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A heat energy recovery system from tunnel waste water

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Minimising the maintenance costs of water ingress in transportation tunnels is a significant challenge. Decreasing the overall cost of a ground source heat pump system is equally challenging. An effort to address both issues at once has been made in relation to groundwater ingress in the Glasgow Subway system. Inflowing water is a valuable resource which could be channelled through a water source heat pump (WSHP) to produce heat energy for domestic or public use (heating and domestic hot water). Water flow and water temperature have been recorded for a year at 21 different points within the network of the underground tunnels and platforms. The points of highest water influx were identified, and the heat energy content of each has been calculated. Working from these data, several options were identified for capturing the water and diverting it to a WSHP to recover heat. A final design for a pilot system within the tunnels was developed. The findings of this study are expected to contribute a renewable heat solution through a cost-effective heat pump system design.

Notation

COP_H	coefficient of performance
E	required energy: kW
G	heat energy flux: kW
H	total heating effect
S_VC	specific heat capacity of water: J/(l K)
Z	flow rate: l/s
$\Delta\theta$	temperature drop: °C
ρ	density of water: kg/m^3

Introduction

The need for finding alternative sources to replace conventional fuel is becoming more and more urgent. The basic factors that have led the UK government to favour more environment-friendly methods of heating are the obligation of reducing the carbon dioxide (CO_2) emissions to the 1990s' levels by 2020 (Scottish Government, 2012) and to reduce fully the carbon dioxide emissions of heating by 2050 (Climate Change Act 2008, 2008). Ground source heat pump (GSHP) systems have shown the potential to reduce energy consumption, and as a result, a carbon dioxide reduction (Ground Source Heat Pump Association, 2015) compared with conventional heating systems (electricity, oil, gas).

Heat pumps have long been a key technology for exploiting low-grade heat. They use compression (the same principle as a refrigerator) to extract tepid low-grade heat to produce heat for space and/or water heating in general (NRC, 2015). They can also be reversed to produce cooling. Heat pumps are designed to move thermal energy opposite to the direction of spontaneous heat flow by absorbing heat from a cold space and releasing it to a warmer one. A typical heat pump uses less energy input (compared to all other conventional heating means, e.g. gas and petrol) to accomplish the work of transferring energy from the heat source (aquifer) to the destination for space heating/hot water (Branz, 2015).

This study has investigated the possibility of harvesting heat from the water ingress inside Glasgow's Subway tunnels by using a heat pump. The Glasgow Subway is a circular underground passenger railway system in the centre and west of the city. It contains twin tunnels, allowing clockwise circulation of trains on the 'outer' circle and anticlockwise on the 'inner' circle. Fifteen stations are distributed along the route length of just over 10 km. The River Clyde dissects the circular route, with eight stations north of the river and seven to the south, as shown in Figure 1.

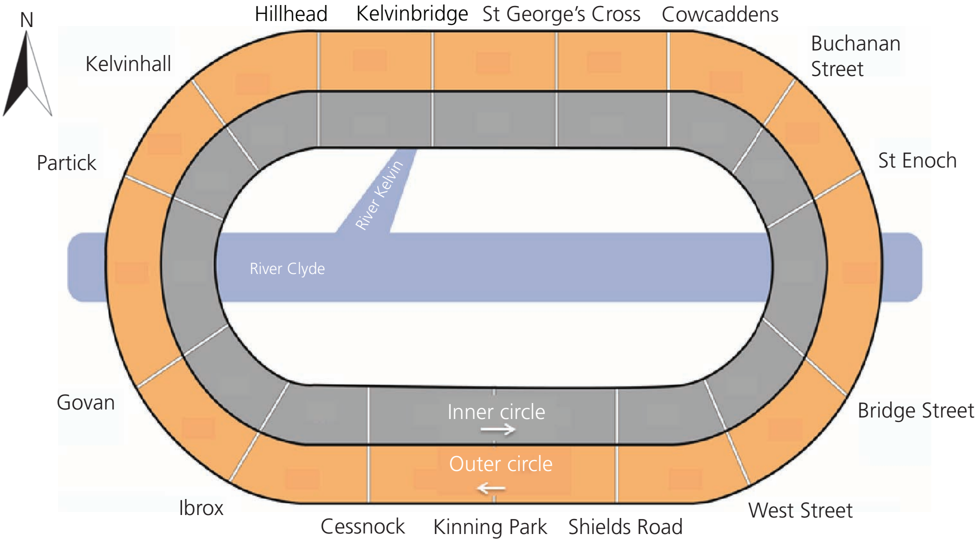

Figure 1. A typical Glasgow Subway map

At present, water ingress into the subway tunnels causes environmental (water pollution), operational (interference with train operations) and aesthetic (unsightly) problems. The authors attempt to explore the possibility of turning this multifaceted problem into an opportunity for space heating and domestic hot water (DHW) through a WSPH, which is a type of geothermal heat pump system.

Geothermal heat pumps are of two types: closed-loop systems and open-loop systems (US DOE, 2015). A closed-loop system heat pump – usually called a GSHP – circulates an antifreeze solution through a closed loop that is buried in the ground or submerged in water. A heat exchanger transfers heat between the refrigerant in the heat pump and the antifreeze solution in the closed loop. The loop can be in the following configurations: horizontal, vertical or pond/lake. Such a closed-loop system has been implemented at the Budapest Metro (BKV Zrt, 2011) to provide space heating and hot water for one station. An array of pipes embedded in the platform maintains the water at a stable temperature.

An open-loop system heat pump – usually called a water source heat pump (WSHP) – uses well or surface water as the heat exchange fluid that circulates directly through the system. The water returns into a recharge well or surface discharge afterwards. This is a practical option when there is an adequate supply of water. This is the case in the location of this case study, where a WSHP through an open-loop system is expected to provide heating through the constant water ingress into the subway tunnels.

Methodology

The problem of water ingress into the subway tunnels requires frequent emptying of water collected in sumps into the city's sewer system. The sumps (Figure 2) are generally flat-bottomed rectangular chambers formed either within the tunnel invert or station platforms and range from 0·50 to 2·50 m deep from the access level. The pumping stations inside each sump are generally equipped with two submersible pumps. The excess water from the tunnels is pumped out and discharged into the sewerage network adjacent to each station. A total of 21 sumps located inside the tunnel system had been monitored (Figure 3).

A series of measurements were undertaken from May 2014 to April 2015 in all sumps: water flow and water temperature and outdoor weather conditions were simultaneously measured for a year (May 2014 to April 2015). Geological and geotechnical parameters around each station were also studied to identify sites suitable for heat pump locations. Water sampling was carried out at all sumps for the chemical analysis of the water regime.

In addition to the above, outdoor weather data were also compiled simultaneously (temperature, humidity, atmospheric pressure and rainfall), using Glasgow Caledonian University's meteorological station located in the Glasgow city centre in close proximity to the underground tunnel network.

Water flow measurement

Drop test

In each sump, there is a probe that when the water reaches a certain level the pump starts pumping the water out of the sump. This period is called 'active time'. When the pump stops functioning, the water level rises up to a point that the pump will start working again. This period is called 'inactive time', and this is the actual water flow. Given that the dimensions of each sump are known, the water flux is calculated by measuring the difference in water level inside the sump during the inactive time (Figure 4).

This height difference between the active and the inactive time multiplied by the area (surface) of the sump gives the water volume that is being pumped out. Dividing this volume by the time

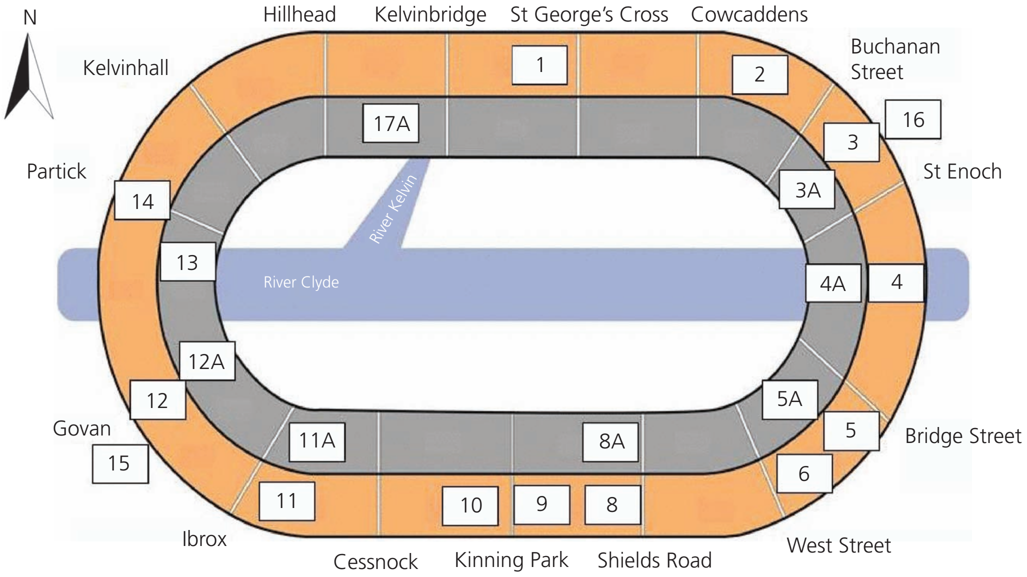

Figure 2. Sump locations in the Glasgow Subway system

Figure 3. A typical sump located between the rail tracks in the Glasgow Subway system

(seconds) that the pump is active gives the discharged volume during the active time of the pump. The water flow value during the active time (when the water was discharged) was cross-checked with an additional flow measuring method as described in the following.

From the lower point when the pump has stopped to the time that the water takes to reach again the highest point in the sump was also measured (i.e. until the pump starts working again). This depth multiplied by the sump surface gives the water volume that flows into the sump in a specific period of time (*F*). This is the average water flux in each sump. At least two consecutive measurements were undertaken every month during each site visit in each sump to have more accurate averages of the water flux. If the water flow values during those two measurements had a difference of more than 5%, another two measurements were undertaken. The differences between the two methods were below this limit throughout the monitoring period.

Readings were taken with a rigid measuring stick as well as with an automated depth meter, in which a water-sensitive sensor at the end of the measuring cord completes a circuit when it touches the water level, sounding a buzzer. This calibrated cord indicated the distance from both of the water levels to the surface.

Ultrasonic flow meter

In order to cross-check the water flux in each sump, a second method was used as well. A digital ultrasonic 'clamp-on' flow meter was used to provide more accurate water flow measurements (Dynasonics TFX/DMS 1002 ultrasonic flow meter with clamp-on pipe transducer). The device was calibrated prior to each measurement by inputting in the software the pipe material (unplasticised polyvinyl chloride or steel), the diameter of the pipe (ø120 or ø160) and the liquid that goes through the pipe, in our case: water.

The portable transducers (Figure 5) were clamped onto the pipe, applying also liquid silicon to the transducers to assist in 'reading' the flux. This enables the flow meter to show the water flux (Figure 6).

Temperature measurements

Water temperature was measured inside each sump, and the average was calculated. A digital thermometer with an external probe (Tinytag, TGP-4020, range = −40 to +125°C, accuracy = ±0·35°C in the 0–60°C range) was used to record the temperature every 10 s. The thermometer was kept in place for 2 min (as a minimum), so a minimum of 12 temperature measurements were received from each measuring point (Figure 7).

Sump 1

Sump's dimensions: 2·00 × 0·90 × 2·15 (overall depth)
Area (surface of the sump) A 1·80 m²

1st measurement	Pump started			
	Start level – (higher point)	B	1·11	m
	Stop level – (lower point)	C	0·31	m
	Depth dropped (B – C)	D	0·80	m
	Volume (A × D)	E	1·44	m^3
	Time	F	138	s
			2′ 18″	min, s
	Flow (E/F)	G1	0·01043	m^3/s
			10·43	l/s
	Total vol. discharged (G1 × F)	G2	1440·00	l

1st measurement	Pump stopped			
	Start level – (lower point)	C	0·31	m
	Stop level – (higher point)	B	1·13	m
	Depth raised (B – C)	D	0·82	m
	Volume (A × D)	E	1·48	m^3
	Time	F	790	s
			13′ 10″	min, s
	Flow (E/F)	G2	0·00187	m^3/s
			1·87	l/s

Sump's dimensions: 2·00 × 0·90 × 2·15 (overall depth)
Area (surface of the sump) A 1·80m²

2nd measurement	Pump started			
	Start level – (higher point)	B	1·13	m
	Stop level – (lower point)	C	0·37	m
	Depth dropped (B – C)	D	0·76	m
	Volume (A × D)	E	1·37	m^3
	Time	F	133	s
			2′ 13″	min, s
	Flow (E/F)	G1	0·01029	m^3/s
			10·29	l/s
	Total vol. discharged (G1 × F)	G2	1368·00	l

2nd measurement	Pump stopped			
	Start level – (lower point)	C	0·37	m
	Stop level – (higher point)	B	1·15	m
	Depth raised (B – C)	D	0·78	m
	Volume (A × D)	E	1·40	m^3
	Time	F	743	s
			12′ 23″	min, s
	Flow (E/F)	G2	0·00189	m^3/s
			1·89	l/s

Figure 4. Two consecutive water flow measurements in sump 1

Results

Perennial water inflow was observed in only three out of a total of 21 sumps: 1, 2 and 17A (Figure 1). Water flow rates and temperature values are shown in Tables 1–3. Outside temperature and relative humidity values are also shown in these tables for reference. The following five stations are the closest to those three sumps with the highest and perennial water flux: Buchanan Street, Cowcaddens, St George's Cross, Kelvinbridge and Hillhead (Figure 1).

To assess where heat output could be delivered and used, a heat load calculation (in kilowatts) in accordance with BS EN 12831:2003 (BSI, 2003) was completed for each of the above five stations (Table 4). Detailed calculations at one of the stations (St George's Cross) are shown in Table 5 as an example.

St George's Cross Subway station was chosen for the pilot installation of a WSHP. Although not the highest flow, sump 1 (located near St George's Cross station) was chosen because this station has the shortest distance from the source point (water sump 1) to the sink point (station's ticket office).

A water sample from sump 1 was analysed by the Glasgow Scientific Services laboratory in Springburn, Glasgow, a division of Land and Environmental Services of the Glasgow City Council. The result of the chemical analysis for this water sample

Figure 5. The transducers clamped onto the discharge pipe

Figure 6. The ultrasonic flow meter showing the water flux (l/s)

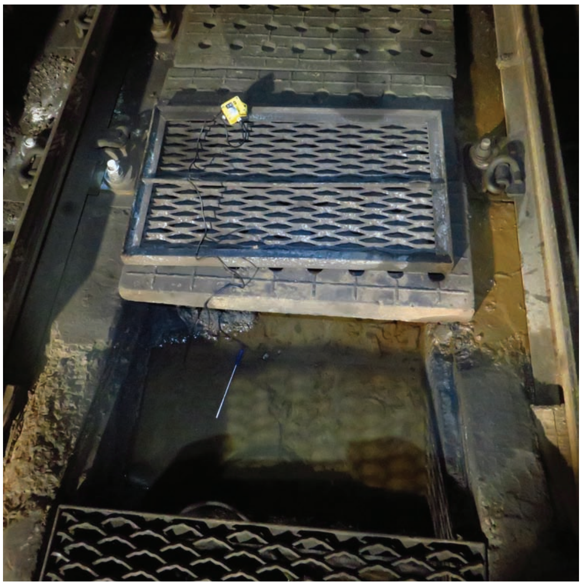

Figure 7. Digital thermocouple taking readings from a sump

indicated a low percentage of iron (Fe; 0·042 mg/l), which allowed the heating system to be designed by using copper pipes.

The heat energy, H (in kilowatts), can be calculated from the following formula (Banks, 2009)

$$1.\quad H = Q \times \rho \times S_{\mathrm{vc}} \times \Delta t$$

where Q is the water flow of the system ($\mathrm{m^3/s}$) (water flow in sump 1 = 0·00307 $\mathrm{m^3/s}$), ρ is the density of the water ($\mathrm{kg/m^3}$) (1000 $\mathrm{kg/m^3}$), S_{vc} is the heat capacity of water (kJ/(kg K)) (4·18 kJ/(kg K); 1 kJ/s = 1 kW) and Δt is the temperature difference (°C) (temperature difference in sump 1 = 4°C).

Month	Year	WF1: l/s	WT1: °C	OMT: °C	OMH: %
May	2014	6·7	14·17	11·40	80
June	2014	6·3	13·45	16·70	83
July	2014	5·3	14·95	15·80	77
August	2014	3·9	16·03	16·00	88
September	2014	1·9	15·40	15·00	67
October	2014	1·8	16·13	12·00	67
November	2014	1·8	13·72	10·00	75
December	2014	2·0	13·20	4·10	96
January	2015	2·1	14·13	5·80	77
February	2015	2·2	12·12	5·70	80
March	2015	1·5	12·81	5·40	81
April	2015	1·6	14·02	9·40	68

WF1, water flow; WT1, water temperature; OMT, outdoor mean temperature; OMH, outdoor mean humidity

Table 1. Readings from sump 1

Month	Year	WF2: l/s	WT2: °C	OMT: °C	OMH: %
May	2014	6·4	14·22	11·40	80
June	2014	6·8	15·28	16·70	83
July	2014	4·9	13·47	15·80	77
August	2014	3·6	15·76	16·00	88
September	2014	2·2	15·30	15·00	67
October	2014	2·1	15·88	12·00	67
November	2014	1·9	15·41	10·00	75
December	2014	2·1	13·45	4·10	96
January	2015	2·2	14·30	5·80	77
February	2015	2·1	12·62	5·70	80
March	2015	1·8	13·93	5·40	81
April	2015	2·0	14·24	9·40	68

WF2, water flow; WT2, water temperature; OMT, outdoor mean temperature; OMH, outdoor mean humidity

Table 2. Readings from sump 2

The average water flow from May 2014 to April 2015 for sump 1 (Table 1) is 3·07 l/s = 0·00307 $\mathrm{m^3/s}$, which will yield the following heat output: $H = 0{\cdot}00307 \times 1000 \times 4{\cdot}18 \times 4 = 51{\cdot}33$ kW.

However, the total heat load at St George's Cross station is 5·2 kW (Table 4); thus, the provision of heating and DHW from sump 1 is feasible.

A basic design for the provision of heating and DHW from sump 1 was undertaken (Table 6), and a WSHP of 9 kW output was required to meet this subway station's heating and DHW demand.

Month	Year	WF17A: l/s	WT17A: °C	OMT: °C	OMH: %
May	2014	11·5	12·60	11·40	80
June	2014	12·1	13·11	16·70	83
July	2014	12·1	13·62	15·00	77
August	2014	10·7	13·75	16·00	88
September	2014	9·8	13·80	15·00	67
October	2014	9·6	12·94	12·00	67
November	2014	9·4	10·71	10·00	75
December	2014	9·7	10·65	4·10	96
January	2015	10·3	11·84	5·80	77
February	2015	10·4	11·62	5·70	80
March	2015	10·6	13·63	5·40	81
April	2015	10·3	13·21	9·40	68

WF17A, water flow; WT17A, water temperature; OMT, outdoor mean temperature; OMH, outdoor mean humidity

Table 3. Readings from sump 17A

Station name	Total design heat load: W	Total design heat load: kW
Kelvinbridge	4755	4·8
St George's Cross	5185	5·2
Cowcaddens	3369	3·4
Buchanan Street	3778	3·8
St Enoch	4486	4·5
Bridge Street	4577	4·6
West Street	4029	4·0
Shields Road	4189	4·2
Kinning Park	2983	3·0
Cessnock	4106	4·1
Ibrox	3243	3·2
Govan	30 331	30·3
Partick	45 650	45·7
Kelvinhall	2599	2·6
Hillhead	6641	6·6

Table 4. Heat loads for the 15 subway stations (according to BS EN: 12831:2003)

The water from the sump will be pumped out through a submersible pump and rise up to the ticket office by way of an insulated 28-mm-dia. copper pipe (Figure 8). The heat pump and the associated equipment will be installed at the station cleaners' room at the ground floor (Figure 9).

The heat pump will feed four new low-temperature fan coil radiators, which will be sufficient for heating the station while replacing the existing four electric radiators at 2 kW each (Figure 10). This system is expected also to provide cooling as a by-product during summer months working in the reverse cycle.

Discussion and conclusions

One of the key findings of the study is the relatively stable and high water temperatures available within the Glasgow Subway tunnel system. For example Table 1 shows that the water temperature during the monitoring period was between 12 and 16°C and was never below 12°C, even in the middle of winter. This compares favourably with typical shallow geothermal water temperatures of 9–10°C reported by Hytiris *et al.* (2016) in Glasgow. Therefore, a higher coefficient of performance (COP_H) is likely. The COP_H of a heat pump is the ratio of heating or cooling provided to the electrical energy consumed by the pump. A higher COP_H equates to lower operating costs (Nave, 2016). Typically, a WSHP can perform at COP_H of more than 3, but the

St George's Cross room name	Transmission heat load, T_i: W	Ventilation heat load, V_i: W	Higher temperature factor, f: p.u.	Heating-up capacity, $R_{H,i}$: W	Total design heat load, $H_{L,i}$: W
Ticket office	845·62	215·37	1	239·20	1300·19
Hallway (ground)	448·60	74·72	1	82·81	606·13
Hallway (upper)	337·90	36·62	1	40·56	415·08
Canteen	987·77	232·25	1	257·40	1477·43
Female toilet	276·31	78·83	1·6	58·24	448·32
Male toilet	276·31	78·83	1·6	58·24	448·32
Store	377·76	31·36	1	80·21	489·33
Total	3550·28	747·98	—	816·66	5185·00

Table 5. Thermal needs of St George's Cross Subway station offices

Heating	Input: kW	Output: kW	Cost/kWh: £	Cost/d (16 h): £	Cost/year (210 d): £	Carbon dioxide emissions: kg CO_2/kWh	By-product
Current: four electric radiators (2 kW)	8	8	8 × 0·12 = 0·96	0·96 × 16 = 15·36	3225·6	0·47	None
Proposed: WSHP	3	9	3 × 0·12 = 0·36	0·36 × 16 = 5·76	1209·6	0·14	Cooling

St George's Cross Subway station total heat load (5·2 kW)

Table 6. St George's Cross station's current and proposed systems

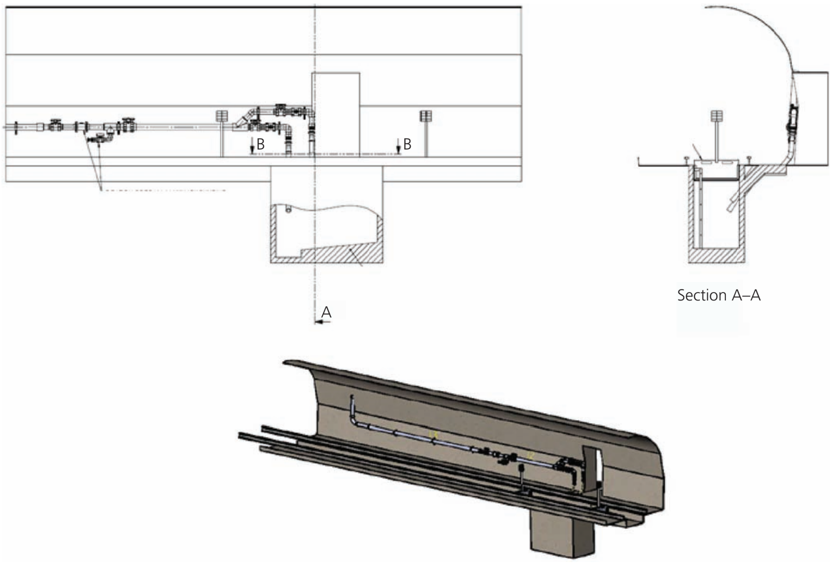

Figure 8. St George's Cross heating system diagram (track level)

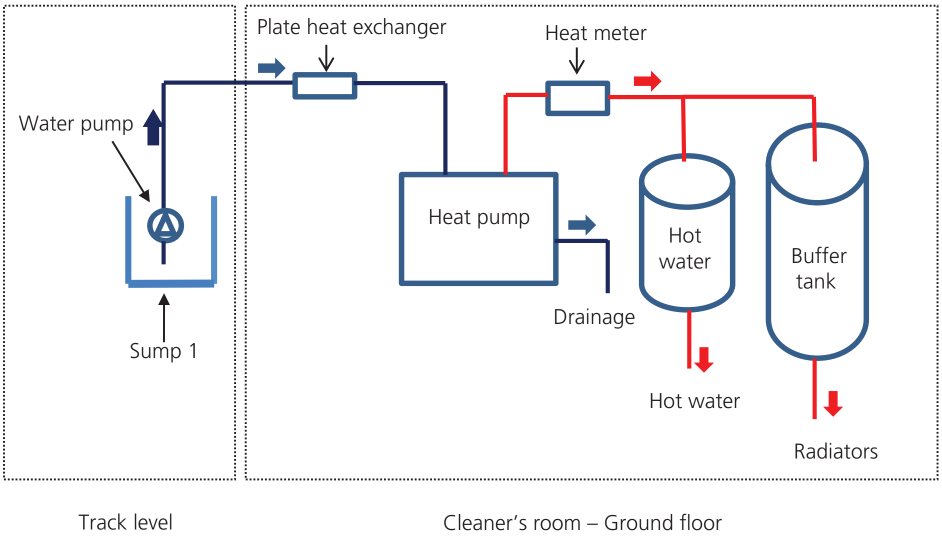

Figure 9. A simplified schematic diagram of the system at St George's Cross station

higher intake temperature in this study's case would enable an even higher level of performance. This, however, needs to be verified by a field trial, and the installation of a WSHP at St George's Cross station is currently being completed for this purpose. Once the installation is complete, the authors intend to monitor the actual performance of the heat pump together with its electricity consumption to confirm the $\mathrm{COP_H}$ of the system.

An indication of the likely cost and carbon dioxide savings ('carbon savings') of the proposed WSHP system is shown in Table 6. A WSHP system installed at just one station within the underground transport network could save over £2000 per annum and lead to over 70% reduction in carbon dioxide emissions. This compares favourably with typical GSHP installations (Table 7), which have a 67% reduction in carbon dioxide emission. Keeping in mind the calculations shown earlier are not for the most voluminous water flow (sump 17A has much higher flow rate – Table 3), greater cost and carbon savings are likely across the subway system. This may not only enable the utilisation of heat for the subway's own heating purposes but also provide a marketable and renewable commodity to nearby buildings.

An additional benefit of the proposed solution is the reduction in the amount of water that needs to be discharged to the local

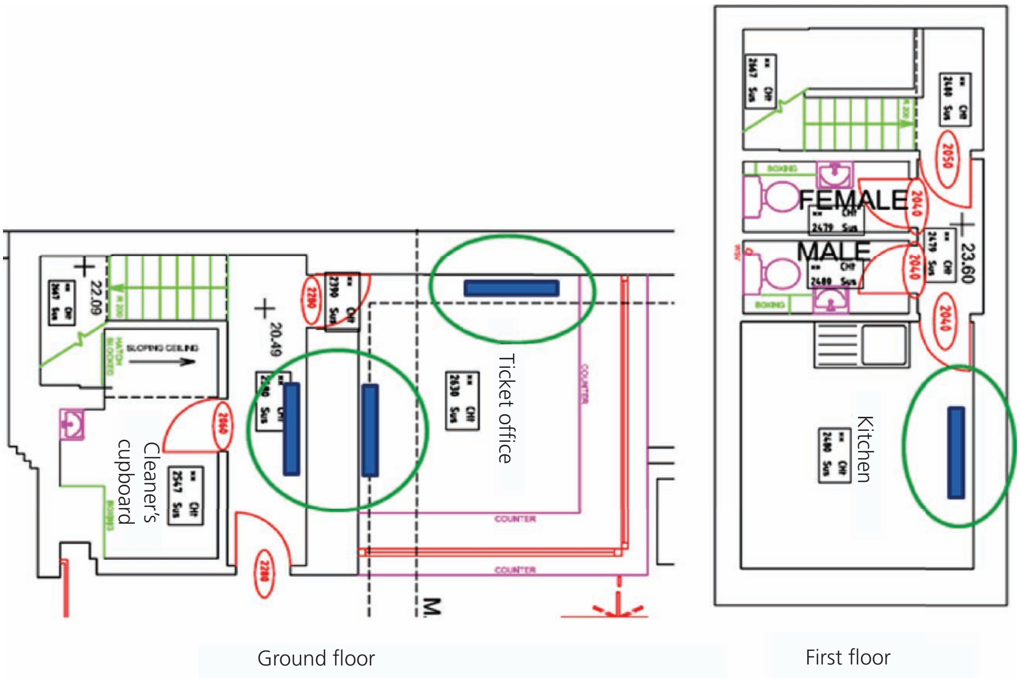

Figure 10. St George's Cross station drawing

Fuel	Average price: p/kWh	Carbon dioxide factor: kg CO_2/kWh	System efficiency: %
Gas	4·29	0·210	90
Oil	5·36	0·246	85
LPG	8·32	0·241	85
Wood pellet	4·77	0·044	90
Coal/solid fuel	4·00	0·380	75
Electricity (standard rate)	14·05	0·540	100
GSHP	14·05	0·177	350
Air source heat pump	14·05	0·210	350

Table 7. Fuel prices and carbon dioxide factors

sewers. This is expected to reduce the operational hours of the existing pumps and potentially contribute to further energy savings.

The authors have thus shown that a problem that currently requires constant maintenance could be turned around into a source of renewable heat with considerable cost and carbon savings. Calculations of water flow rates from water ingress into the subway tunnels show that four of the 15 subway stations could benefit from harvesting heat from this source. Based on the performance of the pilot system currently being installed, a system of WSHPs could be scaled up across the subway network, providing significant benefits to the subway operator and contributing positively to Scotland's renewable heat energy targets.

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