Efficient solution for large heat pumps: wastewater heat recovery

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Abstract

Inside the sewer there is a hidden and rarely used, stable temperature energy source to be found: the communal, household and industrial wastewater. A heat pump based technological solution has been developed to harness and utilize energy resided in wastewater to heat and cool buildings. This means for a city like Rotterdam the potential of min. 50 MW energy-generation!

The challenges are to use this valuable resource on site amongst city circumstances, to make it upsizeable to several MWs requirements and to achieve a highly efficient system (COP above 6!) in order to make it financeable.

Driven from the technology solution's "independence" from the sewers (nothing installed inside the pipeline) the system's implementation is flexible, after eight years of development its possible size only depends on the wastewater flow.

The technology developed has been monitored during operation for over 5 years at different locations (sizes: 1 - 3.8 MW). Learning from this unrivalled operational experience and the monitored performance data the technology solution has been improved through minimizing energy consumption, evolving efficiency of heat exchange, optimizing maintenance requirements and SCADA system.

Additional benefits recognized during realization of the projects:

- Free allocated and valuable spaces on rooftops
- Combined and centralized heating and cooling system
- Potential external use of remaining heating or cooling capacities
- Satisfying simultaneous heating and cooling needs
- Use sewage as heat transporting medium

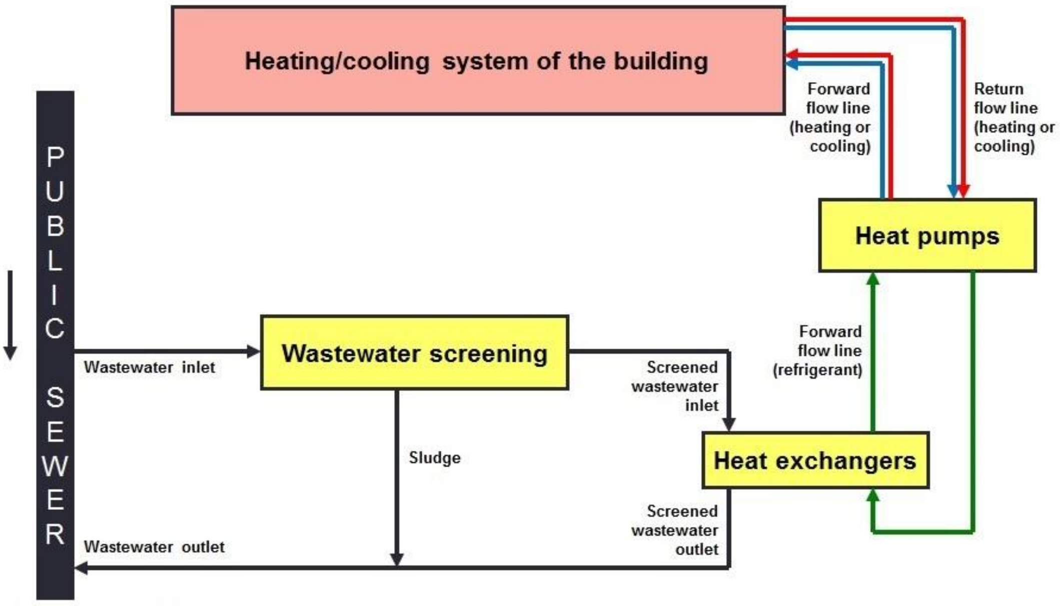
Discussion points: potential unrealized, possible end users and their benefits, influence on the thermal management of a wastewater treatment plant.

Keywords: wastewater; water-water heat pump; screening station; WHRP (wastewater heat recovery plant)

1. Prologue

Thermowatt Ltd. pioneers on the field of heat pump technology, by utilizing thermal energy carried by wastewater for heating and cooling large buildings. The objective of this paper is to share our operational experiences which we were able to gather thanks to our patented technology being utilized. It will give an overview about the versatility and adaptability to various installation and operation conditions and circumstances. In our portfolio we already have 5 operating systems above 1 MW thermal capacity each and 1 under construction.

I will introduce shortly the technology itself and then give an overview on the construction and operation aspects and consumer benefits at our biggest project, the Budapest Military Hospital of 3.8 MW capacity. In the following one operational plant and the system currently under construction will serve as examples on how – in order to realize the potential – special conditions can be respected whilst unique requirements are being fulfilled.



2. Foreword

One of the greatest challenges of the 21st century is satisfying our energy needs. In many cases the traditional fossil energy cannot be the solution due to strict environmental and other legal regulations [1] or simply because employing it would be just too expensive. The key is using alternative energy sources and innovative technologies!

Heat pumps are today's favourite example of technologies based on alternative energy sources. . The efficiency of these devices depends to a great extent on the temperature of the heat source.

Below the surface, inside the sewer, there is a hidden and rarely used energy source to be found. This is the communal, household and industrial *wastewater*. The temperature of communal wastewater (collected and channelled through the sewage system) is stable and in average ranges between 10-20°C, while that of industrial wastewater can get even higher. The steady temperature makes wastewater an ideal heat source to feed heat pumps. Utilizing wastewater as an energy source is not a completely new idea, however until now, there has not been a technology developed to harness it economically for large buildings and building complexes.

3. The Thermowatt technology

The Hungarian Thermowatt Ltd. has developed a technology to harness and utilize energy contained in wastewater to cool and/or heat buildings in a modern, environmentally friendly and economical way. The most important difference between the Thermowatt system and other solutions is that the Thermowatt system does not require installation of heat-exchangers inside the sewage system in order to regain heat. It places all appliances outside the pipeline either underground or directly above the surface. Wastewater streams from the main collector into a chamber then flows through a filtrating station in order to separate sludge. The screening is crucial in order to prevent the heat-exchangers [2] from obstruction, however there is no muncher, the heat exchangers are self-cleaning without any internal moving parts. The filtered solid particles are contained in a closed system and then they are returned into the main collector, so that the cooled/heated returning water flow washes the solids back to the sewage system eliminating the need for removal of filtered solid particles.

Figure 1. General System Flow Sheet

The heat energy recovered by the heat exchangers is transferred [3] into utility heating or cooling via water/water heat pumps. The same exact heating system is applied for both cooling and heating. In order to operate in the most efficient and energy saving technique, the system elements are carefully designed, optimized and harmonized. The technology has also been tested in extremely low and high outside temperatures (from -17 to +37°C) and under fluctuating quantity and quality wastewater conditions.

The available heat pump energy efficiency values with wastewater utilizing system are the following:

- Heating mode: COP = 5.5 – 6.5 [4]
- Cooling mode: EER = 6.0 – 7.0

To cover the heating or cooling demand of a building through the utilization of wastewater as a heat source a sufficient amount of wastewater has to be available. To recover 1MW of heating energy there is a need for 140–160 m^3/h of wastewater. This amount depends on the temperature of the wastewater and the technical efficiency of the system. The system's General Flow Sheet is shown on Figure 1.

3.1. Deployment and operational advantages

- This system can be used in both cooling and heating mode: great savings can be achieved, since the same system is applied for both cooling and heating of the buildings
- Fast and easy installation: in comparison to geothermal systems the deployment requires far less space. Thermal probe or establishment of a collector field is not necessary, therefore space, time and money can be saved
- City centre installation is possible
- Easy accessibility and maintenance (especially important consideration for the operator)
- The integrated control system ensures simple and easy supervision (even remotely)
- Low operational costs
- Generates additional income for wastewater utility

An additional advantage of the system is that there is no CO_2 or other greenhouse gas (GHG) emissions on the spot (zero emission). Employing alternative energy helps to meet the Energy Directives that require an ever-growing percentage of energy used to come from renewable sources. Thermowatt also generates a significant competitive edge on a corporate and as well as on an industrial level.

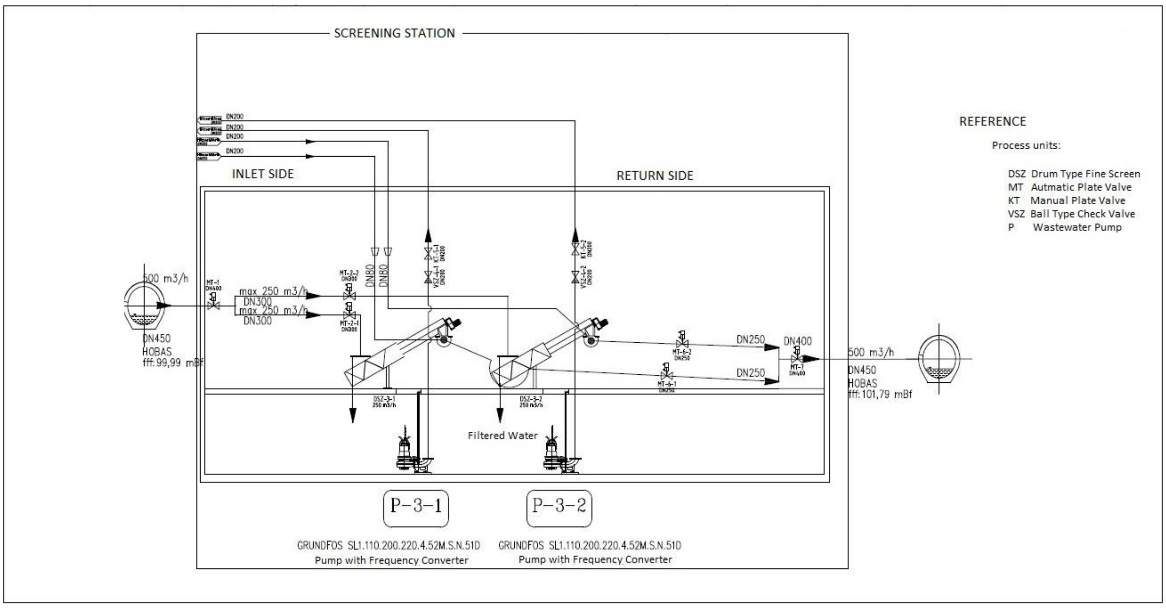
Deploying the system is the most advantageous, where**…**

- … the building has significant cooling energy requirements. The cooling system runs at a temperature differential of 7/12°C, but it can also reach higher rates (8/20°C). The efficiency of the system is greater when cooling energy is supplied.
- … the building has heating demands as well. The forward water temperature of the heating system serving consumers is not higher than 50–55°C. It can be justified as a support energy source for systems of higher temperature rates.
- … cooling and heating requirements arise simultaneously: efficiency of the system is remarkably higher when both thermic sides of the heat pump can be utilized.

4. Various applications of the Thermowatt technology

Since the launch of the first project in 2011, Thermowatt has already completed 5 systems above 1 MW capacity and the 6^{th} is in its realization phase. The local conditions and costumer requirements being different, we cannot meet two identical systems. In this paper I would like to show, how to adapt the technology to the needs and demands and provide an optimum solution to the user. I have selected 3 characteristic examples from our portfolio to give a relatively detailed view of our approach:

- Budapest Military Hospital
- Budapest Sewage Works – Ferencváros Pumping Station



- Újpest Municipality – Market Hall and Municipal Buildings (under construction)

4.1. The Budapest Military Hospital Project

The Wastewater Heat Recovery Plant (*WHRP*) at Budapest Military Hospital (*Honvédkórház*) has been put into operation in August 2014. The system is based on the main sewerage collector line led in the very proximity of the hospital's property, having an average daily flow of 12,000 cubic meters. The wastewater flow sheet below on Figure 2. gives an overview of the screening station operation which can be called the very centre of the Thermowatt technology.

Figure 2. Screening Station Flow Sheet

The system size was set to 3.8 MW heating capacity according to the available heat source determined by the collector's flow, and respecting the 5°C temperature gap at the wastewater side. The corresponding cooling capacity of the plant is 2.9 MW, giving the opportunity to utilize the plant during the summer season. The installed capacity covers about 40% of the hospital's total heating need but there was a very special opportunity in the heating system: the air handling units were connected to a dedicated heating circuit, allowing their direct and separated heat supply.

For the heat pumps' operation efficiency the most critical parameter is the gap between source and sink temperatures, in order to maximize the efficiency this temperature gap should be minimized along with the maintained heating (or cooling) service.

As far as the temperature of the hot water supply of the air handling unit's heating coil we have the widest liberty of determining the design value, and we can go down to 32°C while delivering 24°C air supply (with -5 lower limit of external temperature). In order to adapt the air handling system to this low temperature (32 °C) of hot water supply, every heating coils of the air handling units had to be replaced with larger surface ones. As an integral part of the project the supply section of all together 123 air handling units were provided with new large replacement heat exchangers for the job.

According to the thermal load calculations the 32°C heating water temperature and the available 3.8 MW heating capacity are sufficient down to -5°C external temperature, therefore in case of colder weather further heat should be added: by using the remaining heating system's higher temperature heating water (60 to 70°C), we can raise the air handling units supply water temperature up to 37°C representing 50% additional heating power and allowing to manage even -20°C external temperature when maintaining the necessary fresh air supply.

The available cooling capacity of 2.9 MW of the plant is connected directly to the cooling central of the hospital; the chilled water supply temperature is 6 °C. The WHRP's cooling performance alone can manage about 80 % of the summer season and when extra cooling power is needed, the previously used chillers are there to back up the system.

However their performance is mostly equal but two different models of Carrier water-water heat pumps were selected for the system. One of them is a fixed speed high efficiency unit (30XWHP1612) [5] which performs its best close to his maximum capacity, the other one is a controlled compressor speed type through variable frequency drive (30XWHV1570) [5], providing superior efficiency at part loads within the range of 30-80%. The optimum efficiency operation strategy is combining the use of the two heat pumps:

- Below 40% of total capacity need only heat pump #2 (variable frequency drive) is used with part load condition.
- In the range of 40% to 50% only heat pump #1 operates around its full load capacity in its optimal condition.
- Above 50% of system need heat pump #1 is working at full load and heat pump #2 completes it to the necessary level of capacity.

The plant operation is managed and supervised by an individually developed software running on a PLC based process control system taking care of the heat pumps, frequency controlled pumps of the hydraulic circuits and the complex control of the wastewater filtering station including pumps, valves, pit wastewater level and screening units. The system monitoring and parameter setting can be done by the local HMI touch screen panel or for authorized users on computer or smartphone through the internet. For documentation, analysis and research purposes the main operation data are logged every 10 minutes.

4.1.1. Main operation data

The system's main characteristics can be seen on Table 1 and 2.

Table 1. Budapest Military Hospital WHRP Heating

Description	***Dimension***	***Value***
System Capacity	kW	3 800
Forward water temperature	°C	32
Return water temperature @ system capacity	°C	22
Water flow	m3/h	330
Wastewater temperature (average)	°C	17,2
Wastewater flow	m3/h	480
Primary water temperature heat pump in	°C	12
Primary water temperature heat pump out	°C	6
Auxiliary power (pumps + screening)	kW	75
Heat pump input power @ system capacity	kW	525
Heat pump efficiency @system capacity (COP)	kW/kW	7,23
Overall efficiency @ system capacity	kW/kW	6,33

Table 2. Budapest Military Hospital WHRP Cooling

Description	*Dimension*	*Value*
System Capacity	kW	2 980
Forward water temperature	°C	6
Return water temperature @ system capacity	°C	12
Water flow	m3/h	420
Wastewater temperature (average)	°C	22,3
Wastewater flow	m3/h	480
Primary water temperature heat pump in	°C	27
Primary water temperature heat pump out	°C	33
Auxiliary power (pumps + screening)	kW	80
Heat pump input power @ system capacity	kW	551
Heat pump efficiency @system capacity (EER)	kW/kW	5,41
Overall efficiency @system capacity	kW/kW	4,72

4.1.2. Operating conditions and registered data

The system is running since August 2014, so we have got two complete operation years and almost two full heating and cooling seasons. The switch from cooling to heating (vice versa) is done by a complete hydraulic reconfiguration of the system:

- In heating mode, the heat pumps' evaporators are connected to the wastewater heat exchangers and the condensers provide heating of the building
- In cooling mode, the heat pumps' condensers are connected to the wastewater heat exchangers and the evaporators produce chilled water for cooling purposes.

It is also important to mention that in heating mode the two heat pump condensers are in series in order to match the 10 °C temperature gap of this building's heating system. The first full year of operation was 2015. The system operation switch from heating to cooling occurred on 15 April, and from cooling to heating on 15 October.
The following tables (i.e. Table 3, 4, and 5) show the main performance and efficiency data of this year's operation:

Table 3. Year 2015 Heating Energetics Review

Description	*January*	*February*	*March*	*April*	*October*	*November*	*December*	*TOTAL*
Heating supply [GJ]	2 546	2 404	1 856	769	862	2 629	2 092	**13 158**
Electrical consumption [kWh]	146 242	140 186	108 252	42 979	59 891	175 075	151 022	**823 647**
Plant efficiency	4.84	4.77	4.77	4.97	4.00	4.17	3.85	**4.44**
Auxiliary consumption [kWh]								**262 800**
Net heat pump efficiency [kWh/kWh]								**6.52**
Thermal power use rate	25%	26%	18%	16%	18%	27%	21%	**22%**

Table 4. Year 2015 Cooling Energetics Review

Description	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*TOTAL*
Cooling supply [GJ]	453	1 035	1 503	3 058	3 236	1 764	347	**11 396**
Electrical consumption [kWh]	29 303	80 270	96 854	207 901	230 481	138 895	30 031	**813 735**
Plant efficiency	4.30	3.58	4.31	4.09	3.90	3.53	3.21	**3.89**
Auxiliary consumption [kWh]								**306 600**
Net heat pump efficiency [kWh/kWh]								**6.25**

Thermal power use rate	12%	13%	20%	39%	42%	23%	9%	**25%**

In 2016 the cooling season is almost complete, with the following operation data:

Table 5. Year 2016 Cooling Energetics Review

Description	***April***	***May***	***June***	***July***	***August***	***TOTAL***
Cooling supply [GJ]	1 025	1 198	2 611	3 124	3 139	**11 097**
Electrical consumption [kWh]	66 385	86 924	179 430	218 141	212 671	**763 551**
Plant efficiency	4.29	3.83	4.05	3.98	4.10	**4.4**
Auxiliary consumption [kWh]						**275 400**
Net heat pump efficiency [kWh/kWh]						**6.32**
Thermal power use rate	13%	15%	34%	40%	40%	**29%**

The supplied energy and the electrical consumption data originate directly from the system's operation log. The auxiliary consumption is a calculated value based on the system's 24/7 operation and the average values observed during the continuous personal monitoring. It is important to mention that about 45-55% of the auxiliary power can be connected to the primary thermal energy generation (wastewater pumping and screening) and the rest belongs to the distribution of the consumer side.

The examination of these figures is very instructive concerning the energetics aspect of the system operation. If the auxiliary power is taken into consideration on the basis of installed capacity's consumption, it seems to be fairly low (cca 14% both for heating and cooling). However, being its use is almost constant during the full operation time, its role becomes very important in low consumption periods. It can grow even above the heat pumps input need. The auxiliary consumption's rate based on the total energy input is respectively 32% in heating (2015), 38% and 36% in cooling in the past two seasons. In our job for system efficiency optimization this is a very important element to be considered when planning future systems. On the other hand the heat pump operation is corresponding to the previous expectations and calculations.

4.2. Budapest Sewage Works – Ferencváros Pumping Station – System Concept

The Ferencváros Wastewater Pumping Station is the biggest and oldest pumping station of the city, responsible for the transfer of almost 20% of the total Budapest wastewater flow and its average performance is 150,000 m^3/day. The plant itself has about 10,000 m^2 building area with 1,300 kW heating and 500 kW cooling capacity need and a traditional, 70/50°C radiator based heating system. The exceptional local opportunities were the huge available quantity of wastewater and a big potential outside customer in close proximity, ready to purchase thermal energy.

From the engineering point of view this WHRP has a very important technological specialty: The total quantity of the transferred wastewater is mechanically treated (screened) for the pumping operation, giving opportunity to simplify the heat recovery technology by leaving out its screening unit or replacing it with a much simpler muncher.

During the design period the biggest question mark was put on the wastewater access: how to find a rational and economical way, while in full respect of the plant's own technology. Finally a very original wastewater supply method was selected.

The main pump building is located very close to the heat recovery machinery unit. The pumping itself is done by 18 individual pumps connected to a circular shaped main collector line (DN 1400), which is constantly pressurized by the actually operating pumps. Then the pumped wastewater leaves the plant trough one of the two installed distance lines (DN 1000) toward the Central Treatment Plant. The collector line can be separated into two halves, in order to ensure maintenance or repair interventions without stopping the pumping service. The

Thermowatt system's wastewater supply is connected to both halves of this collector line with suitable separating valves ensuring the open connection in any operation mode of the pumping station. If one of the collector line halves is out of operation (for any reason), this side of the supply connection is closed (preventing the bypass flow), but the operating side can remain open and functioning.

Using only less than 5% of the pumped wastewater quantity for heat recovery purpose, the simplest return routing could be led directly to the pumping station inlet channel with a free flow outlet.

As all pumping stations the wastewater is screened, in order to prevent pump damage. At this station the screening is done by a 20 mm gap vertical bars apparatus. Further mechanical treatment is not necessary given the Thermowatt heat exchangers have sufficient self-cleaning capacity.

As the operation of the pumping station is controlled by the plant's actual flow need, the collector line's pressure fluctuates accordingly. The wastewater supply of the WHRP should be levelled, so a VFD driven speed regulated booster pump manages the stabilized operation pressure.

The localization of the Ferencváros Pumping Station offers a very special business opportunity – there is a prominent thermal energy consumer in the very proximity, namely the MÜPA (Palace of Arts), with its all year round cold energy need. It can be easily served with the plant's installed cooling capacity which during the heating season can be operated nearly free of charge. It means that the WHRP heat source is partly the cooling service instead of the wastewater. In practical terms the heating need is fully produced, and the source of it is composed from the outside cooling charge and the recovered from the wastewater in such quantity that it ensures the system's energy equilibrium. To keep this balance, the WHRP's hydraulic circuit is provided with the necessary motorized mixing valves, and VFD controlled pumps. There are forward and return distance lines between Ferencváros Pumping Station and MÜPA of DN300 and DN200 size allowing the cooling and in a second phase the heating energy supply from the WHRP on a purely benefit driven way. Main system characteristics are given on Table 6. and Table 7.

Table 6. Ferencváros pumping station WHRP heating

Description	***Dimension***	***Value***
System Capacity	kW	1 230
Forward water temperature	°C	63
Return water temperature @ system capacity	°C	50
Water flow	m3/h	83
Wastewater temperature (average)	°C	17,8
Wastewater flow	m3/h	250
Primary water temperature heat pump in	°C	12
Primary water temperature heat pump out	°C	7
Auxiliary power (pumps + screening)	kW	22
Heat pump input power @ system capacity	kW	292
Heat pump efficiency @system capacity (COP)	kW/kW	4,2
Overall efficiency @ system capacity	kW/kW	3,92

Table 7. Ferencváros pumping station WHRP cooling

Description	***Dimension***	***Value***
System Capacity	kW	1 204
Forward water temperature	°C	7
Return water temperature @ system capacity	°C	12
Water flow	m3/h	105
Wastewater temperature (average)	°C	22,3

Wastewater flow	m3/h	240
Primary water temperature heat pump in	°C	27
Primary water temperature heat pump out	°C	33
Auxiliary power (pumps + screening)	kW	35
Heat pump input power @ system capacity	kW	235
Heat pump efficiency @system capacity (EER)	kW/kW	5,12
Overall efficiency @system capacity	kW/kW	4,45

These figures above do not apply for simultaneous cooling and heating.

4.3. Újpest – Market Hall, City Hall and Municipal Buildings (under construction)

Újpest is one of Budapest's 23 districts, and it is located in the northern part of the Hungarian capital. The idea of installing a WHRP came about with the municipal investment of a new market hall replacing the old one, which resulted in the full reconstruction of the district's most representative square (St. Stephens) comprising of a church and the city hall as well.

There is a main collector sewerage line at the southern edge of St. Stephens square with an above 800 m^3/h wastewater flow providing solid basis for WHRP construction. Given that the new market hall is a municipal investment and the municipal building is very close as well, together with the general need of using green energy were the elements of the decision to install a new WHRP there.

For several technical and feasibility reasons the setup of the system is the following: The WHRP main underground building is located near the main collector line allowing an easy and short bypass connection between the sewerage and the screening pit. This building is housing the wastewater screening station, the heat exchangers and the heat pump serving the municipality buildings through installed distance lines. The transformer for the WHRP power supply is also located in this underground building.

The sizing of the wastewater connection, the screening station pit and the machine rooms takes into consideration a future capacity increase of 1.8 MW above the actual one (0.7 MW here and 1.0 MW in the new market hall building).

The heat pump serving the new market hall is located in that building and is connected by another distance line to the heat exchanger group of the underground WHRP. This heat pump has the task above the standard heating and cooling functions: the production of sanitary hot water. In heating season it can be done easily with raised heating set points, but in cooling mode this should be done in a simultaneous service without overheating the primary circuit which would affect the operation and efficiency of the other heat pump(s). In order to obtain the desirable operation the heat balance of the heat pump providing cooling as master operation should be maintained by a heat exchanger connected to the return line of the condenser circuit. If the hot water production alone can maintain the heat pump's heat balance, the other side of the heat exchanger is closed, but if excess heat is present it will be carried away with the help of a suitable amount of primary water (coming from the wastewater heat exchanger) on its appropriate temperature. In terms of numbers the hot water production is done on 60/55°C and the operation temperature level of the primary circuit is 27/33 °C in cooling mode. The amount of primary water maintaining the heat balance is controlled by a dedicated VFD pump.

This technological detail was the main reason of placing the new market hall heat pump directly into the mentioned building: only one circuit (i.e. the primary one) needs pumping in the distance line, which can represent considerable energy input economy. Main characteristics are given on Table 8 and 9.

Table 8. Újpest Market Hall WHRP heating

Description	***Dimension***	***Value***
System Capacity	kW	1 690
Forward water temperature	°C	60

Return water temperature @ system capacity	°C	50
Water flow	m3/h	212
Wastewater temperature (average)	°C	17,8
Wastewater flow	m3/h	240
Primary water temperature heat pump in	°C	12
Primary water temperature heat pump out	°C	7
Auxiliary power (pumps + screening)	kW	36
Heat pump input power @ system capacity	kW	423
Heat pump efficiency @system capacity (COP)	kW/kW	4,0
Overall efficiency @ system capacity	kW/kW	3,69

Table 9. Újpest Market Hall WHRP cooling

Description	***Dimension***	***Value***
System Capacity	kW	1 748
Forward water temperature	°C	7
Return water temperature @ system capacity	°C	12
Water flow	m3/h	105
Wastewater temperature (average)	°C	22,3
Wastewater flow	m3/h	240
Primary water temperature heat pump in	°C	27
Primary water temperature heat pump out	°C	32
Auxiliary power (pumps + screening)	kW	42
Heat pump input power @ system capacity	kW	302
Heat pump efficiency @system capacity (EER)	kW/kW	5,78
Overall efficiency @system capacity	kW/kW	5,08

These figures above do not apply for simultaneous cooling and heating.

5. Conclusion

Over 5 years of operational experience in different large building sites prove that this Heat Recovery from Communal Wastewater Technology is versatile in its range of applications, it has demonstrated efficiency in different setups and customer needs. The experienced performance on different sites generally corresponds to the foreseen data and enables future projects to be predictable. The use of achievable capacity is limited by the wastewater flows but makes Heating and Cooling of large buildings feasible with water to water heat pumps.

Later developments of the heat pump as part of the system keeps it running on its highest performance level at all times among other solutions. Accelerating technical developments brings new refrigerants [4] [6], more efficient heat pumps with extended temperature limits which further widens the application field of this Wastewater Heat Recovery technology. Despite the obtained results, we are in the beginning phase of conducting research and developing the wastewater technology solution including key elements like screening equipment, special heat exchanger and control software. Utilization of this widely accessible heat resource in city centres offers a sustainable solution due to a favourable and steady temperature of the communal wastewater. Our efforts concentrate on contributing to an environment conscious energy management.

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