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Recovery and Valorisation of Energy from Wastewater Using a Water Source Heat Pump at the Glasgow Subway: Potential for Similar Underground Environments

Konstantinos Ninikas *, Nicholas Hytiris, Rohinton Emmanuel and Bjorn Aaen

School of Computing, Engineering & Built Environment, Glasgow Caledonian University, Cowcaddens Road Glasgow, Scotland G4 0BA, UK; N.Hytiris@gcu.ac.uk (N.H.); Rohinton.Emmanuel@gcu.ac.uk (R.E.); Bjorn.Aaen@gcu.ac.uk (B.A.)

* Correspondence: Konstantinos.Ninikas@gcu.ac.uk or kninikas@uth.gr; Tel.: +44-(0)7476232167

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Abstract: An installation of a Water Source Heat Hump (WSHP) at Glasgow's Underground Station, has been using the subsurface wastewater ingress to heat the office at St. George's Cross station. The performance of the Glasgow Subway's new heating system was observed for a few months. The energy output readings are being presented. An average coefficient of performance (CoP) of 2.5 and a 60% energy input reduction for the heating system based on the old heating system's energy demand indicates the actual system's performance. The purpose of this research is to detect the likelihood of implementing the same setup in similar underground environments where the excess wastewater may support a viable and eco-friendly heating system. Fifteen cities across Europe have been identified and presented, with the adequate water quantities, where similar heating systems may be applied. The output of this study indicates not only the financial benefit but also the energy and carbon reduction of this trial. It highlights main subjects which were encountered in such a challenging subway system. Future steps to commercialize the excess heat energy output are explored together with opportunities to promote the same setup in similar cases.

Keywords: wastewater management; environmental sustainability; waste resources; renewable energy

1. Introduction

Glasgow's subway system has been operational for the last 120 years [1]. Two identical tunnels are connecting fifteen stations with an overall length of ten kilometers (Figure 1). At least at half of the stations, the water enters into the track bed within the tunnels for different reasons (old construction, change of the aquifer in certain locations etc.). The water enters via weaknesses within the tunnel lining. Although the underground system is continually being maintained, water always finds a new way to enter. This is quite challenging because of the fact that the excess water may affect the operation of the underground. This water is being directed to a discharged system through pumping stations along the fifteen stations.

A research project was initiated by the Glasgow Caledonian University in collaboration with other European Universities to apprehend the potential of shallow geothermal energy in the underground tunnels of Glasgow and demonstrate that a water source heat pump (WSHP) may perform well without the need of boreholes which are necessary in a typical WSHP setup. In addition to this, an improved wastewater management system could successfully extract heat from this waste resource. This could go further by developing a viability study and a business case for shallow geothermal water extraction [2], which is expected to highlight barriers and opportunities for bringing geothermal heat technologies to practice and finally to the market.

For over a year (15 months) readings were undertaken inside the Subway with regards to the water's flux and temperature. The peak water flux was acknowledged, and an assessment displayed the heat energy potential at each station [3]. A feasibility study presented the likelihood of using this water to replace the old electric fired heating setup. The aim was to conclude into the viability of implementing a new heating setup for one station with the wastewater as the key element for this. This was expected to eliminate the usual cost of a WSHP once the water retained an unwavering temperature and flux without the need for boreholes.

At the same time, a business case with regards to the heat potential of the excess heat and how this can be commercialized has been developed [2].

The most common use of wastewater to recover heat is based on other setups such as heating buildings [4,5]. However, non-water-based heat recovery has been already implemented in underground environments using dissimilar sources; such as the relatively warm air from the tunnels or the heat emitted by the customers using the underground [6]. The wastewater ingress within a subway system was a different approach to recover heat, which was designed and implemented in the Glasgow subway system and more specifically at one of the fifteen Subway stations.

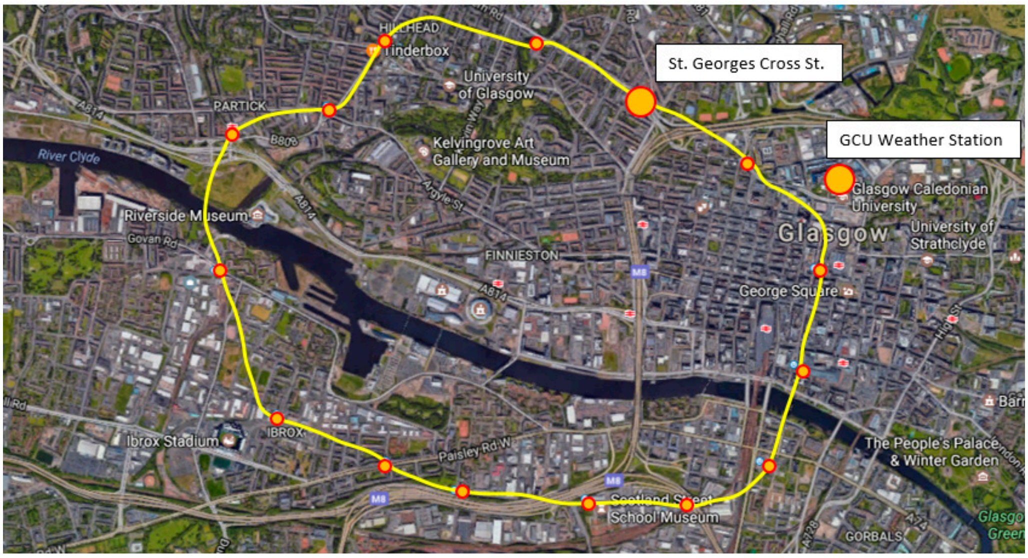

Figure 1. The Glasgow Subway map with the trial Station (St. George's Cross), Source [7] & Google maps.

The different approach in this study is the "change of path" of the wastewater, meaning that the cost of dealing with this waste through pumps who need periodical maintenance has been reduced due to the alternate use of this water via a WSHP.

Successful performance of the WSHP installed at Glasgow Subway was initially presented at the RTESE2018 (Recent Trends in Environmental Science and Engineering) Conference in Canada [7], and the positive outcomes of managing the wastewater through the heating system are described below. Based on these experiences, this study explores options to implement the same setup in other cities across Europe with wastewater existence within their underground systems. Limitations and constrains are presented in the following sections. It is an intricate task to put together all the necessary parameters to access the likelihood of applying a similar yet viable heating solution in a totally different underground environment.

2. Wastewater Readings and WSHP Installation

The field trial location was selected on the basis of four factors: distance (from the "source" to the "sink"), reliability of water flow; temperature and quality of water. Given this, the St. George's Cross Station was the one chosen for the trial case (Figure 1).

The tunnel's deviations for the temperature are shown in Table 1 (average temp. = 14.2 °C)

Table 1. Glasgow and wastewater temperatures during the monitoring period.

Year	Month	Glasgow's Mean Temperature (°C)	Wastewater's Mean Temperature (°C)
2014	May	11.6	14.1
2014	Jun.	16.7	13.4
2014	Jul.	14.7	14.9
2014	Aug.	16.1	16.0
2014	Sept.	15.0	15.4
2014	Oct.	12.0	16.1
2014	Nov.	10.1	13.7
2014	Dec.	4.1	13.2
2015	Jan.	5.8	14.1
2015	Feb.	5.7	12.1
2015	Mar.	5.4	12.8
2015	Apr.	9.6	14.0
2015	May	13.1	14.1
2015	Jun.	13.0	14.6
2015	Jul.	14.8	14.8

The water flux shown below in Table 2 was the basic factor which led to the trial heat pump installation.

Table 2. Water flow at the trial station [7].

WF1: Water Flow (Station St. George's Cross)		
Month	**Year**	**WF (L/s)**
May	2014	6.7
Jun.	2014	6.3
Jul.	2014	5.3
Aug.	2014	3.9
Sept.	2014	1.9
Oct.	2014	1.8
Nov.	2014	1.8
Dec.	2014	2.0
Jan.	2015	2.1
Feb.	2015	2.2
Mar.	2015	1.5
Apr.	2015	1.6
May	2015	1.5
Jun.	2015	1.4
Jul.	2015	1.3
Average Flow		2.75

The water flux rate of some previous years was measured prior to the heating system's design to confirm the lowest required flux rate was always obtainable to operate the heat pump (0.5 L/s). The water temperature readings for the same period of time, established a relatively stable value which was expected to maintain the heat pump performance at a good level with the minimum operating temperature difference. This was planned, designed and carried out on location during the last quarter of 2015.

St George's Cross station's heat demand was calculated to be 5.2 kW [8]. Therefore, a 9 kW water source heat pump was necessary to cover the heating and the domestic hot water demand. A schematic of the design (Figure 2) outlines the basic parts of this trial installation. The equipment complied with the fire regulations which was very critical due to the location of the trial [9] which was underground. The overall installation cost of this trial was £44,000. This included the heat pump and the associated equipment, pipe works and labour cost. The benefit of this trial, which kept the cost low, compared to a typical WSHP setup, was the lack of boreholes, once the water was present at the trial site. However, the downside was the increased labour cost due to the fact that all works were undertaken during the non-operational Subway hours (from midnight to 5 a.m.).

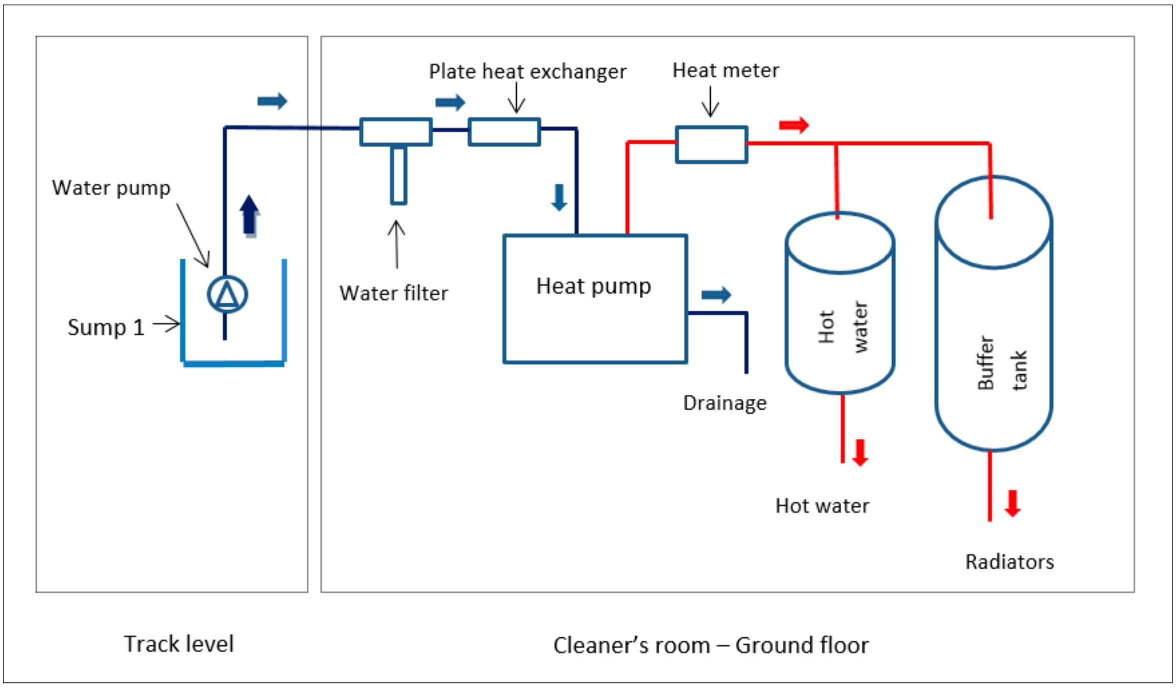

Figure 2. Station's diagram of the heating system (Source: [7]).

3. Heating System's Performance

The heating system at the Station is operational 18 h per day for seven days a week. A buffer container keeps the water at 50 degrees Celsius. Every seven days, the water from 50 degrees is electrically raised over 65 degrees automatically against Legionella. The room temperature has been set to 21 degrees Celsius during the whole day.

A monitoring apparatus (heat meter) was installed to capturing the output in kW for every kW of energy input. The following Table 3 demonstrates the relation between the input and output, energy wise, which is referred as the Coefficient of Performance (CoP).

Table 3. St. George's Cross heating system's coefficient of performance (CoP).

Month	Year	CoP
Dec.	2015	2.51
Jan.	2016	2.76
Feb.	2016	2.31
Mar.	2016	2.25
Mean value CoP		2.48

The WSHP is extracting 30 L/min water. This provides all the necessary heating and DHW (Domestic Hot Water) for the station. One third of the water ingress at that specific section of the underground system is being used for this heating system. Apart from this outcome, a major achievement is the reduction of using the existing pumps to discharging the wastewater from the station. It has been estimated that the pumps now operate two thirds compared to the pre-trial period. There is a lack of delivery plan for the rest of the discharged water (no extra need for heating close to the source) therefore, the rest of the wastewater is still following the same path to the sewers.

The station's old heating system was based 100% in electricity (electric fired radiators), consuming 10 kW without counting for the DHW. The WSHP requires a 4 kW input covering the DHW as well [10]. The payback period for this trial setup considering all the installation costs is projected to be 12 years. It has to be taken into consideration the savings in terms of CO_2 emissions once the electricity has been minimised so dramatically.

4. Discussion

A key issue to address a major topic which troubles not only governments, but each one of us is a mild changeover from current fossil fuels to future low-carbon energy alternative sources.

This consists of investigating potential urban waste heat sources which may be applied to recover energy using the current technologies in the field of heat recovery. Secondary energy sources especially in urban areas have the potential to be integrated into heating networks, on underground rail tunnels [11]. At the London Underground, an approach to exploit the underground latent heat with vertical Ground Heat Exchangers (GHE). The results exhibited that heat extraction amounts of GSHPs installed near the underground tunnels can be considerably improved by up to ~43% [12]. Embedded tunnel liner heat exchangers have been implemented in Austria, demonstrating a feasible solution for newly constructed tunnel in order to recover heat energy [13].

In terms of waste, most governments are oriented to identify economic and environmental benefits of treating waste as a valuable resource and preventing them from being unnecessarily disposed. This, aims to ensure that heat and power systems may efficiently use of the energy generated by a number of renewable methods. A recent example is the use of heat pumps to amplify the natural warmth of wastewater. Scottish Water worked with an external partner and facilitated the installation of the UK's first wastewater heat recovery scheme at Scottish Borders College campus in Galashiels (Borders College). The college's heating needs are covered partially with heat pumps, producing savings in energy, costs and carbon emissions. This has gone through an investment bank, aiming to promote the use of waste for energy production [14].

4.1. Lessons Learned

In our case, the new heating system at the station using the subsurface wastewater wasn't an easy transition from the old electric heating system to the new one. The trial period was very critical for the users (Station's Staff) as well as the company's stakeholders. The heat pump has a different behaviour in terms of comfort compared to the electric radiators. The electric ones, radiate heat at high temperature (around 80 degrees Celsius). On the contrary, the fan coil units used for a heat pump setup need time to reach a stable ambient temperature blowing warm air. The goal and the result is in both cases the same, a room temperature at 21 degrees.

During the very first months of operation, refurbishment works were undertaken at track level, within the tunnels. This may have caused the heat pump system's malfunction which led to reduced performance. After inspecting the installation, it was discovered that the heat exchanger was not fully operational due to blockage with sediment. Following this, a new spare part (heat exchanger) was positioned together with a water filter to handle any future issues which may be caused due to unexpected changes to the wastewater quality.

Through the water source heat pump (WSHP) a reduction with regards to the water, which is being pumped out of the system has been achieved. At St. George's Cross Station, one-third of the wastewater is now being used via a heat pump for the heating and DHW. Following that point (Station) the water is directed to the Station's sewer. This, contributes to further savings (less man-hours and money for the discharge pump maintenance and also less energy spent due to fewer operating hours). The reason for extracting only 1/3 of the wastewater is that only this amount is necessary to cover the station's thermal needs. This (water volume) is in small scale compared with the potential of using the same heating system in two more SPT's (Strathclyde Partnership Transport) areas that have been mentioned.

4.2. Opportunities for Similar Underground Systems

Heat Mapping is a method to help detect and measure the heat demand using a Geographic Information System (GIS). The Scottish government has supported the development of the Scotland's heat map [15,16]. This is a very useful tool to compare and plan for solutions with regards to detailed heat demand and identifying opportunities for decentralised energy projects across Scotland. By superimposing the Glasgow Subway map on to the Glasgow Heat map (Figure 3) and with the use of a GIS software, the potentials can be realized. The annual heat demand (kWh/year) is displayed in colour variation this map, is updated constantly, therefore this tool is extremely accurate and very helpful in assessing the areas which should be targeted to provide the subway's excess heat output.

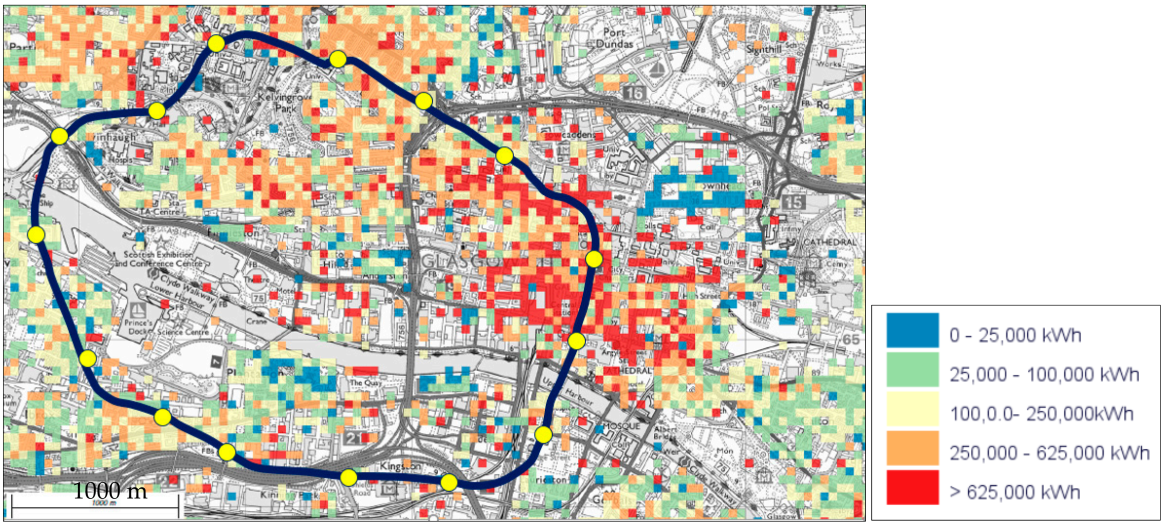

Figure 3. Superimposing the Glasgow Subway map on to the Glasgow's Heat Map. Source: Scottish Heat Maps. Legend: Colour marking of heat demand in Glasgow.

According to the "heat map", the northern part of the subway (eight stations above the river; Figure 3) seems to have more heat demand therefore a potential to commercialize its heat energy excess.

Based on a feasibility study that has been undertaken [2], a 745-kW output can be commercialised in areas close to the subway system. This study is at a high level, therefore, a detailed assessment based on the current status (property ownership, current heating systems, use of the buildings etc.) should be commenced to identify the actual potential customers for this excess heat (Figure 4), which has been calculated after covering the Subway's own heat demand for the 15 stations. Even though, according to the same heat map, the heat demand in the south part of the underground is not significant, the same effort should be undertaken to identify potential users due to the recent interest of developers to invest in new properties, southwest of the Glasgow City, which were not in high demand the last couple of decades.

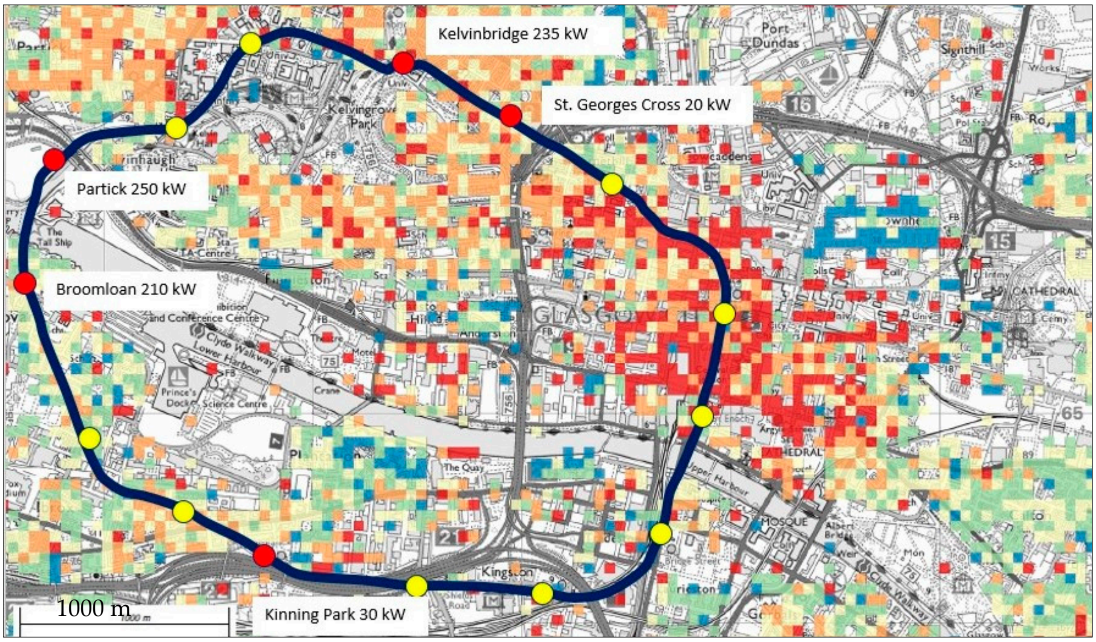

Figure 4. The calculated excess heat output (745 kW) for the Glasgow Subway System.

This approach could go further and spread over to other European cities with a similar setup (presence of water in their subway system). The GCU (Glasgow Caledonian University), in collaboration with other universities across Europe, has already studied and identified the potential of applying similar heating systems in capitals or major cities with the existence of subway systems. The following Table 4 is the result of this collaboration, indicating the capacity and the potentials (energy wise) of taking advantage of similar systems.

Table 4. Energy potential in other cities with a metro system.

Cities with Metro	Population (Thousands)	Waste Water Mass Flow (m^3/day)	Energy Potential (MW)	Km of Metro	Stations
Athens	3750	281,604	68	84.5	94
Berlin	3388	1,198,585	290	151.7	173
Brussels	1000	353,774	86	39.9	59
Budapest	1696	600,000	145	38.6	52
Glasgow	600	1730	0.75	10.5	15
Lisbon	529	187,146	45	26.8	55
London	8540	2,628,184	635	400	270
Madrid	3100	1,096,698	265	293	301
Paris	2181	771,580	187	197	303
Prague	1171	414,269	100	65.2	61
Rome	2554	903,538	218	60	37
Sofia	1246	44,802	107	40	35
Stockholm	762	269,576	65	108	100
Vienna	1599	565,684	137	78.5	104
Warsaw	1693	598,939	145	29	58

Further research has to be undertaken to pinpoint the particularities in every City, aiming to detect in details the capability of exploiting shallow geothermal sources around Europe. Table 4, indicates the heat energy potential only from the water. If other potential can be also identified (air) [17], then a higher number in terms of energy is believed to be attainable.

4.3. Challenges for Widespread Implementation of WSHP Systems in Urban Environments

There are some limitations, barriers and opportunities to extensively apply shallow geothermal heat harvesting to the whole Subway network and elsewhere. The continuity of water is one of them. Out of the fifteen stations, a heating system based on the water can be assumed only in few sites due to different water ingress at each location. This waste resource has not been fully exploited due to some constrains mentioned previously.

However, a number of implements have to be acknowledged and developed to transform such opportunities into real applications and viable projects. The heat map is one, but not the only necessary tool. Underground companies across Europe with a similar setup (existence of wastewater in large quantities) have to proceed with specific steps through feasibility studies to identify key characteristics of the water to be able to commercialize this resource. A year round survey is necessary with regards to the following: quantity, quality and temperature of water. These three, are essential to assess the real potentials for heat recovery and afterwards to seek for customers to provide this secondary energy source.

On the other hand, developers and businesses have to seek for new ways of exploiting available resources in close proximity to their plots based on key words such as sustainability and waste resource management towards energy.

It is rather difficult, in financial terms, to adopt a different way of using a waste resource as a new energy source. The initial cost is higher compared to a typical heating setup (gas- or oil-based heating systems). However, the need to alter the perspective of using diverse resources is becoming more intense than ever. Until now, the direct use of the wastewater within an underground environment as an energy source is limited. Apart from the Glasgow subway system, no other subway has used directly the water to produce heat energy out of it. The immense water quantities are a promising secondary energy source if the basic steps described previously will be taken into consideration. Alongside, subsidy schemes supported by public bodies or investment consortiums may assist in putting forward such technologies and familiarise not only the stakeholders, but also the public on how to accept smart reuse of a waste resource.

5. Conclusions

The current study presents the outcome of a trial heating system from a waste resource and the importance of a primary energy saving in the Glasgow Underground using the wastewater through a WSHP.

This trial demonstrates that this positive feedback provides a promising output for implementing a viable waste to energy case. It also highlights the opportunity to roll out similar heating setups to other underground networks across Europe. Nonetheless, further similar cases have to be studied to ensure an economical viable installation. A number of incentives may additional support this relatively new heating technology, such as the Renewable Heat Incentive (RHI) [18].

The benefit of reducing the operational as well as the maintenance cost of the existing wastewater discharge system has also to be considered as another positive outcome apart from using a water sourced heat pump with an overall reduced cost due to the non-existence of boreholes which is translated into less capital cost for such an installation.

Additional tools to identify the actual areas where the heat demand is high are also needed to make this a reality with an affordable cost [19]. A detailed analysis of the energy supply potentials in areas in close proximity to the Glasgow Subway System has been undertaken demonstrating future possible applications.

The existence of the Glasgow Heat Map (through the Scottish government) has shown potential areas with a high heat demand helping to identify potential customers for the excess heat output. This is expected to assist in scheduling further heat output exploitation. Even though a number of cases with regard to the use of waste resources to produce energy in underground environments have already been implemented, there has not been anything similar to the Glasgow Subway approach detected elsewhere. As this study presents, direct use of the wastewater to produce heat energy has potential in European cities with a metro system. After taking readings and measurements of the water's temperature and flow, then it is all about achieving the right collaborations between the Metro company and the nearby premises/businesses. The closer the distance between the source of energy and the final distribution point is, the more efficient and cost effective the installation will be. Commercial alliances and further funding have to be found through national or European schemes and trusts to subsidise large-scale heating installations in order to exploit the excess heat output. This approach is expected to assist in applying the same setup and take advantage of shallow geothermal sources in similar underground environments worldwide.

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