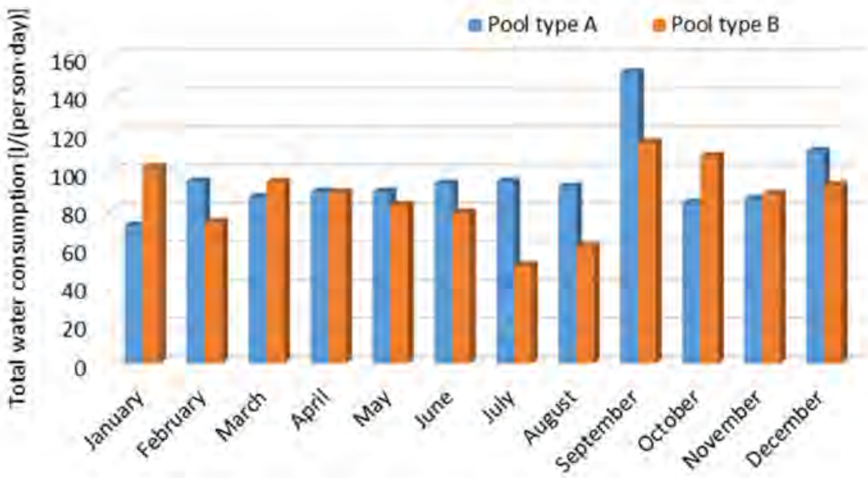

Figure 5. Total water consumption in both of A and B swimming pools [56].

The average consumption of total water in the analysed facilities of both indoor swimming pools in 2012 is approx. 93.3 L/person.

The calculated annual average values do not take into account the periods of operational, technical breaks and holidays.

The measurements show that the practical annual water consumption is lower than the current requirements adapted in regulation on the determined average standards of water consumption, which was set for swimming pool facilities at 160 L/person [56].

2.4. Grey Water

GW is the term used to describe the wastewater from activities such as bathing, showering, laundry, dishwashing. GW differs from "black water" which is wastewater used in toilet flushing, urinals and designated for sewage systems.

GW may be collected from showers, bathtubs and sinks and reused for toilet flushing and irrigation [57].

In traditional swimming water systems, where no recovery or advanced water saving facilities are mounted, the used DHW in the swimming pool facilities from the handbasins, showers or filter rinsing, toilet directly is discharged together to the sewage system.

Figure 6 shows the generated wastewater in swimming pools, where the sewage can be divided into two groups. The first is known as black sewage, i.e., those that come from flushing toilets, while the second group includes GW, or those that come from showers or filter rinsing.

Figure 6 presents the types of sewage, where GW can be divided into little polluted, originated from handbasins, showers; and heavily contaminated, containing impurities from washing machines and kitchen sinks.

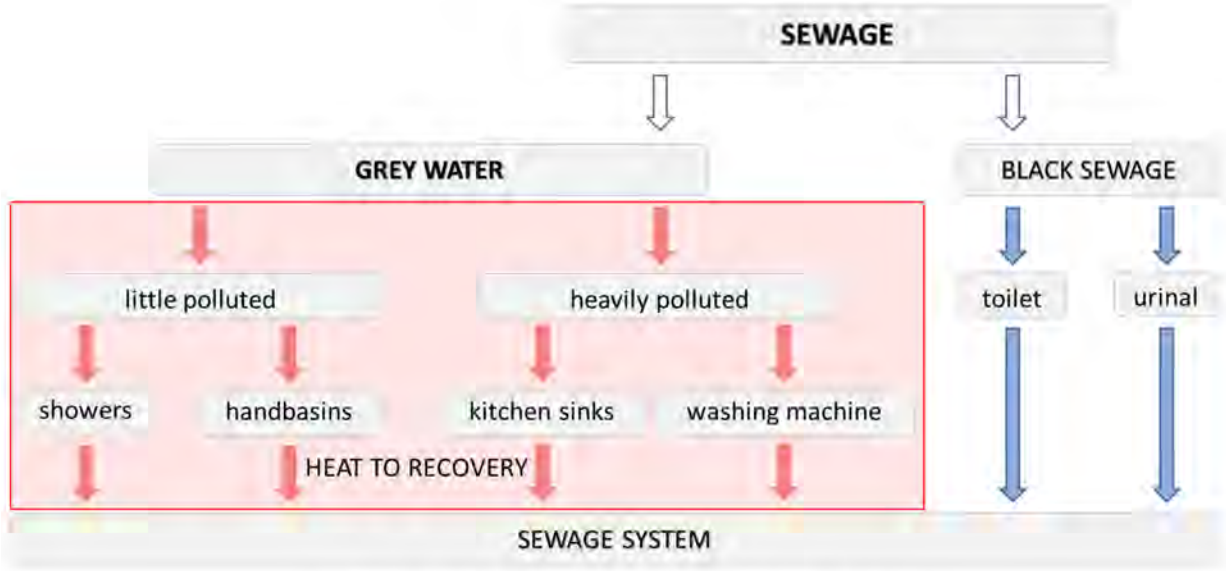

Figure 6. General types of sewage in Europe regulation.

As presented above in Figure 6, the wastewater discharged into the sewage system has a significant amount of heat that can be recovered, so the sewage system an essential heat source which needs instant strategies, technical arrangement and advanced solution to save the wasted thermal energy and solve the associated environmental issues. On the other hand it is clear that indoor swimming pools produce huge amounts of GW per day with useful temperature; at the same time GW possesses huge amounts of ready-to-use thermal energy.

Table 5 presents the temperature field of sewage in swimming pools. It can be concluded that the heat can be recovered from GW, so this article deals with the heat recovery issue from GW in swimming pool and presents the benefits of heat reuse potential from GW.

Table 5. Type of sewage in swimming pools [55,56,58,59].

Source of GW in Swimming Pool	DHW in °C	GW Temperature in °C
Showers, handbasins	39–42	28–41
Filter rinsing	-	25–35
Swimming pool water losses	-	25–35

It is necessary to note that GW differs significantly from toilet flushing water, both in the amount and variety of chemical components and bacteria (excreta to toxic chemicals).

According to national standard PN-EN 12056-1:2002 [60], GW is defined as faecal-free, contaminated water that is produced during bathing, hand-washing or washing except toilet flushing. It owes its name to its colour and status, so it is highly contaminated and does not qualify as potable water.

3. Energy Consumption in Swimming Pools

Swimming pool water heating is one of the largest energy consumptions in buildings, after space heating, air conditioning and lighting [61].

Indoor swimming pools like most other building types with larger structure have their costly energy requirements, keeping in mind that the swimming facilities not only involve the actual swimming pools, but also the associated infrastructure planning, such as lightning, gym equipment, pumps, fans, technical services, power for filters and backwashing pumps and in general cases water treatment, heating and indoor heating and ventilation, automation, sewerage management, air-handling systems and car parking, etc. [37,38].

Conventional heat sources can be used to heat the water in swimming pools (heat exchangers cooperating with a boiler or from district heating network). The heating process basically is connected with increased operating costs and high consumption of energy. In order to reduce energy, a more effective solution should be adapted, which can use of a renewable energy source or hybrid energy systems, waste heat recovery, e.g., from GW, etc. [62].

The heat requirements in outdoor swimming pool depend on the following factors:

- Pool surface area;
- Water depth;
- Target water temperature;
- Availability of a pool cover;
- Ambient air temperature, wind speed, etc.;
- Colour of the pool;
- Meteorological conditions of the area where the pool is located.

Meanwhile, indoor swimming pools depend on the following factors:

- Pool surface area;
- Water depth;
- Target water temperature.

Swimming pool buildings have many functional facilities; they are not only the pools themselves, but also the technical rooms accompanying them for services. There are different functional zones such as dressing rooms, offices and storage rooms. Different technical requirements must be considered to successfully complete the functionality of swimming pools facilities. Operation costs incurred in individual zones have influence on the entire facility issue and needed technical requirements. Recently, studies indicate that the costs for common applications including space heating, water heating and power consumption of industrial processes represents almost 60% of total costs; Figure 7 shows the details of these costs [63]. Electricity in swimming pool facilities is required, for example: room lighting, swimming pool hall lighting, water pumping, building automation system as well as office and administrative needs.

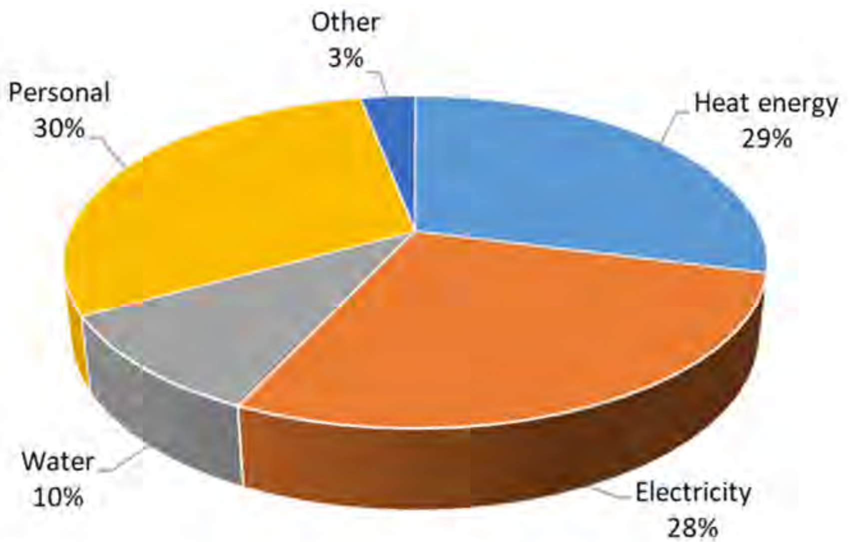

Figure 7. Main costs fields for swimming pools operation [63].

It is obvious that significant reduction in space heating energy can be obtained by good thermal insulation of the building envelope, especially in the indoor swimming pool construction. Figure 8 presents the main areas for swimming pool heating [6]. From Figure 8 it is apparent that the main heating filed around 50% is consumed for swimming pool water heating and preparing of DWHR for showers.

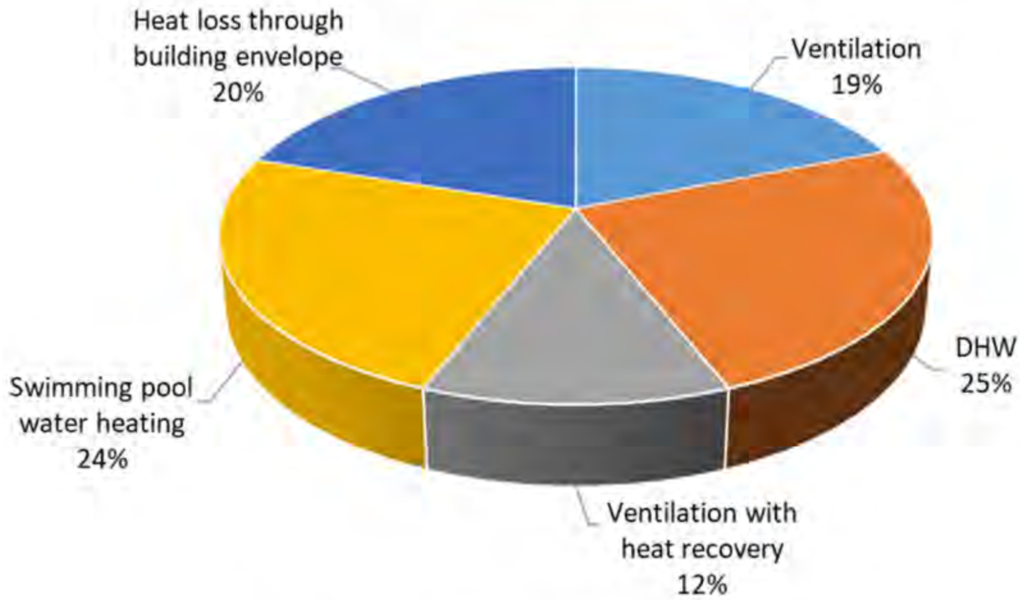

Figure 8. The main areas of indoor swimming pool heating [6].

Figure 9 shows the main fields of power consumption in new indoor swimming pools [6], where the ventilation systems consume around 30–40%, power consumption for water treatment varies in the range of 30–40%, water circulation pumps (for heating purposes) 3–5%, and lights in the range of 15–25% [6].

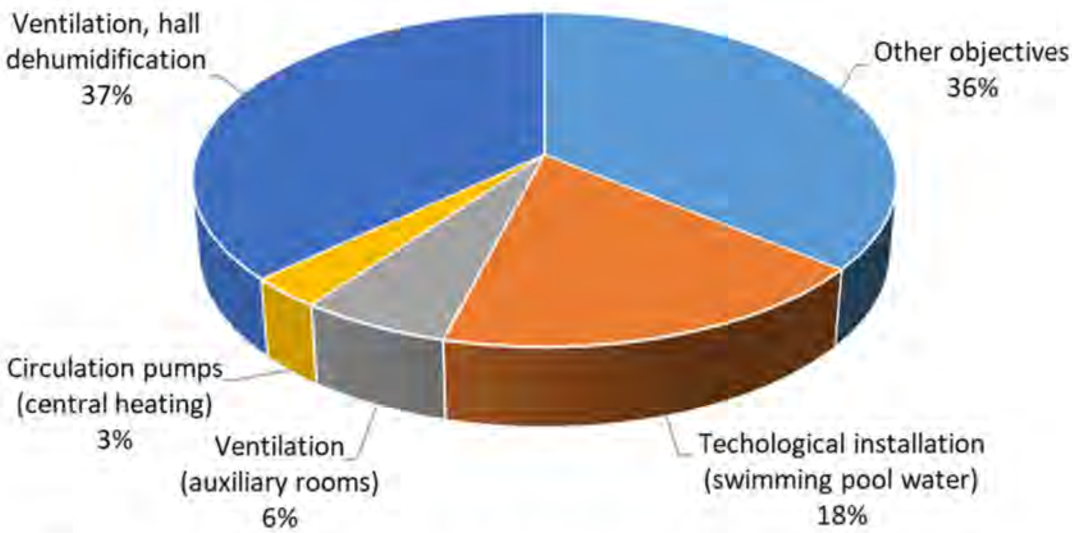

Figure 9. Example of power consumption distribution in indoor swimming pool based on [6].

B.J. Cardoso et al. in [64] compared energy and water consumption in five sports complexes in Portugal. They concluded that a direct comparison of annual water and energy consumption is not appropriate and, therefore, they used performance indicators (energy consumption per usable facility area and energy consumption per water surface area).

As shown in Figures 7–9, the consumption of heat energy is high in swimming pool facilities. Therefore, it is worth investing in heat recovery systems. This will allow to reduce the need for heating pool water and preparing DHW.

Swimming pools, regardless of the season, day and number of users, require almost constant operation of water treatment, pool and utility water heating systems supplied to the showers, heating, mechanical ventilation and air conditioning systems. Care should be taken to ensure that the operation cost of indoor swimming pool is as low as possible.

According to the list given in [65], the greatest amount of energy needed for heating purposes—80%—is consumed by the hot water preparation processes and ventilation. Therefore, the heating processes should be rationally managed and recovered. In order to reduce the consumption of heat energy in the case of heating swimming pool and preparation of DHW. The heating technologies in Europe use mainly renewable energy sources [62,66,67]. Renewable sources and technologies such as solar thermal collectors or heat pumps or hybrid systems can be applied. On the other hand, heat recovery technology may be used to reuse the heat from GW and from swimming pool showers and from filter rinsing during swimming pool water discharge [68,69]. In the last few decades, commercial technologies have been developed to use the waste heat in swimming pools [70–74].

Moreover, the literature review presents the differences in approaches and technologies for pool water consumption and the possibility of using heat pumps, due to the assumed pool thermal requirements and the seasonality, fluctuation of water heating and the impact of energy consumption values [62,75]. In the analysed literature, the heat recovery systems focus mainly on the application of heat exchange process and the design structure and construction of heat exchangers [76–80].

Many publications refer to and encourage the trend of reducing the consumption of non-renewable energy sources; the European Union Directive also includes the promotion and necessity of using environmentally friendly applications [81]. The authors in this article analyse the possibilities of reducing energy consumption in swimming pool buildings by using various methods and energy saving technologies. This approach is a particularly beneficial process for heat recovery applications in indoor swimming pools.

3.1. Energy Sources for Swimming Pool Water Heating

Efficient and ecological swimming pool water heating has become increasingly important to initiatives to protect the environment and the development of new technologies. The vast majority of the north European countries have only a few months per year to enjoy the recreational activity without the use of a heating system, but many south European countries enjoy favourable climate conditions to extensive swimming facilities throughout the year [37,82].

The way we use and produce energy has a huge negative impact on global climate change. These changes are due to the released large amounts of greenhouse gases into the atmosphere.

Figure 10 shows the main energy sources for heating systems in Poland based on Energy Regulatory Office data [83]. From the presented values, it is evident that coal is the majority source (74%) in the Polish energy system, even as it is known that burning fossil fuels leads to air pollutants that are harmful to the environment and human health [83,84].

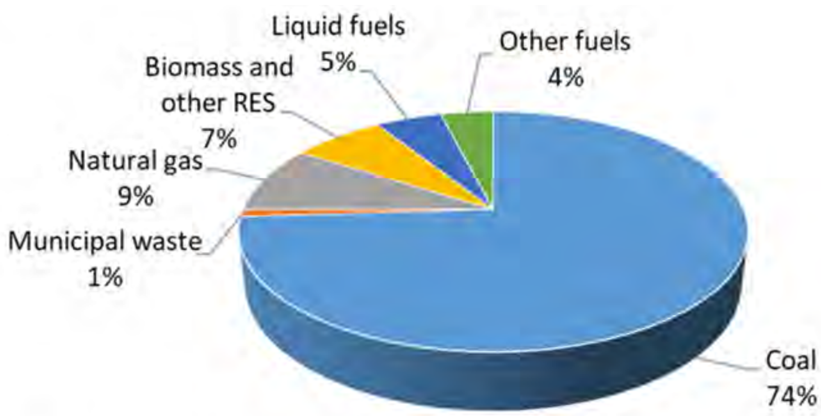

Figure 10. System heat sources in Poland [83].

Poland has become the 21st largest CO_2 emitter country in the world, according to data from 2017 as shown in Figure 11 [84].

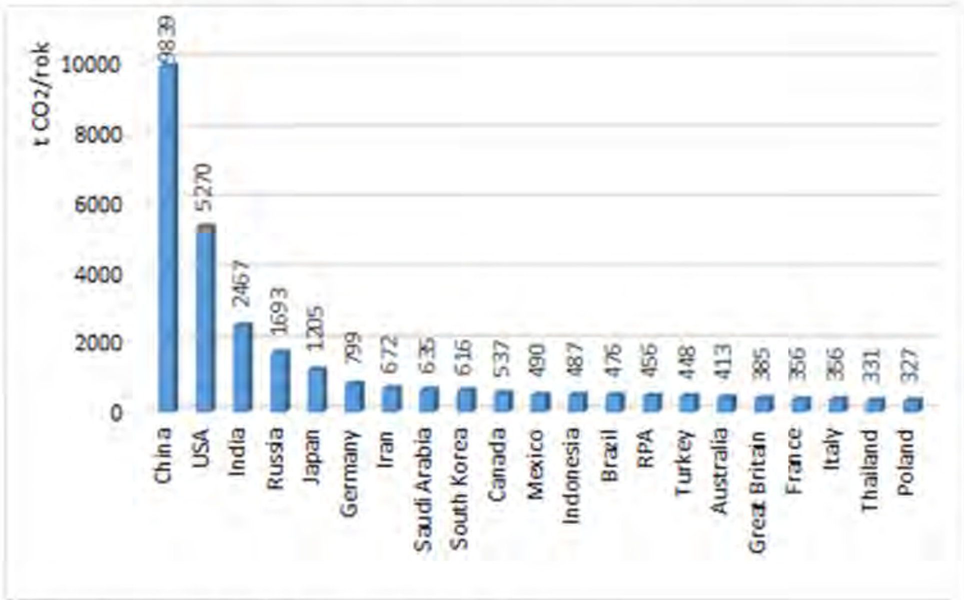

Figure 11. Global energy related CO_2 emitters (2017) [84].

On the other hand, in 2017, Poland was ranked 5th among the European Union countries, behind Germany, Great Britain, France and Italy in terms of the amount of CO_2 emitted. In Europe, the largest CO_2 emitters are Germany, which in 2017, according to Global Carbon Atlas data, emitted almost 800 metric tons of this gas. For comparison, in Poland the value of emissions in 2017 was 327 metric tons of CO_2. After the technical changes in 2018, Poland became the third CO_2 emitter in the European Union [84].

CO_2 is one of the gases contributing to the greenhouse effect and plays a dominant role in the national emissions—81.34%. Apart from carbon dioxide, greenhouse gases include: CH_4 and N_2O, as well as industrial gases (F-gases). The shares of individual gases are shown in Figure 12 [84].

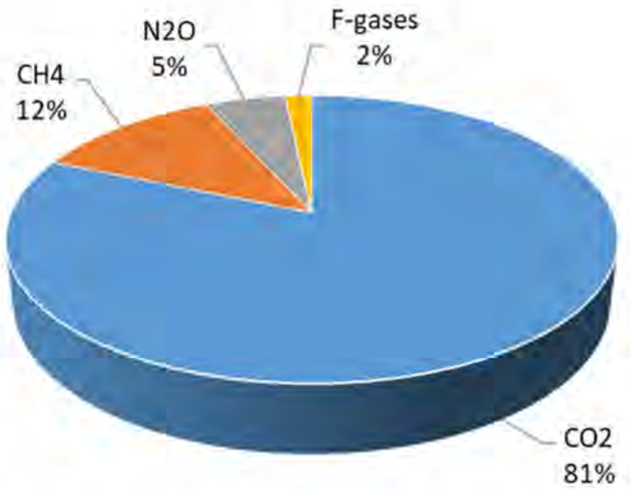

Figure 12. Shares of individual GHG in the total national emission in 2017 [85].

Figure 13 shows the changes in CO_2 emissions in the years 1988–2017. CO_2 emissions in 2017 were estimated at approximately 336.56 million tonnes. It is 28.7% less compared to the emissions in 1988, but as Figure 13 shows, CO_2 emissions from 2000 were estimated at a similar level. The main source of CO_2 emissions is fuel combustion, which accounted for 92.5% of the total CO_2 emissions in 2017.

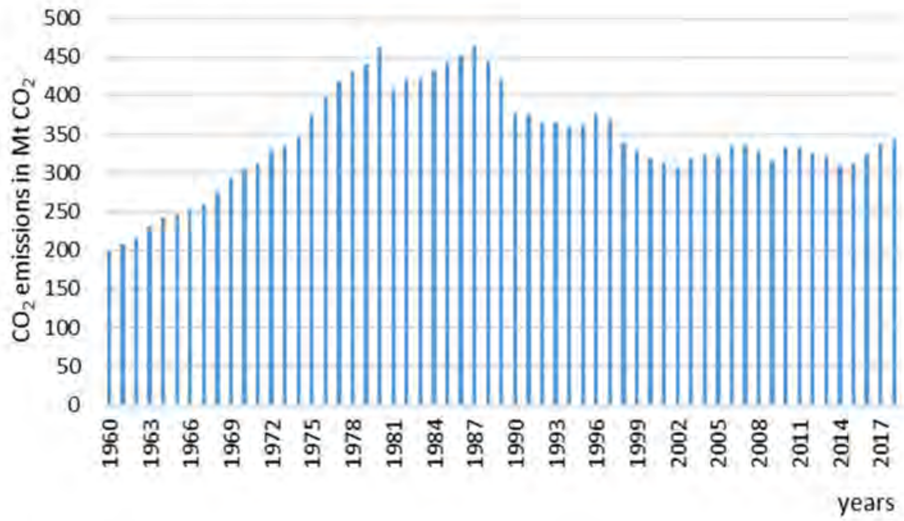

Figure 13. CO_2 emissions in Poland in the years 1960–2018 [85].

To reduce CO_2 emissions, it becomes obligatory to use energy-saving technologies, increase efficiency and recover energy from various processes and technological systems [86].

3.2. Conventional Energy Sources

There are many water heating technologies to heat the water in swimming pools. Figure 14 shows the schematic layout of applied traditional, renewable and hybrid technologies for swimming pool water heating and preparing DHW systems, which can be: coal, gas, oil fired boiler, hybrid or district heating network [87,88].

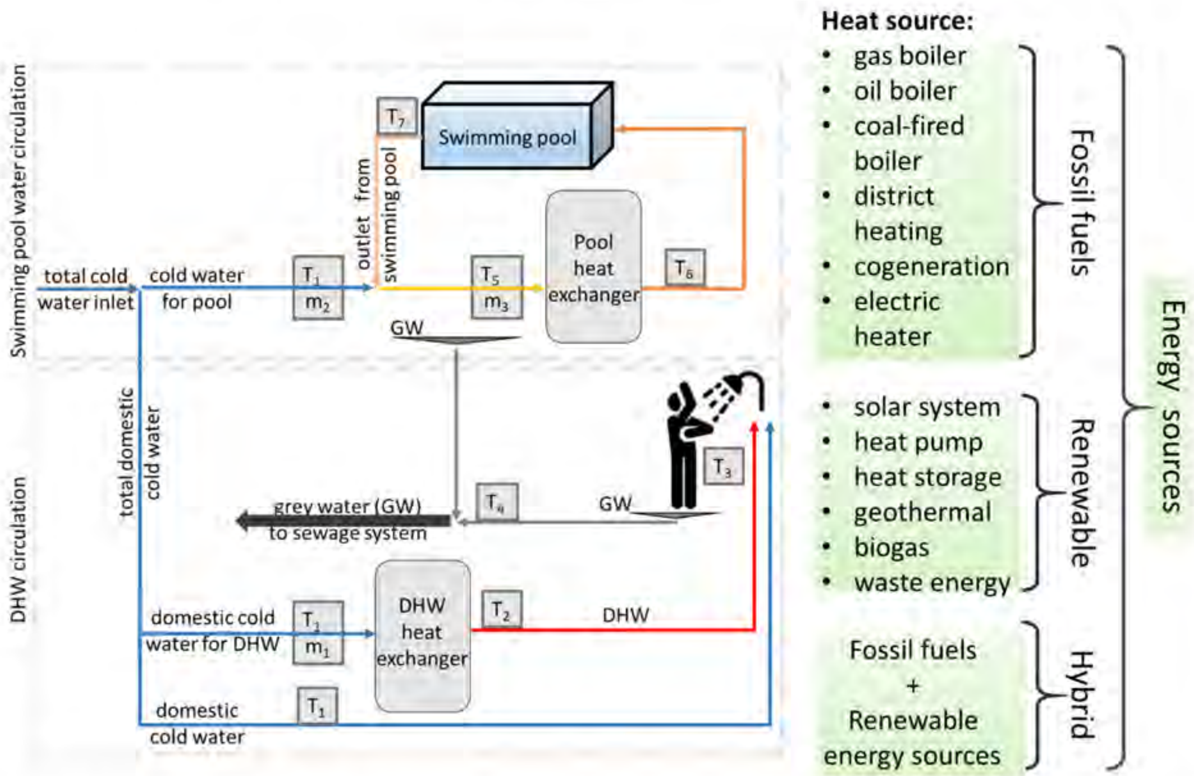

Figure 14. Schematic layout of the applied energy source for swimming pool water heating and preparing DHW system.

It is important to point out the fact stated in [89] that in the case of selection of a heat source for a swimming pool, the focus should be on the heat balance. The pool water heating (pool filling condition) and separately the heat balance for the pool water treatment station (such as: fresh water inflow and water circulation through the treatment station, temperature drop of the circulating water) should be included in this balance. The larger of these two values should be used for further calculations [89].

Usually, the price issue becomes one of the key criteria for choosing the appropriate heating system, especially during a period of rising energy prices. Therefore, combined heat and power system (CHP) is one of the options often chosen, for the reasons of operating costs, to generate electricity and heat in cogeneration. Such a solution allows to reduce the environmental impact by reducing CO_2 emissions. Rodak M. [90] compares energy costs from a CHP system powered by natural gas, where the mechanical energy is converted into electrical energy in a generator coupled to the engine and thermal energy is received in the form of hot water through a system of heat exchangers. In this article [90], a swimming pool facility consuming about 400 kW of electricity and 436 kW of heat per hour of operation was analysed. The analysis has shown that the investment in building a cogeneration system pays for itself within the first few years of operation. For buildings serving more than one function, such as sanatoriums equipped with an indoor swimming pool, Jarosiński M. et al. in [91] proposed the use of tri-generation, which simultaneously generates heat, electricity and cold, a facility whose power ordered in gas is 711 kWh (the total thermal power of the installed three gas boilers in the boiler room is 890 kW). The economic analysis showed that small size tri-generation systems are strongly dependent on gas and electricity prices. The results of the analysis indicated that, with a proportional increase in the price of gas and electricity, the profitability of the investment increases. An interesting solution was presented by Ren Craft [91], who supplied and commissioned a biomass boiler plant with two boilers by total capacity of 500 W for an indoor swimming pool of 1960.8 m^2 and cubic capacity of 8765 m^3 in Witoszów Dolny in Poland. In the Water Park in Tychy, which is self-sufficient in terms of energy by using two biogas heat and power plants (in a sewage treatment plant in Tychy and in the Tychy Water Park), 20,500 MWh of electricity and heat were produced during the period from May to December 2018, where the excess (2200 MWh) electricity was sold to Tauron [92].

Authors in many publications [90–92] look for the most energy-efficient solutions and technologies for water heating and preparing DHW in indoor swimming pools; each of these solutions has its pros and cons. It is necessary to assess only the feasibility and environmental sustainability of solutions, energy generation technologies, also the possibility to maximise the trade-off between the performances of technical–environmental efficiencies and financial–economics analysis [93–95]. Currently, one of the most accessible solutions are systems supported by renewable energy sources (solar collectors, heat pumps, hybrid systems, etc.). From an environmental point of view, the wastewater thermal potential of swimming pool GW, a valuable heat source, and many of its thermal transport properties suggests that it should be viable. Therefore, it is very reasonable in swimming pool complexes not only to recover the heat from GW in buildings, but also to include reporting, monitoring and management energy saving processes, mainly where the waste heat is produced continuously in extensive, measurable and in large quantities [29,30].

3.3. Renewable Energy Sources

According to the "Clean Heat" statistics [83], only 10% of Polish heating systems meet the required efficiency criterion. According to EU regulations, for heating systems an effective heat source is one which uses: 50% of energy from renewable sources, or 50% of waste heat, or 75% of the heat from cogeneration, or 50% in total energy from sources as above [96]. The authors of the report [83] indicate the need to improve the situation in the energy sector by increasing the share of energy obtained from RES. In terms of the building itself, there are many strategies to reduce energy [97]. The literature analysed the possibilities of using renewable energy sources to heat swimming pool water in order to reduce total costs. The factors in favour of using solar collectors are the low cost of heat generation, the possibility of year-round operation and their use for heating the hot water as well as long warranty periods for the collectors themselves. However, most of them were considered for open swimming pools. The authors of [36] propose the use of solar panels with an additional roof construction to reduce energy consumption in an open pool in Greece. K. Kaci et al. in [98] analysed the performance of hybrid-solar-heated open swimming pool in Algeria using TRNSYS software. The authors concluded that solar water heaters with a glass cover have worse optical parameters than those without a glass cover. The SWOT (Strengths Weaknesses Opportunities Threats) analysis for the open pool proposed by M. Pietras-Szewczyk [99] presented the advantage of using the solar collector installation combined to other solutions (air heat pump, powered by PV system), as a cheap and eco-efficient solution. For the Mediterranean climate, an interesting solution of swimming pool are submerged PV panels. M. Clot et al. in [100] analysed the possibility of using such panels for underflow pools as well as for pools with a skimmer, including the possibility of storing solar radiation for heating the water of the pool.

Sayegh et al. [101] performed a solution for the cooperation of flat solar collectors in solar-powered absorption cooling systems (using a heat storage tank and auxiliary heater) for residential buildings. In Poland, the average annual sum of solar radiation intensity in the Lower Silesian Region is at the level of 1200–1300 kWh/m^2 (the average for Poland is 1000 kWh/m^2) [99], so it encourages to use solar applications in swimming pools.

In the case of outdoor swimming pools, if a comfortable and stable pool water temperature is expected, the manufacturer [102] proposes an air-to-water heat pump, because of its independence from the sun. If a low operating cost is expected, it proposes a solar installation although this solution requires a larger installation area (compared to the heat pump) and heat exchanger to separate the swimming pool water from the collectors.

For indoor swimming pools, M. Jordaan and R. Narayanan compared different methods of heating, including flat plate, evacuated tube collector and PV solar panels based on (TRNSYS) transient simulation study [103,104]. The authors have shown that in the analysed weather conditions of Australia, the evacuated tube collectors are the most optimal among the solar thermal collectors due to their enhanced efficiency (in comparison with flat collectors). Direct photovoltaic heating is the least efficient thermal solution, but the electricity generated can significantly reduce costs, by using it for heat pump applications. Regardless of the type of solar collectors, their area had to be twice as big as the water surface area of the analysed pool in case of maintaining the set temperature of the pool water [103].

As it results from the above considerations, the impact of weather and solar conditions, as well as the type of pools and expectations in relation to operating costs and pool water temperature parameters influence the size and efficiency of solar collector systems.

For an open swimming pool used from spring to autumn, air-water heat pumps are a very good solution. The outside air temperature rarely drops below 5 °C and often exceeds 20 °C. This makes the pump very efficient, achieving an even higher COP than in ground-to-water and water-to-water systems. For year-round swimming pools, the best choice will be ground-to-water or water-to-water pumps. In summer, their operating parameters will be less favourable, but the pump will work significantly better in winter when the demand for heat is the highest [105]. R. López et al. in [106] analysed the performance of the heat pump for the energy needs of the swimming pool located in Mexico. In Polish conditions, heat pumps are more often used to reduce the cost of air heating in swimming pool halls. Such a solution was presented by K. Ratajczak and E. Szczechowiak in [107]. However, solutions with heat pumps are used to heat pool water are also used. Then heat pumps can work in two operation modes. The first is when the pool is one of the heat receivers (due to the efficiency of the heat pump, each of the main heat consumers should be heated as a separate priority). The second type of installation is dedicated systems where the heat pumps are used only to heat the swimming pool water. To ensure the safety of pool water, considering the chemical compounds contained in the pool water (especially chlorine), the heat exchanger between the refrigerant and the pool water should be made of stainless steel or titanium. In heat pumps not dedicated directly to pool heating, an intermediate circuit between the heat pump and pool water should be built to avoid condenser degradation [102]. The factors in favour of using heat pumps are their independence from sunlight, small footprint and the possibility of direct connection of swimming pool water. However, this solution also has disadvantages, which may include: the costs of electricity consumption (mainly by compressor operation), the cost of installation itself with cooling circuits and automation and short warranty periods.

Thermal energy storage improves the energy efficiency of renewable heating systems [108–110]. Sensible and latent heat storage can be used in heating systems. This solution allows to use the stored energy during periods of lower renewable energy supply. The following types of heat storage can be used for heating purpose (depending on the size of the installation and the geological structure): phase change materials (PCM), aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), tank thermal energy storage (TTES), pit thermal energy storage (PTES), cavern thermal energy storage (CTES), etc. [108–110].

3.4. GWHR Systems in Indoor Swimming Pools

Wastewater heat recovery systems have attracted considerable research attention in recent years. The first stage in the use of heat is to determine the sources, assess the potential of wastewater and measure the usage patterns [63,65,111].

One of the most promising energy saving system especially for indoor swimming pools is the GWHR. The most important types of heat recovery that are relevant to the discussed issues in this article are:

- Heat recovery from water discharged into the pool's drainage system: this type of heat recovery practically takes place without an auxiliary source of energy, it is the most economical form of energy saving in an indoor pool and should therefore not be missing in any pool installation.
- Heat recovery from rinsing water for filters: this type requires, in addition to a heat exchanger, a tank for storing the cooled filter rinsing water. If there is an available space for storage, it can be integrated into the system; there is also an economic option to save energy.
- Heat recovery from wastewater: it concerns heat recovery from discharged sewage in sanitary facilities (showers and handbasins) at the swimming pool. Heat exchangers and heat pumps can be used in this case.

The temperature of inlet cold water supplied to the indoor swimming pool varies between 6 and 16 °C depending on the season according to [58] and between 5 and 15 °C according to [55]. An average temperature value of 10 °C can therefore be assumed. The temperature of GW varies between 25 and 41 °C depending on the source of origin and is practically constant, regardless of the season [55,58,59,112].

The average production of GW in swimming pool is about 30,000 L per day. However, a significant problem arising here is the considerable pollution of used water with slurry in swimming pools (like fats, detergents, hair, etc.), hindering heat recovery [23,24,112]. Therefore, warm sewage in the indoor swimming pool is a constant source of heat throughout the year, which can be used to preheat swimming pool water or DHW. It is advisable to recover the heat from the GW for heating the cold water. In these systems, a heat exchanger is the basic element between the sewage and the cold water.

Depending on the source of GW, the heat will be recovered as a first stage in DHW heat exchanger from the discharged water from the showers, rinse water from filters or overflow water from pools. This stage will significantly reduce the required energy to heat the pool water.

Figures 15 and 16 presents exemplary simple diagrams of heating systems without and with GWHR from the showers.

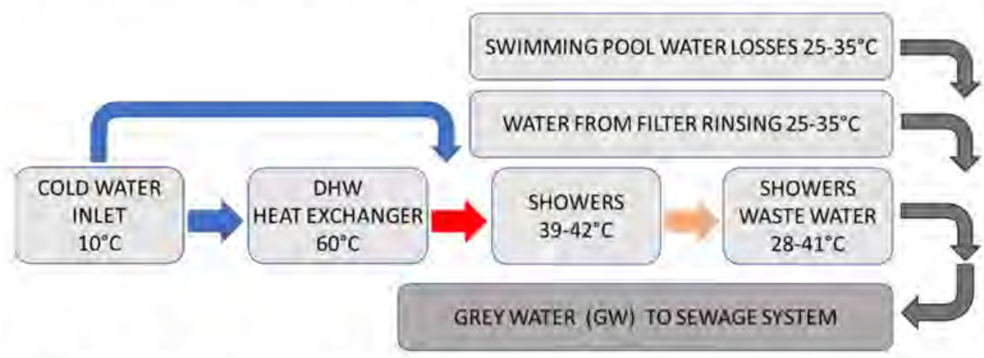

Figure 15. Block diagram of the showers in pool heating system without GWHR system.

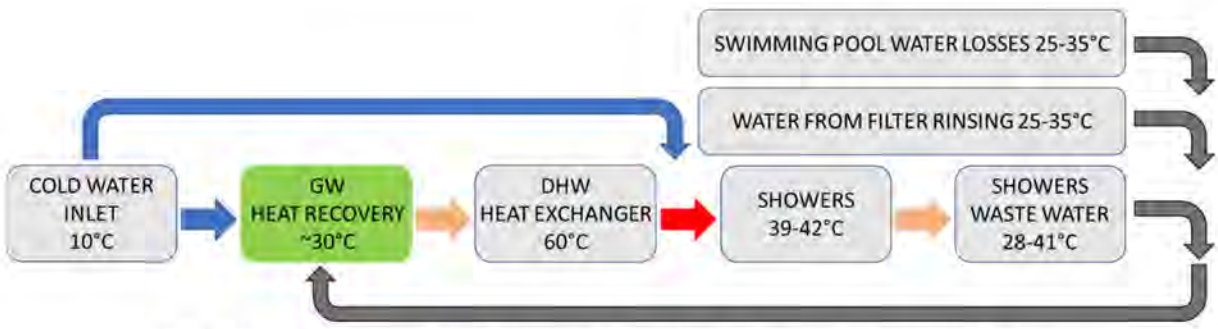

Figure 16. Block diagram of the showers in pool heating system with GWHR system.

For Poland's weather conditions, the most optimal solution to maintain the appropriate water temperature at the lowest possible operational costs is to recover the heat from GW. This article analyses the feasibility of using GWHR system for the showers and backwater from swimming pool filters in indoor swimming pools in Poland. Water consumption analysis in the recreation centre was carried out on the basis of water flow rate and water temperature of real measurements from swimming pool showers. The results of survey data are presented in Section 4. Technical details of heat recovery technology as well as the economic issue will be closely described in next coming article.

4. Case Study of Heat Recovery System for Swimming Pool

The case study of the heat recovery system which was carried out for the swimming pool object is an Aquapark. It is part of the conference and recreation centre in central Poland. This centre used for sports and recreation apart from water attractions, hotel, catering and wellness services are available for the guests. The measurements were carried out for a swimming pool facility. The swimming pool centre consists of:

- A sports swimming pool—dimensions 25 m × 16 m, depth from 1.80 m to 2.20 m and water temperature 27 °C [24]; it is divided into 6 tracks, one of which is shallow and is used for training and swimming lessons;
- A recreational swimming pool—with dimensions of 16 m × 9 m, depth from 0.90 m to 1.30 m and water temperature of 30 °C [24]; equipped with water jets, geysers and massage couches;
- Three water slides 52 m long (inner for children), 136 m (external), 108 m (external), with visual and acoustic elements;
- Paddling pool with small slide (children's pool)—with theoretical water temperature at 33 °C;
- Two jacuzzis, i.e., with octagonal hot water pools equipped with underwater massage jets—with water temperature at 36 °C [24].

Figure 17 presents the simple scheme of analysed case of DHW system and swimming pool water heating system. There are two heat exchangers in this swimming pool water heating system. The first is responsible for maintaining a constant temperature of pool's water circulating in the pool circuit in which the water is cooled by Δt = 1–2 °C as a result of passing through the pool's technological system [22–24]. The second heat exchanger is responsible for heating the domestic cold water from 10 °C to 60 °C.

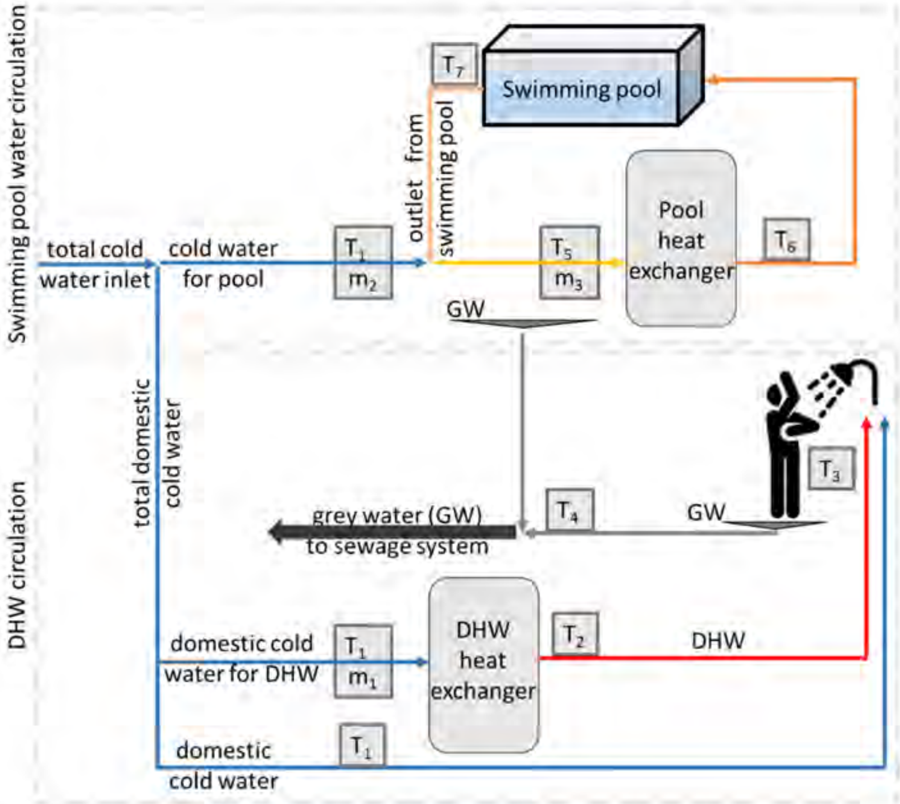

Figure 17. Scheme of DHW and swimming pool water heating system.

4.1. Description of the Conducted Measurements

The measurements of water consumption and water temperature in swimming pool were carried out by three non-invasive devices, with measurement accuracy range ± 1.0%, as follows:

1. Portable ultrasonic flow meter FLUXUS F601 provided by Flexim, DN 10 to DN 400, −30 to +130 °C;
2. Portable ultrasonic flow meter Portaflow C provided by Fuji, DN 13 to DN 400, −40 to +100 °C;
3. Wireless temperature measurement sensors provided by Wisensys, −50 to +150 °C.

The measurements of heating system presented in Figure 17 for DHW consumption were carried out during two months from 19 January 2013 to 17 March 2013. Figure 18 presents the measurement results which were obtained for DHW flow rate, while Figure 19 shows the cold and DHW temperatures for the showers. The average hot water temperature was 45.7 °C and for cold water it was 14.6 °C. Figure 20 presents the average daily DHW consumption in the implemented measurements, which was 31.9 m^3/d. During the analysed period, the minimum and maximum DHW consumption values were 21.2 m^3/d and 41.2 m^3/d, respectively. The energy saving analyses in a further section of this article are based on the feasibility of heat recovery from the GW in the analysed system.

The heat potential of GW from the showers can be used to preheat the water in the showers and swimming pool water by using the GWHR system.

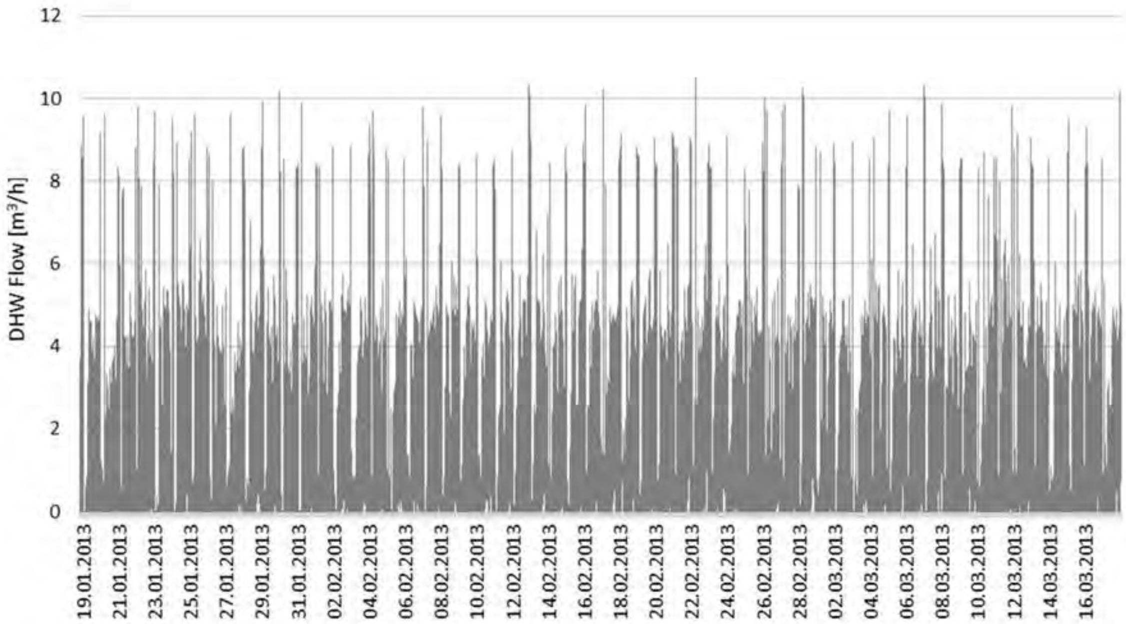

Figure 18. The measurement of DHW flow rate carried out.

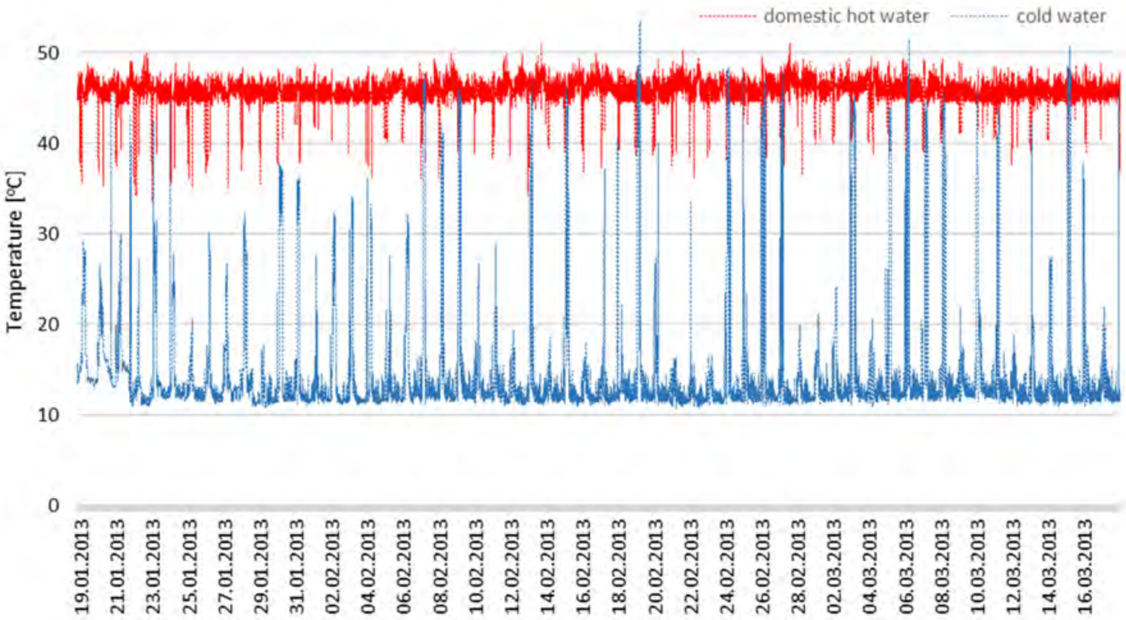

Figure 19. The measurement of DHW temperature carried out.

4.2. Consideration of Standards in View of Energy Saving Analysis

Part of the analysis was carried out on the basis of assumptions, comparing different available guidelines, regulations and standards in Poland and Germany.

For the analysed recreation centre building, calculations were carried out on the base of German standard DIN 19643-1 [22,23], for the filtered water and the amount of circulated water in the pool water heating system, the results are compared with the old, simplified method included in the international guidelines of INTERNORM of 1976 and 1978 [24]. Part of the analysis was carried out on the basis of assumptions, for comparing different available guidelines, regulations and standards.

Figure 20. Average daily DHW consumption in the implemented measurements.

The maintained calculation formulas like that for filtration rate and efficiency, active capacity of equalising tank, are presented below, then the calculations results are summarised in Table 6 for the analysed swimming, recreational and paddling pools. The parameters which are currently in use for the swimming pool water filtration system were also compared with the latest given guidelines of DIN 19643-2012 standard [23].

Table 6. Results of calculations for the analysed recreation centre.

Swimming Pool Characteristics				
Pool dimensions	25 m × 16 m			
Water surface	400 m^2			
Pool depth	1.8–2.2 m			
Pool volume	800 m^3			
Water temperature	27 °C			
Water supply to the basin	Bottom channels			
Daily operating time of the installation	24 h			
Max. number of swimmers	90 person/h			
Fresh water volume	42.62 m^3			
Attractions	-			
	Requirements of simplified method [24]	Requirements of accurate method [24]	DIN 1997 [22]	DIN 2012 [23]
Filtration efficiency	160.00 m^3/h	177.60 m^3/h	177.60 m^3/h	177.60 m^3/h
Filtration rate	20.95 m/h	23.25 m/h	23.25 m/h	23.25 m/h
Amount of backwater to rinse 1 filter	15.27 m^3	15.27 m^3	15.27 m^3	10.18 m^3
Equalising tank—active capacity	31.25 m^3	30.46 m^3	30.46 m^3	25.37 m^3
Recreational Pool Characteristics				
Pool dimensions	16 m × 9 m			
Water surface	144 m^2			
Pool depth	0.9–1.3 m			
Pool volume	158.4 m^3			
Water temperature	30 °C			

Table 6. *Cont.*

Water supply to the basin	Bottom channels			
Daily operating time of the installation	24 h			
Max. number of swimmers	35 person/h			
Fresh water volume	15.34 m^3			
Attractions	slide			
	Requirements of simplified method [24]	Requirements of accurate method [24]	DIN 1997 [22]	DIN 2012 [23]
Filtration efficiency	93.60 m^3/h	141.56 m^3/h	141.56 m^3/h	141.56 m^3/h
Filtration rate	18.38 m/h	27.80 m/h	27.80 m/h	27.80 m/h
Amount of backwater to rinse 1 filter	15.27 m^3	15.27 m^3	15.27 m^3	10.18 m^3
Equalising tank—active capacity	22.79 m^3	21.66 m^3	21.66 m^3	16.57 m^3
Children's Pool Characteristics				
Pool dimensions	4 m × 4 m assumption			
Water surface	16 m^2			
Pool depth	0.3–0.6 m assumption			
Pool volume	7.2 m^3			
Water temperature	33 °C			
Water supply to the basin	Bottom channels			
Daily operating time of the installation	24 h			
Max. number of swimmers	4 person/h			
Fresh water volume	1.70 m^3			
Attractions	little slide			
	Requirements of simplified method [24]	Requirements of accurate method [24]	DIN 1997 [22]	DIN 2012 [23]
Filtration efficiency	11.20 m^3/h	60.00 m^3/h	60.00 m^3/h	60.00 m^3/h
Filtration rate	4.56 m/h	24.44 m/h	24.44 m/h	24.44 m/h
Amount of backwater to rinse 1 filter	7.37 m^3	7.37 m^3	7.37 m^3	4.91 m^3
Equalising tank—active capacity	8.47 m^3	8.05 m^3	8.05 m^3	5.60 m^3

Filtration efficiency Q in m^3/h—the requirements for the simplified method are calculated according to pool water surface area A in m^2 [24]:

- For swimming pool

$$Q = 0.4 \cdot A \tag{1}$$

- For recreational swimming pool with water slide

$$Q = 0.65 \cdot A \tag{2}$$

- For children's pool with water slide

$$Q = 0.7 \cdot A \tag{3}$$

Filtration efficiency Q in m^3/h—the requirements for the accurate method [24], DIN 1997 [22] and DIN 2012 [23] are determined respectively by the following formulas:

- For swimming pool

$$Q = 0.222 \cdot \frac{A}{k} \tag{4}$$

- For recreational swimming pool with water slide and children's pool with water slide

$$Q = 0.37 \cdot \frac{A}{k} + 35 \text{ (but no less than 60)} \quad (5)$$

where: A is the pool water surface area in m^2 and k is the load factor = 0.5 and 35 m^3/h is the addition for every slide.

The filtration rate vFR in m/h for swimming and recreational pool with water slide and children's pool with water slide for the above-mentioned two methods is determined by the following formula [22–24]:

$$v_{FR} = \frac{Q}{F_{FR}} \quad (6)$$

where F_{FR} is the actual filtration area in m^2.

Active capacity of equalising tank V_Z in m^3 for swimming and recreational pool with water slide and children's pool with water slide for all methods is determined by the following formula [22–24]:

$$V_Z = V_V + V_W + V_R \quad (7)$$

where: V_V is the volume of water displaced by swimmers in m^3, V_W is the amount of overflow water in m^3 and V_R is the amount of backwater to rinse 1 filter in m^3.

V_V in m^3 is determined by the formula [22–24]:

$$V_V = 0.075 \cdot \frac{A}{a} \quad (8)$$

where a is the area per 1 person in the pool m^2:

a = 4.5 for swimming pool;

a = 2.7 for the recreational pool with slide and for the children's pool with slide.

V_W in m^3 is determined by the formula [22–24]:

$$V_W = 0.052 \cdot A \cdot 10^{(-0{,}144 \cdot Q/l)} \quad (9)$$

where l is length of overflow gutters in m.

The requirements [24] do not provide the necessary equations to calculate the amount of backwater to single of rinse filter V_R in m^3. Therefore, in a simplified and accurate method [24] for all three basins it was calculated according to the standard [22], which is based on the guideline [24]:

$$V_R \geq 6 \cdot A_F \quad (10)$$

where A_F is the single filter area in m^2.

For all three basins, the value V_R, according to DIN 2012 [23], is determined by the formula:

$$V_R \geq 4 \cdot A_F \quad (11)$$

where A_F is the single filter area in m^2.

Comparing the results included in Table 6, it can be observed that in the case of the simplified method [24], the circulation of pool water is significantly reduced. Moreover, in the case of DIN 2012 [23], the volume of the equalising tank is approx. 30% lower than the other methods, which results from the difference in the calculation of the amount of backwater to rinse single filter.

4.3. Energy-Saving Analysis

Buildings are responsible for approximately 40% of energy consumption and 36% of CO_2 emissions in the EU. European directives insist on the necessity of energy recovery and improved energy efficiency which have the potential to lead to significant energy and CO_2 emission savings [96,113–115]. A wastewater heat recovery system could effectively recapture and reuse instantly up to 70% of waste energy, reducing energy consumption in a cost-effective manner [96,113–115].

The energy savings analyses and calculations were carried out on the basis of actual measurement data and based on the regulations and standards [22–24].

4.3.1. Feasibility of Heat Recovery in the Analysed Swimming Pool

As mentioned above for the carried-out measurements, the daily DHW consumption in the analysed swimming pool facilities varied in the range of 21.2–41.2 m^3 per day, average 31.9 m^3 per day, as shown in Figure 20. For this measurement period, it was 1851 m^3 GW, meaning that huge amounts of grey water and therefore of energy are discharged directly into the sewer without heat recovery. From the energy saving practical point of view, DHW preparation requires supply a large heat energy. This heat can be recovered by using the GWHR system by implementing a heat exchanger in the existing pool, which can save a significant amount of heat energy.

The analysis was conducted for heat recovery from GW discharging from the showers to the sewage system as shown in Figure 21. The proposed system in Figure 21 does not take into account the specific technical solution details of recovery system or pool water treatment, filters, rinsing waters, etc. The analysis was focused mainly on the water flow and the temperatures of domestic cold and hot water, which were measured in the recreation centre building as explained in Figures 18 and 19.

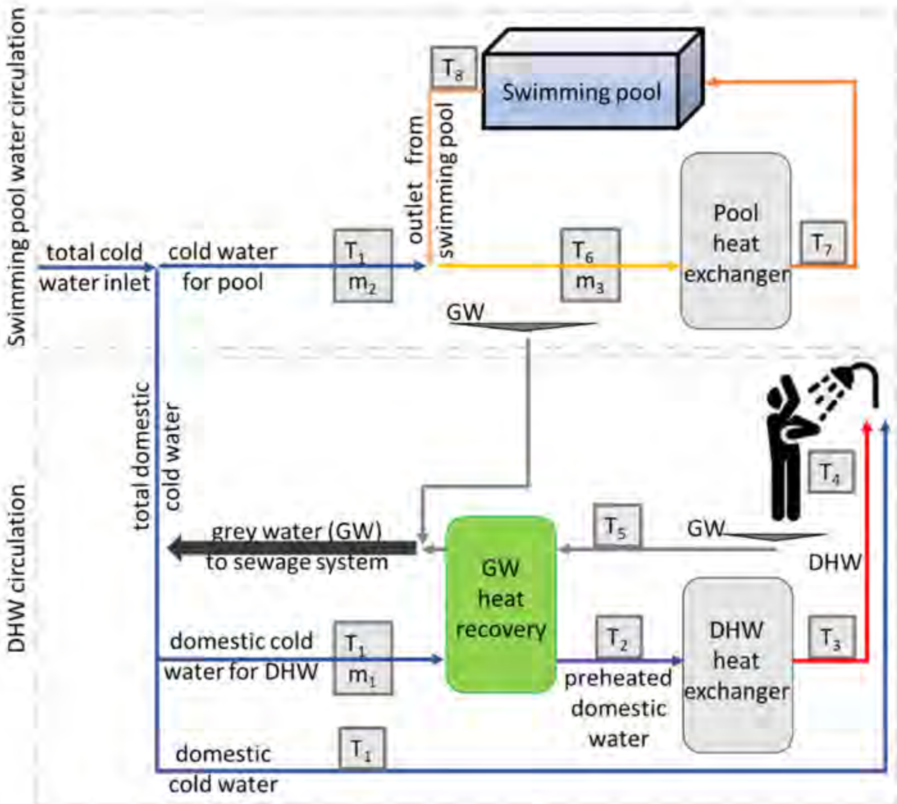

Figure 21. Proposed GWHR system from showers for swimming pool.

The energy savings which is result from the proposed technology were defined as the difference between the heat consumption for preparing DHW, with Q_2 and without heat recovery Q_1. The energy recovered for DHW can be calculated by using the following formulas:

$$Q_1 = m_1 \cdot \rho \cdot c_p \cdot (T_3 - T_1) \cdot 3.6 \cdot 10^{-3} \quad (12)$$

$$Q_2 = m_1 \cdot \rho \cdot c_p \cdot (T_3 - T_2) \cdot 3.6 \cdot 10^{-3} \quad (13)$$

where: m_1 is the mean flow rate of hot water in l/s, c_p is the specific heat in kJ/(kg · K), ρ is the water density in kg/m^3, Q_1 and Q_2 in GJ.

The values of water flow m_1, domestic cold T_1 and hot water T_3 temperatures have been obtained from measurements. The water temperature T_4 in the shower varies between 39 and 42 °C [55,58,59,112]. The GW temperature T_5 to the GWHR system varies between 28 and 41 °C [55,58,59,112]. The preheated domestic water temperature from GWHR system T_2 was assumed at 30 °C.

Figure 22 presents the energy consumption for DHW with and without GWHR. Table 7 present the results of energy savings analysis for DHW during the analysed period; it is clear that the energy saving will be reduced for lower heat recovery temperatures.

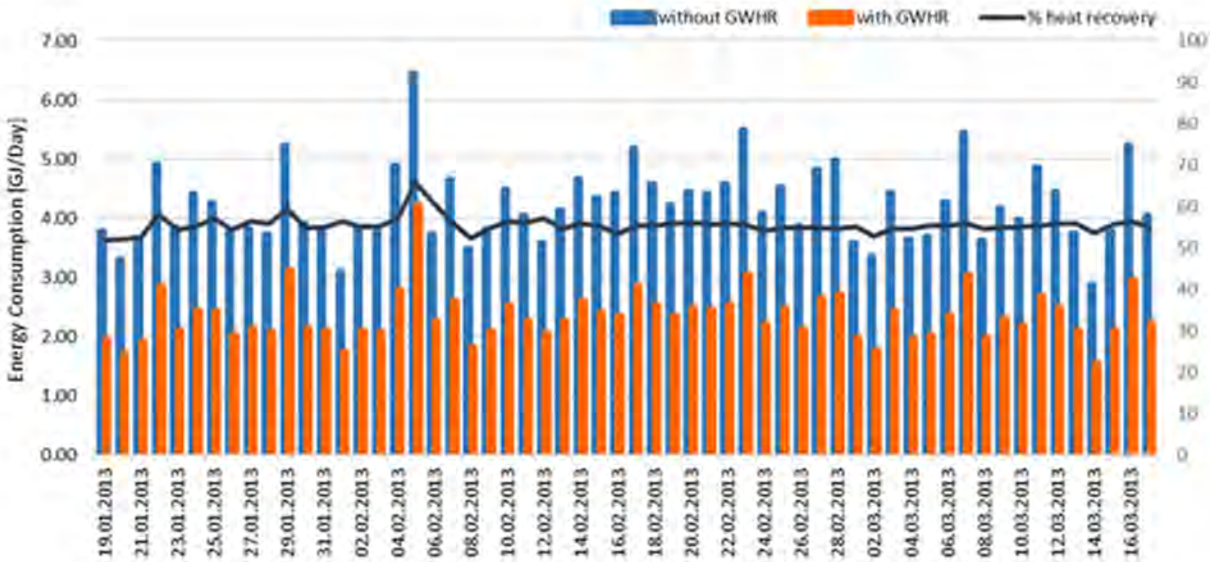

Figure 22. Energy consumption for DHW with and without GWHR system.

Table 7. Results of energy saving analysis by using GWHR system for DHW in the analysed period.

GWHR System for DHW	Energy Savings in GJ per Day			Energy Savings in %		
	Min.	Max.	Average	Min.	Max.	Average
	1.34	2.43	1.87	34	48	45

4.3.2. Heat Recovery from DHW for the Case Study in the Analysed Swimming Pool

The analysis was carried out for the case study of heat recovery from the GW discharged from showers, which is presented in Section 4.3.1. However, the basis of assumption of this analysis was the water consumption ranging from 50 to 80 L/person according to Table 1 [6] and the assumed temperature of water in the shower as 40 °C [55]. The preheated domestic water temperature from GWHR system T2 was assumed as 30 °C, and the inlet domestic cold water temperature T1 was assumed as 10 °C [55,58].

The functional time of the pool is assumed to be 12 h, from 8 am to 8 pm [55] and the average pool occupancy is assumed to be 50%. The calculations were carried out using Equations (12) and (13).

Table 8 presents the used values for analysis; Table 9 presents the results of energy savings analysis for DHW during the analysed period.

4.3.3. Heat Recovery for Preheating the Pool Water in Case Study in the Analysed Swimming Pool

For pool water preheating analysis, the temperature assumptions presented in Figure 23 were adopted.

Table 8. Assumptions for calculations.

Swimming Pool	
Max. number of swimmers	90 person/h
Recreational Pool	
Max. number of swimmers	35 person/h
Children's Pool	
Max. number of swimmers	4 person/h
Total number of swimmers	129 person/h
Domestic cold water temperature T_1	10 °C
Preheated domestic water temperature T_2	30 °C
DHW temperature T_3	60 °C
Showers water temperature T_4	40 °C
Min. water consumption	50 L/person
Max. water consumption	80 L/person
Open time (assumed)	12 h
Average use of the pool (assumed)	50%

Table 9. Results of energy saving analysis by using GWHR system for DHW.

GWHR System for DHW	DHW Consumption in m^3/h			Energy Savings in GJ per Day			Savings in %
	Min.	Max.	Average	Min.	Max.	Average	
	3.23	5.16	4.19	3.25	5.20	4.23	40

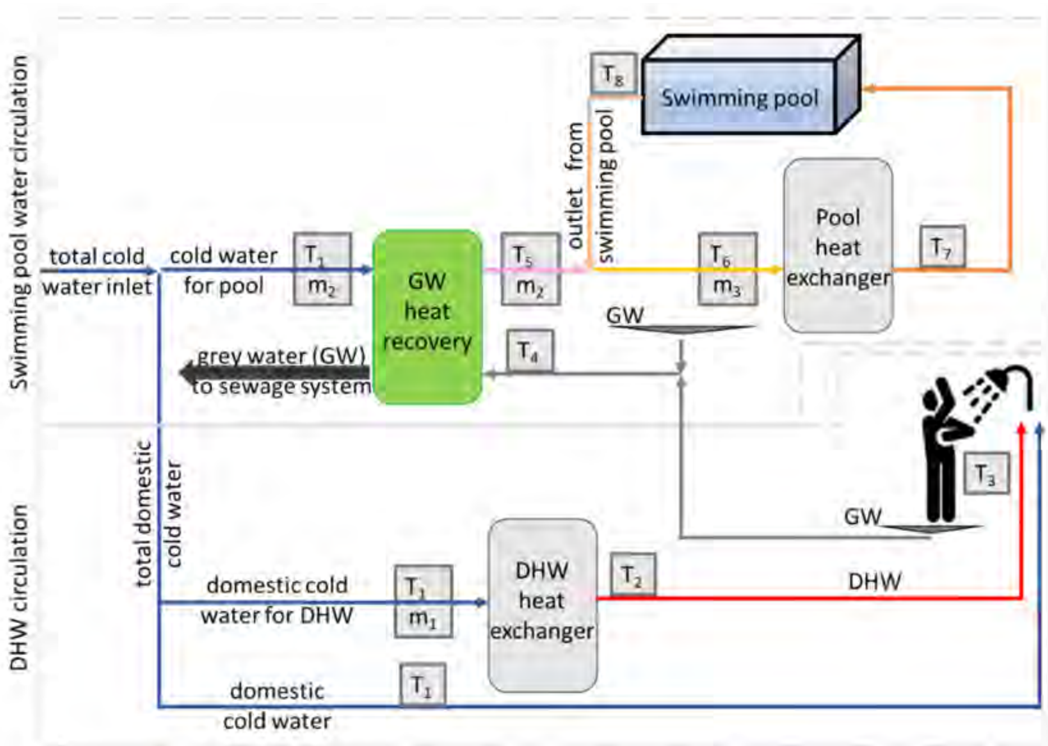

Figure 23. Proposed GWHR system for swimming pool water refilling system.

The calculations were carried out by using Equations (12) and (13), the changing temperatures are respectively from T_2 to T_5 and T_3 to T_6.

The temperature differences in the heat exchanger for pool water heating is obtained at 1–2 °C. Therefore, temperature T_6 is lower by 2 °C than the required temperature of pool water basins. Swimming pool water temperatures T_6 are presented in Table 6. The preheated pool water temperature from GWHR system T_5 was assumed 20 °C.

The amount of water refilled m_2 in the swimming pool during the day is 42.62 m^3. The energy savings during the analysed period from the GWHR system for cold water heating to the required level are 1.79 GJ per day. For the recreational pool where the amount of refilled water in the pool per day is 15.34 m^3, the savings will be 0.64 GJ per day. For a children's pool where the amount of refilled water m_2 in the pool is 1.7 m^3 per day, the savings will be 0.07 GJ per day. Table 10 presents the results of energy saving analysis.

Table 10. Results of energy saving analysis by using GWHR system for preheating the pool water.

GWHR System for Pool Preheating	Water Amount in m^3/Day	Energy Savings in GJ per Day	Savings in %
Swimming pool	42.62	1.79	67
Recreational pool	15.34	0.64	56
Children's pool	1.70	0.07	48

5. Environmental Impact of GWHR System in Case Study

Improving air quality is a one of the most important environmental challenges in Poland. Polish air is one of the most polluted in Europe; Figure 24 presents the level of pollution in Europe. Environmental impact analysis may take different approaches and indexes, and one of them is the Common Air Quality Index (CAQI). Hence, to address the environmental impact of the proposed DWHR system, this section discloses an evaluation of CAQI index as well as its reduction by means of the applied DWHR systems. CAQI is one of the environmental indexes which can be used to present the air quality information in European cities [116,117].

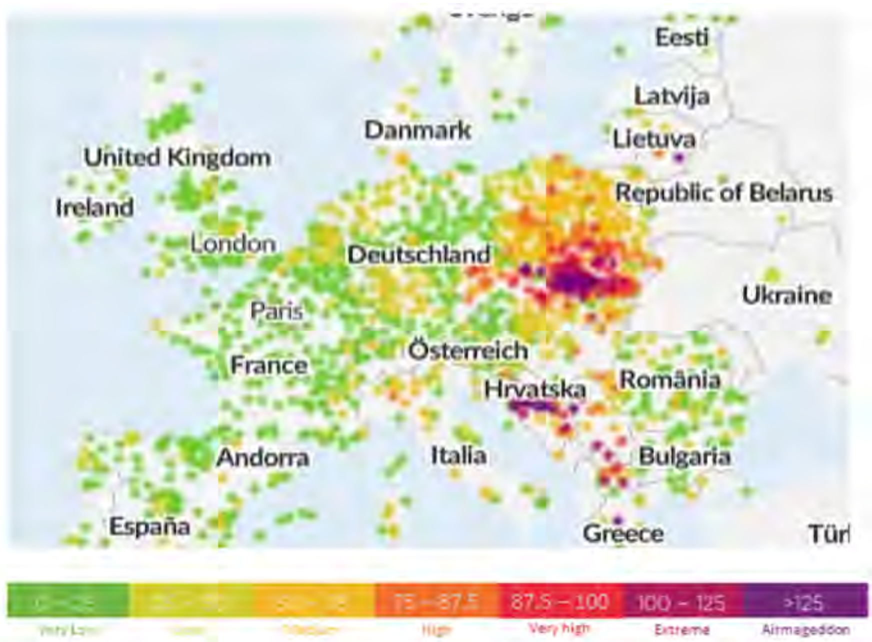

Figure 24. The level of air pollution in Europe (16 February 2021) [116].

In this study, the CAQI index approach was applied. Officially, this index has five levels, which are presented on a scale from 0 as very low to 100 as very high—a relative measure of the amount of air pollution. The CAQI index relates to three main pollutants: PM_{10}, NO_2 and O_3, with the possibility of taking into account others: CO, $PM_{2,5}$ and SO_2 [116,117].

Poland has the most polluted air in Europe, which is clearly shown in Figure 24, including the pollutants according to Airly scale such as CO, SO_2, NO_2, O_3 and dust on the CAQI index [116]. Table 11 shows the level of air pollution in Europe for the selected European countries.

Table 11. The level of air pollution in Europe (16 February 2021) [116].

Air Pollutant \ Country	Poland	Germany	Czech Republic	Slovakia	Austria	Switzerland
CO NO_2 SO_2	0–50	0–50	0–50	0–50	0–50	0–50
Dust	0–125	0–50	0–100	0–75	0–75	0–75

To visualise the differences in air pollution, the Airly platform [116] operates on a scale with seven levels (Airly CAQI), and it informs by colour the state of air pollution. These colours range from green, which indicates very good air quality, to maroon and purple colours where the air pollution standards exceed the permitted level by many times [116].

5.1. Environmental Impact of Fossil Fuel Consumption

According to the Central Statistical Office data [118], the amount of carbon dioxide emissions in 2008–2016 in Poland remained at a similar level and amounted in range of 316 to 340 million tonnes annually. In the analysed period, the largest emitter according to the type of economic activity were the sectors: "electricity, gas, steam, hot water and air conditioning systems production and supply". These sectors emitted approximately 150 to 160 million tonnes of CO_2 during the reviewed period [118].

The analysis published in April 2020 on CO_2 emissions reported in the European emissions trading system [119] presents the ranking of companies and installations emitting the most greenhouse gases in the European Union in 2019. Poland was in first place on this table. Coal power generation is one of the branches of the economy with the greatest negative impacts on the environment and it is responsible for environmental pollution. The energy sector is the largest emitter of greenhouse gases in Poland in 2017; it was responsible for almost 40% emissions as shown in Figure 25 [120].

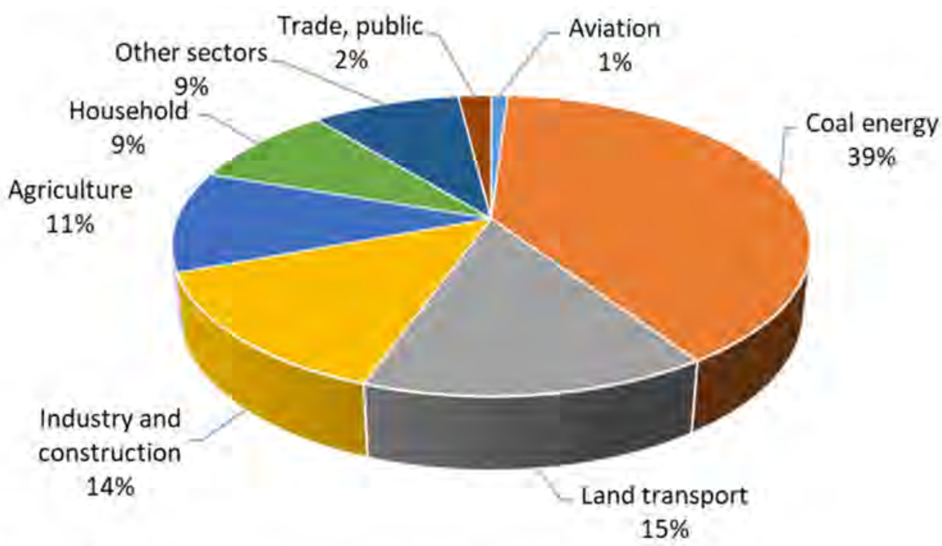

Figure 25. Share of significant sectors in CO_2 emissions in 2017 [120].

Table 12 presents data on calorific values (CV) and CO_2 emission factors (EF) for three selected fuels used in the national economy in 2016, according to The National Centre for Emissions Management [121].

Table 12. CV and CO_2 EF in 2016 in Poland [120].

Heat Source	Fuel	CV in MJ/kg	CO_2 EF in kg/GJ
CHP plants	hard coal brown coal	21.42 8.99	93.46 107.13
Industrial CHP plants	hard coal	22.94	94.66
Heating plants	hard coal brown coal	21.74 9.02	94.94 106.62

The National Emission Balance includes values of air pollutant emissions covered by reporting to the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP) and for the purposes of national statistics and European Union requirements set out in Directive 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants [122].

The national emission inventory covered the scale of SO_X, NO_X, CO and dust emissions, the emitted pollutants during coal combustion [121].

The main source of SO_2 emissions is the energetic combustion of fuels (mainly coal) in stationary sources, which are responsible for almost 100% of the national SO_2 emissions. SO_2 emissions from production processes are associated with oil refining, coke and sulphuric acid production and account for about 3% of national emissions.

In 2017, the estimated SO_2 emissions were 1.4% lower compared to 2016 and lower by 18.1% compared to 2015. Figure 26 illustrates the sectoral shares of national SO_2 emissions in 2017 in Poland.

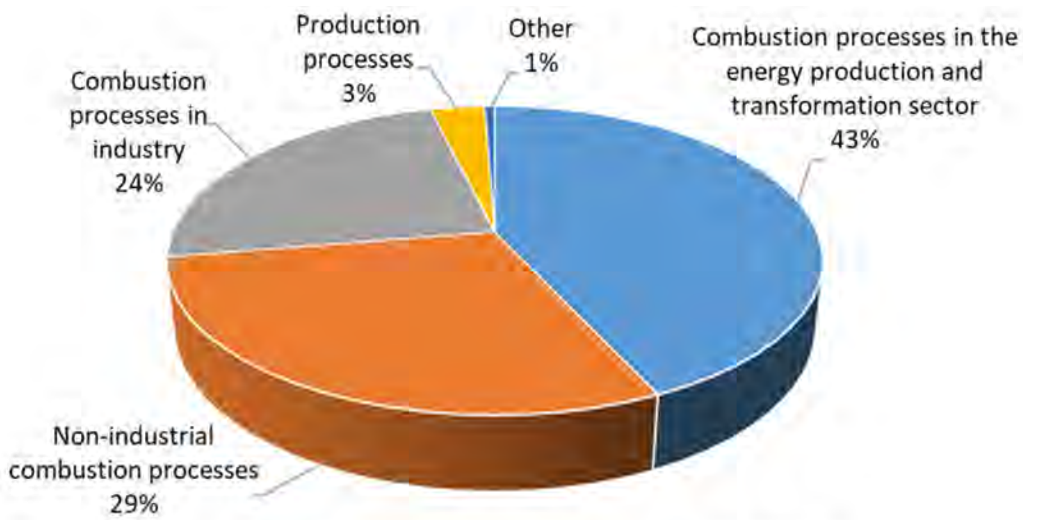

Figure 26. Share of significant sectors in SO_2 emissions in 2017 [122].

The largest source of nitrogen oxides emissions in 2017 was fuel combustion, which was in Road Transport sectors—37%, and Combustion Processes in Energy Production and Transformation sectors—21%, as shown in Figure 27. Nitrogen oxides emissions increased in 2017 by 8% compared to 2016 and by 11% compared to 2015 [122].

On the other hand, the main source of emissions of fine PM2.5 were sources belonging to the category of non-industrial combustion—47%, in which the largest part of emissions (more than 80%) is related to the combustion of hard coal and wood in households [122].

The other major significant sources of dust emissions of this fraction in 2017 were the Industrial Combustion Processes—21%, and from Road Transport sectors—10%. Figure 28 presents the sectoral shares of national PM2.5 emissions in 2017 in Poland.

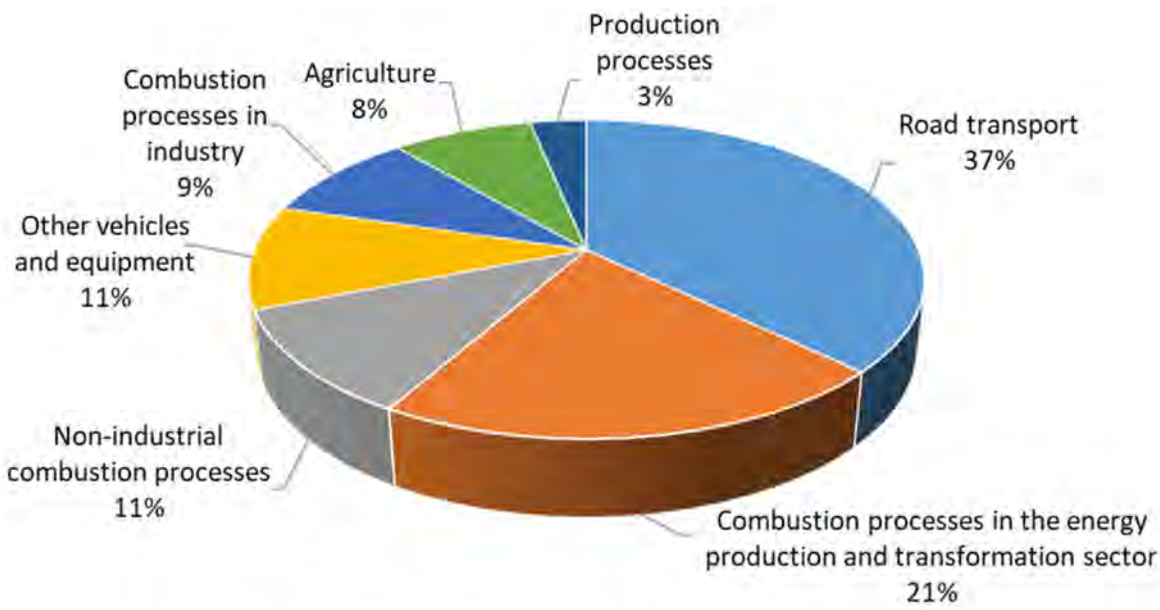

Figure 27. Share of significant sectors in NO_X emissions in 2017 [122].

Figure 28. Share of significant sectors in PM2.5 emissions in 2017 [122].

In 2017, the largest source of carbon monoxide emissions was from non-industrial combustion, which is responsible of approximately 59% of national carbon monoxide emissions. Road transport is another significant source of carbon monoxide emissions and which accounts for around 23% of national emissions. Figure 29 shows the sectoral shares of national CO emissions in 2017 [122].

Table 13 presents the data on NO_X, SO_X and dust emission factors EF from coal according to The National Centre for Emissions management data in 2020 in Poland [123].

Table 13. The mass of pollutant produced by a unit mass of the combusted coal [123].

Pollutants in kg/GJ			
CO_2	NO_X	SO_X	Dust
96.935	0.22	0.41	0.09

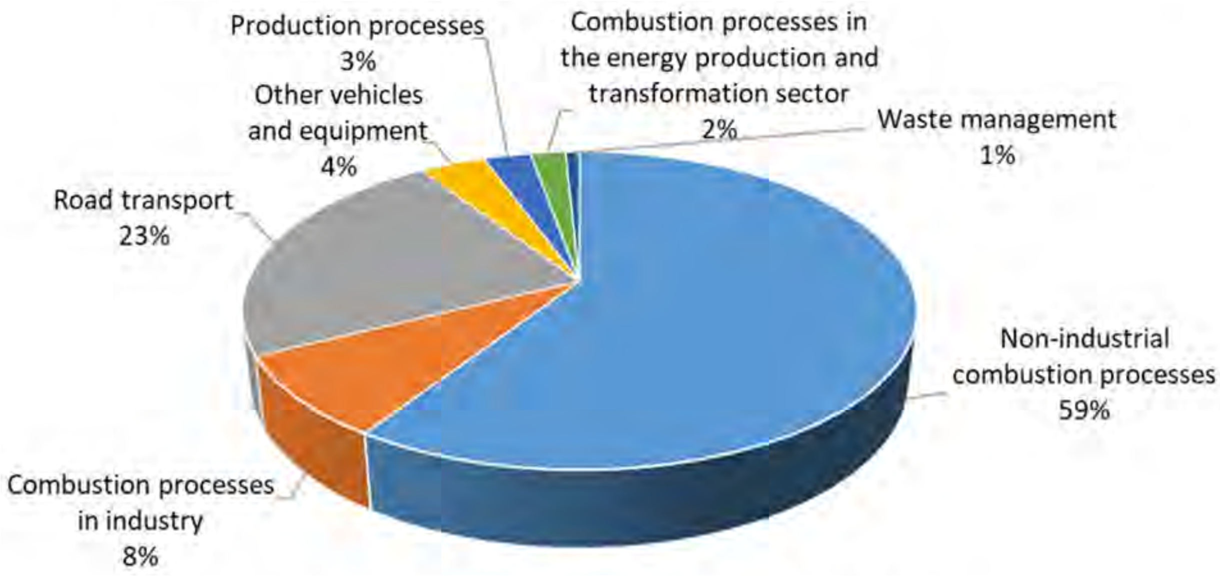

Figure 29. Share of significant sectors in CO emissions in 2017 [122].

5.2. *Air Pollutant for the Case Study in the Analysed Swimming Pool*

Taking into account the above-mentioned information related to the pollutant emissions, the main focus should be focused on the reduction of greenhouse gas emissions and pollutants produced during coal combustion, especially the plans which aim to abandon coal power generation in many EU countries due to emissions reduction targets set in the Paris Agreement [124,125]. The European Union, including Poland, has undertaken to reduce greenhouse gas emissions by 40% in 2030 compared to 1990 values.

Figures 30 and 31 illustrate the air pollution reductions for the analysed measurement period (CO_2 reduction and NO_X, SO_X, dust reduction respectively). These emission reductions can be result by using the proposed GWHR system, taking into account the total water flow supplied to the swimming pool building (for DHW and water heating).

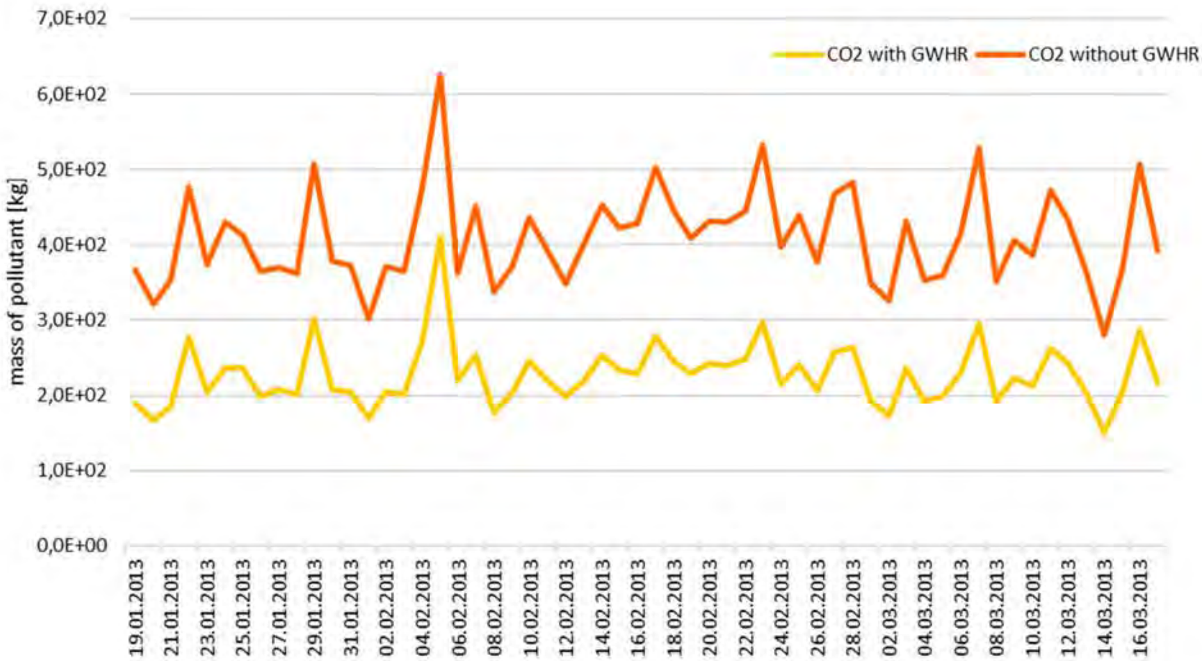

Figure 30. The reduced emissions of CO_2 in the analysed period.

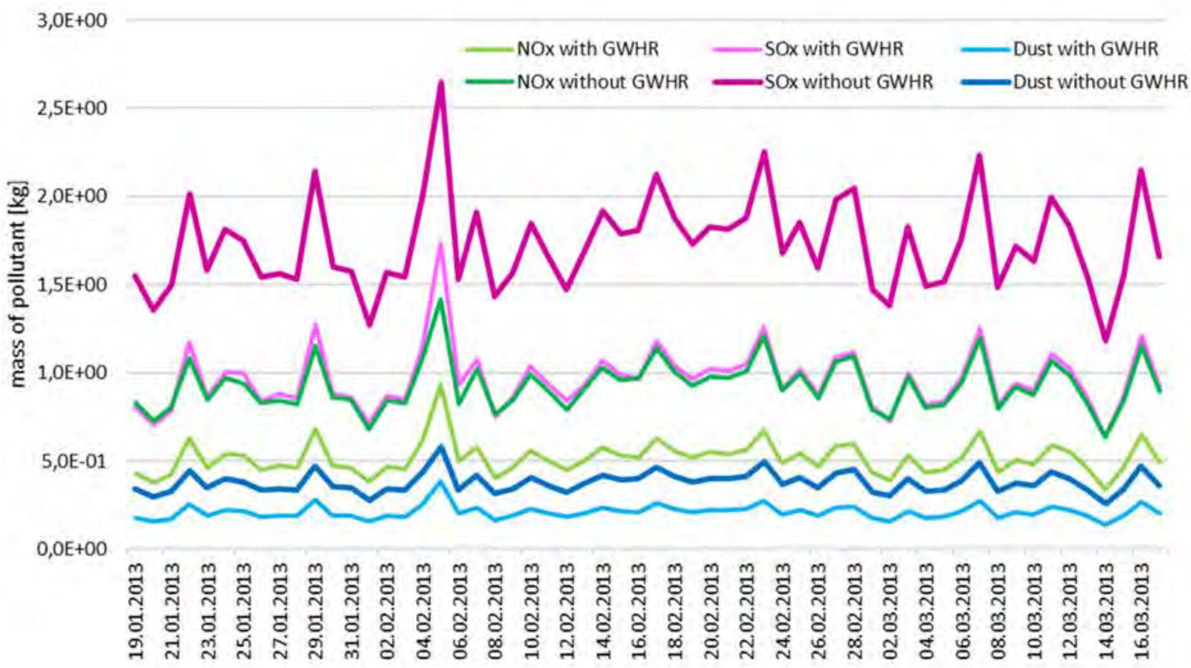

Figure 31. The reduced emissions of NO_X, SO_X and dust in the analysed period.

It is obvious from the provided analysis that the reduction of emitted pollutants is significant into the atmosphere.

6. Conclusions

This article analysed the types of swimming pools, their divisions, specifications, water and thermal requirements, water and energy consumption characteristics, DHW preheating, GW recovery analysis according to European design regulation, guidelines and standards for selected cases in European countries.

It should also be noted that there is no uniform system which defines a given pool and qualifies it to a selected group according to strictly acquired rules. The swimming pool facilities which are currently under construction have various recreational, rehabilitation and physical activity functions.

One of the main analysed objectives was the total water consumption in indoor swimming pools. The main sources of water consumption are determined in a typical pool are backwashing, showers, evaporative losses and leaks. Therefore, the pool water and DHW should be rationally managed and consumed.

As mentioned above, in addition to the water consumption, the energy consumption as an essential issue was analysed as well. Recovering heat from GW as a waste thermal potential of swimming pools provides a valuable heat source. Therefore, it is very reasonable in swimming pools to recover the heat from GW mainly where the waste heat is produced continuously in extensive, measurable and in large quantities in swimming pool.

Additional analyses were conducted concerning heat consumption for DHW preparation, as well as their impact on the environment by using the CAQI index. The swimming pool water heating and DHW preparation processes constitute a large share of energy in the total demand. This share can be as high as 50%.

In the analysed case study during the measurement period, from 19 January 2013 to 17 March 2013, the following data were registered:

- DHW daily consumption included in the range from 21.2 to 41.2 m^3, the average daily consumption is 31.9 m^3;
- DHW temperature included in the range from 33.7 to 51.1 °C, the average DHW temperature is 45.7 °C;

- Cold water temperature included in the range from 10.7 to 53.5 °C, the average DHW temperature is 14.5 °C.

The analysed three cases for water consumption by the proposed GWHR system are:

① For DHW preheating, taking the measured flow and water temperatures as the basis for calculation;
② For DHW preheating, taking the flow rates and water temperatures from guidelines and standards as the basis for calculation;
③ To preheat swimming pool water.

Calculations for the second and third cases were carried out on the base of guidelines, regulations and standards in Poland and Germany, which are compared in Table 6.

For analysed cases, the savings of thermal energy consumption were calculated respectively as illustrated on Figure 22 and mentioned in Tables 7, 9 and 10 as follows:

- For case 1—from 1.34 to 2.43 GJ per day, average 4.19 GJ per day, which gives average 45% energy saving;
- For case 2—from 3.25 to 5.20 GJ per day, average 4.23 GJ per day, which gives 40% energy saving;
- For case 3, depending on the type of swimming pool provide from 48 to 67% energy saving.

The most suitable solution for the analysed case study object seems to be recovery from showers, where there is a continuous water flow and water heating at the same time. In other cases, it is advisable to use additional GW storage tanks and a GW dosing pump system when the water is being refilled, replaced, etc.

As noted before, the amount of heat recovery is related not only to the water flow rate but also to actual cold water and DHW temperatures. The highest recovery value did not always occur at maximum water flow rate.

One of the most important environmental challenges facing Poland is how to improve air quality, especially as the heat energy production in Poland is based mainly on fossil fuels, where the environmental harm associated with the use of fossil fuels continues to grow.

Therefore, the analysed recreational facility of swimming pool, calculations of pollutant emissions and results were obtained for the mentioned case 1 for real system (without GWHR) and with proposed GWHR system. The positive effect of using GWHR system is significant in reducing pollutant emissions of CO_2, NO_X, SO_X and dust, which can vary in the range of 34 to 48%, with an average value of 45%, as illustrated in Figures 30 and 31.

The obtained results ensure that the use of GWHR systems in swimming pools is one of an encouraging and promising acceptably good solution to meet the EU energy and environmental policy targets, especially in reducing energy consumption, increasing energy efficiency technologies and solutions, decarbonisation of heating sector as well as the integration of renewables in a sufficient flexible manner.

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