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Life cycle impacts of shower water waste heat recovery: Case study of an installation at a university sport facility in the UK

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ABSTRACT

Recovering heat from waste water discharged from showers to preheat the incoming cold water has been promoted as a cost effective, energy efficient and low carbon design option which has been included in the UK's Standard Assessment Procedure (SAP) for demonstrating compliance with the Building Regulation for dwellings. Incentivized by its carbon-cost effectiveness, waste water heat exchangers (WWHX) have been selected and incorporated in a newly constructed Sports Pavilion at the University of Brighton in the UK. This £2m sports development serving several football fields was completed in August 2015 providing eight water and energy efficient shower rooms for students, staff and external organizations. Six of the shower rooms are located on the ground floor and two on the first floor, each fitted with 5 or 6 thermostatically controlled shower units. Inline type of WWHX were installed, each consisted of a copper pipe section wound by an external coil of smaller copper pipe through which the cold water would be warmed before entering the shower mixers.

Using the installation at Sport Pavilion as the case study, this research aims to evaluate the environmental and financial sustainability of a vertical waste heat recovery device, over a life cycle of 50 years, with comparison to the normal use of a PVC-u pipe. A heat transfer mathematical model representing the system has been developed to inform the development of the methodology for measuring the in-situ thermal performance of individual and multiple use of showers in each changing room. Adopting a system thinking modelling technique, a quasi-dynamic simulation computer model was established enabling the prediction of annual energy consumptions under different shower usage profiles. Data based on the process map and inventory of a functional unit of WWHX were applied to a proprietary assessment software to establish the relevant outputs for the life cycle environmental impact assessment. Life cycle cost models were developed and industry price book data were applied. The results indicated that the seasonal thermal effectiveness was over 50% enabling significant energy savings through heat recovery that led to short carbon payback time of less than two years to compensate for the additional greenhouse gas emissions associated with the WWHX. However, the life cycle cost of the WWHX is much higher than using the PVC pipe, even with significant heat recovered under heavy usage, highlighting the need to adopt more economic configurations, such as combining waste water through fewer units, in order to maximize the return on investment and improve the financial viability.

Keywords: domestic hot water, showers, waste heat recovery, water heat exchanger, hot water shower system modelling, life cycle cost, life cycle environmental assessment, sport facilities

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1   INTRODUCTION

With significant thermal improvements and adoption of low energy lights and appliances, domestic hot water energy consumption is fast becoming the major component of energy expenditure in modern buildings. The main use of hot water in domestic buildings is for the shower/bath which accounts for nearly 21% of the total consumption (Waterwise 2011). Hot water is normally heated by gas or electric boilers which raise the temperature to over 60°C and mixed with cold water to a temperature of around 40°C, in the case of use for showers, before the water is used. The used water is normally directly discharged into the drain. Despite content of only low grade heat, this water still has a much higher temperature than the incoming cold water, which is in the region of 10°C, hence offering a good potential and opportunity for heat recovery. Among various heat recovery options available for designers, in-line pipe heat exchangers present some distinct advantages as they have no moving parts, compact, proclaimed to have high heat recovery efficiencies and the commonly used material copper is highly recyclable.

Incentivized by its carbon-cost effectiveness and the recognition in the UK's Standard Assessment Procedure - an energy assessment tool for demonstrating compliance with Part L of the Building Regulations for dwellings (DECC 2014) - waste water heat exchangers were incorporated in the newly constructed Falmer Sports Pavilion at the University of Brighton in the UK. This £2m sports development to serve several football fields was completed in August 2015, providing eight water and energy efficient shower rooms for students, staff and external organizations. Six of these are located on the ground floor and two on the first floor, each fitted with 5 or 6 thermostatically controlled shower units. Inline type of waste water heat exchangers were installed, each consisted of a copper pipe section wound by an external coil of smaller copper pipe through which the cold water would be warmed and subsequently supplied to the shower mixers.

This installation provided a research opportunity to fill the knowledge gap in WWHX with the aim to assess its sustainability in terms of the life cycle environmental and economic performance - anticipating that the outcomes could help to support future decision making by the Facility Management Department when considering such technology in new or refurbishment projects. The study commenced with a review of the state of the art of the relevant literatures on WWHX, the life cycle environmental assessment and life cycle cost assessment. Mathematical thermal model was developed and used to devise the on-site measurements to determine the thermal performance of WWHX over a range of flow conditions. The measured thermal performance, in terms of effectiveness, was applied to a computer simulation model specially developed enabling life cycle assessment of energy performance under different projected usage profiles and operational settings. Environmental life cycle impacts of the processes, as encapsulated in the functional unit of the WWHX, together with the results from the energy assessment, are assessed and evaluated.   Results covering high, medium and low usage profiles were compared, discussed and concluded alongside with life cycle cost assessment.

2   LITERATURE REVIEW

To address the research question on what the life cycle environmental and economic impacts are due to the installation of the WWHX, a comprehensive review on exiting literature was conducted covering three key aspects: the thermal performance of the WWHX, life cycle environmental impact assessment and life cycle cost assessment. Results of this review has revealed knowledge of similar research covering the operational, environmental and cost performance within the context of the life cycle of WWHX is currently not available. However, relevant studies which can be used to inform the development of the research have been critically reviewed and summarised in the following sections.

2.1 Waste water heat recovery heat exchanger

There are a number of waste water heat exchanger (WWHX) products available on the market for recovering waste heat from shower water with many of these designed for horizontal installations. Laboratory measurements on the performance of horizontal single pass shower water heat recovery counter-flow heat exchanger of 1.5m long 50mm diameter for use in residential buildings in Hong Kong has shown potential annual energy savings of 4% to 15%

(Wong et al. 2010). Although different heat transfer enhancements have been proposed, such as fixing the smaller cold water pipe to the bottom inside the larger drain pipe in a "pipe in pipe" configuration that can potentially achieve effectiveness as high as 45% (McNabola and Shields 2013), horizontal heat exchangers generally suffer from the intrinsic problem of sediment build up which gradually leads to blockage. Similarly the storage type heat recovery units (Torras et al. 2016) which require regular maintenance are seldom adopted in domestic waste water systems.

However, a simple, effective and nearly maintenance free vertical pipe design has emerged which was developed by Dr Carmine Vasile (Waterfilm Energy Inc. 2015) in 1986. The design is based on the tubular 'falling film' effect, which uses a central tube to replace a length of traditional waste water drainage pipe; braised to the pipe's exterior are one or a number of smaller diameter copper tubes, coiled from end-to-end. When mounted vertically, warm waste water flowing through the inner tube distributes itself as a 'falling film' over the entire inner surface thus maximising heat transfer to the cold water which flows through the outer tubes in opposite directions, making it an efficient counter flow heat exchanger. Under laboratory conditions, Zaloum et al. (Zaloum et al. 2007) showed that the effectiveness of such kind of devices vary between 30 and 70%, depending on dimensions, flow rates and other design details.

Large scale implementation of WWHXs has been modelled and evaluated for a Stockholm hotel and spa, results based on simulation without experimental validation indicated a decrease of 26.5% in heating demand for domestic hot water (Malmström 2015). Comparative study on widespread adoption of solar hot water and WWHX on a city scale highlighted the cost difference of these two options was nearly tenfold, and being much simpler to install, the WWHX was recommended to promote in both new developments and existing homes (Leidl and David Lubitz 2009). Although there are a number of laboratory based studies, most are related to horizontal configurations, there is no detailed study on vertical WWHX providing performance data based on monitoring of real installations.

2.2 Life cycle environmental assessment (LCEA)

Life cycle environmental assessment (LCEA) is a methodological framework for estimating and assessing the environmental impacts attributable to the life cycle of a product or service system. The Life Cycle Assessment (LCA) framework defined in the International Standards Organization (ISO) 14040 and 14044 standards (BSI 2006a, BSI 2006b) provides a systematic approach offering informative results for decision-making (PRé 2015). The process to meet the requirements of the framework is well documented in independent guides, such as European Commission's International Reference Life Cycle Data (ILCD) System Handbook (JRC-IES 2010) and BSRIA Guide to Life Cycle Assessment (Churcher 2013). Literature review indicated a number of existing LCA publications related to buildings and building materials but no peer reviewed publications was found on waste water heat exchanger devices. However, there are a few recent publications on heating system related LCA studies with some relevance to the current study and these include environmental assessment of earth-to-air heat exchanger (Thiers, S. and Peuportier, B. 2008), LCA based environmental assessment of heating and ventilation systems in Dutch dwellings (Blom et al. 2010); life cycle impact of domestic solar assisted heat pumps (Eicher et al. 2014); environmental assessment of ground heat exchanger (Kim et al. 2015) and life cycle sustainability assessment of ground source heat pump (Huang and Mauerhofer 2016).

2.3 Life Cycle Cost Assessment (LCCA)

Life cycle costing assessment (LCCA) is a methodology for systematic economic evaluation of life-cycle costs over the period of analysis. It can be considered as a management technique for assessing the economic implications of competing design alternatives, estimating all major costs of ownership – including design, acquisition and running costs – over the envisaged economic life of the asset (Langston 2005). BS ISO 15686-5 on Life Cycle Costing (BSI 2008a) and its companion guide PD156865 on Standardized Method of Life Cycle Costing for Construction Procurement (BSI 2008c) offer a LCCA framework for construction. The process and details to meet the requirements of LCCA are well developed and documented in independent guides such as the US NIST Handbook (Fuller and Petersen 1996) and BSRIA Guide on whole-life costing analysis (Churcher 2008). Although there are many LCCA publications related to buildings and

building products, only a few are related to WWHX. The cost benefits of drain water heat recovery has been considered in the study of rainwater harvesting and grey water recycling (Stec and Kordana 2015). Financial analyses for similar WWHX installation have been reported for single family residential housings in Poland (Słyś and Kordana 2014, Kordana et al. 2014) but no study has been carried out on non-domestic scale.

3 METHODOLOGY

Opened in 2015, the Sport Pavilion is a two storey multi-use facility at the University of Brighton's Falmer campus, see Figure 1. The ground floor features a plant room and changing rooms for the surrounding sports complex. The upper floor features two further changing rooms, four seminar rooms, toilets and first-aid room.

Domestic hot water is produced by a series of grid supplied natural gas boilers. The eight shower rooms each has its own changing room and a block of five or six showers. Each shower block on the upper floor utilizes a single heat exchanger mounted into the vertical PVC-u drainage stack below; the six rooms on the ground floor could not use this configuration so employed two horizontal heat recovery pipes which are not accessible as they are embedded in the floor screed. The configuration of the shower units, the connection to the heat recovery pipe and indication of monitoring equipment used for one shower unit in a shower room on the first floor are illustrated in Figure 2.
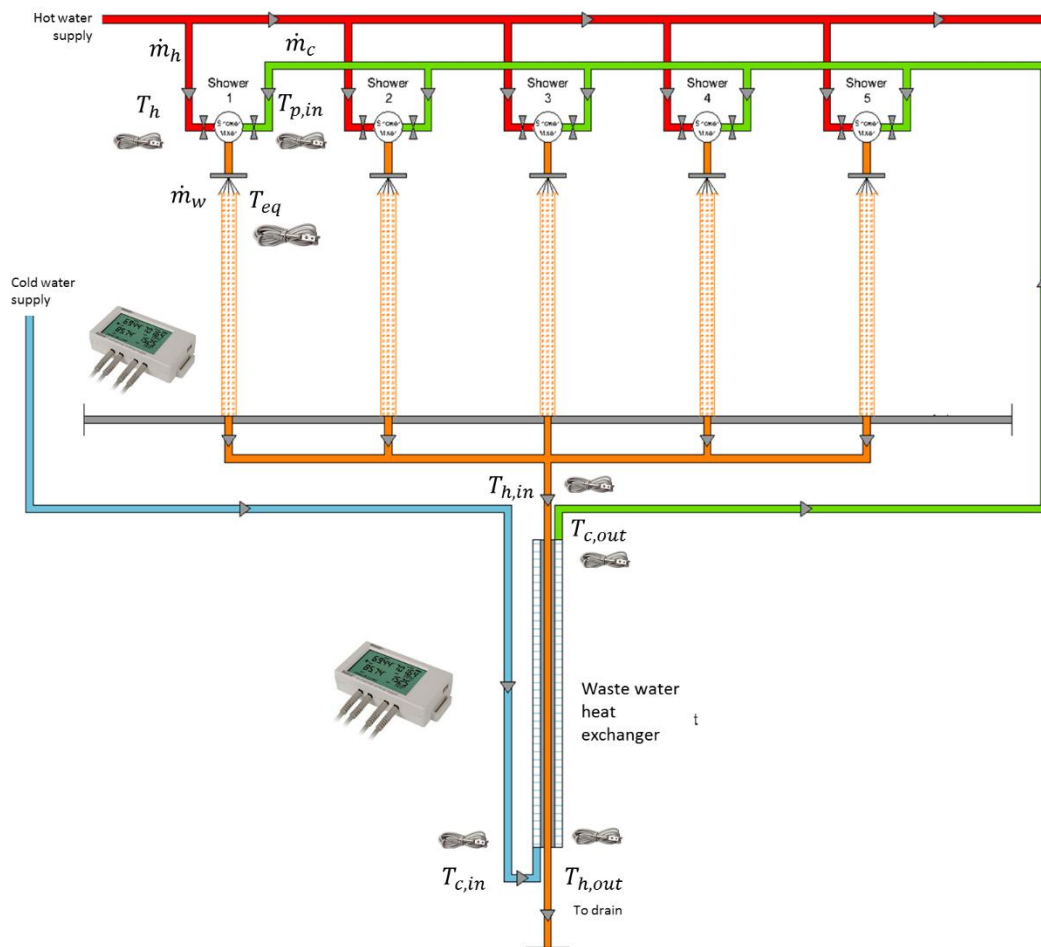

Figure 1 Changing room layout

Figure 2 System configuration and site measurements

3.1 Operational performance

3.1.1 Thermal model

Based on the system schematic configuration, mathematical equations describing the thermal model were established which enabled the identification of key parameters for experimental measurements. The heat recovery unit is a counter flow heat exchanger, its efficiency can be represented by the term effectiveness ε (Holman 2002) as:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}}$$

Where $\dot{Q}_{max}$ is the theoretical maximum heat transfer rate, for counter flow is:

$$\dot{Q}_{max} = C_{min} * \left(T_{h,in} - T_{c,in}\right)$$

If the effectiveness is known then the thermal power exchanged will be:

$$\dot{Q} = \varepsilon * C_{min} * \left(T_{h,in} - T_{c,in}\right)$$

$$C_{min} = \min \begin{cases} \dot{m}_c * c_{p,c} \\ \dot{m}_h * c_{p,h} \end{cases}$$

The heat transfer between the hot fluid $\dot{Q}_c$ and the cold fluid $\dot{Q}_h$ are:

$$\dot{Q}_c = * c_{p,c} * \left(T_{c,in} - T_{c,out}\right)$$

$$\dot{Q}_h = \dot{m}_h * c_{p,h} * \left(T_{h,in} - T_{h,out}\right)$$

At each shower mixer the following mass and energy balance equations are applied:

$$\dot{m}_w = \dot{m}_h + \dot{m}_c$$

$$\left(\dot{m}_h * T_h\right) + \left(\dot{m}_c * T_{p,in}\right) = \left(\dot{m}_w * T_{eq}\right)$$

Where:

C_{min} represents the smaller thermal capacity

$\dot{Q}$ and $\dot{Q}_{max}$ are the actual and maximum heat transfer rate [W]

$\dot{m}_c, c_{p,c}$ and $\dot{m}_h, c_{p,h}$ are mass flow rates [kg/s] and specific heat capacities [J/kg K] of the cold and hot fluids.

T_{eq}, T_h, and $T_{p,in}$ are the temperatures of the water coming out from the shower, hot water and cold water supplies

3.1.2   Site measurements

Temperature and flow data were collected on site to establish the effectiveness of the WWHX. Digital temperature sensors were used to measure the water temperatures directly from water discharged from the showers, the incoming cold water and in the floor drains. Surface digital temperature sensors, tightly adhered with thermal compound clamped directly to the copper pipes were used to obtain temperatures of water before the shower mixer and at the inlets and outlets of the WWHX. Water flow rates were established through measuring water volume collected in containers. The temperatures were continuously monitored and recorded at intervals of 10 seconds by miniature data loggers. The procedure involved repeated flow and temperature measurements with different number of shower units in operation. The main measurements after some pilot tests were repeated in two shower rooms and took place at the beginning, end and middle of the monitoring period.

3.1.3   System simulation

To enable annual evaluation and to apply the results to other types of buildings and system configurations, a dynamic system modelling software, which allowed quasi-dynamic simulation of operation of shower units, was adopted. The selected software for this study (STELLA 2016) provides dynamic visualization linking communication and interaction of complex systems. It has been adopted to evaluate the thermal performance and potential energy savings under different projected usage profiles based on estimates from the facility manager of the Sport Centre. Three profiles were studied: the 'low use' scenario with 12 users taking 3-minute duration shower repeated twice a day per week; the 'medium use' scenario with 15 users taking 5-minute duration showers repeated once per day three time in a week; and the 'high use 'scenario with 15 users taking 7-minute duration showers repeated twice a day, five days per week. The number of showers simultaneously in use is also projected as shown in Figure 3. The model building process is realized through the use of "Stocks and Flows and Causal Loop" diagrams (Richmond 2013), as illustrated in Figure 4, in which building blocks representing the physical system components – the shower mixer and WWHX – and others blocks serving specific functions (such as stock showing the energy saving) are represented. Their causal relationships are defined within and between the blocks as well as through other components such as the connectors and converters.
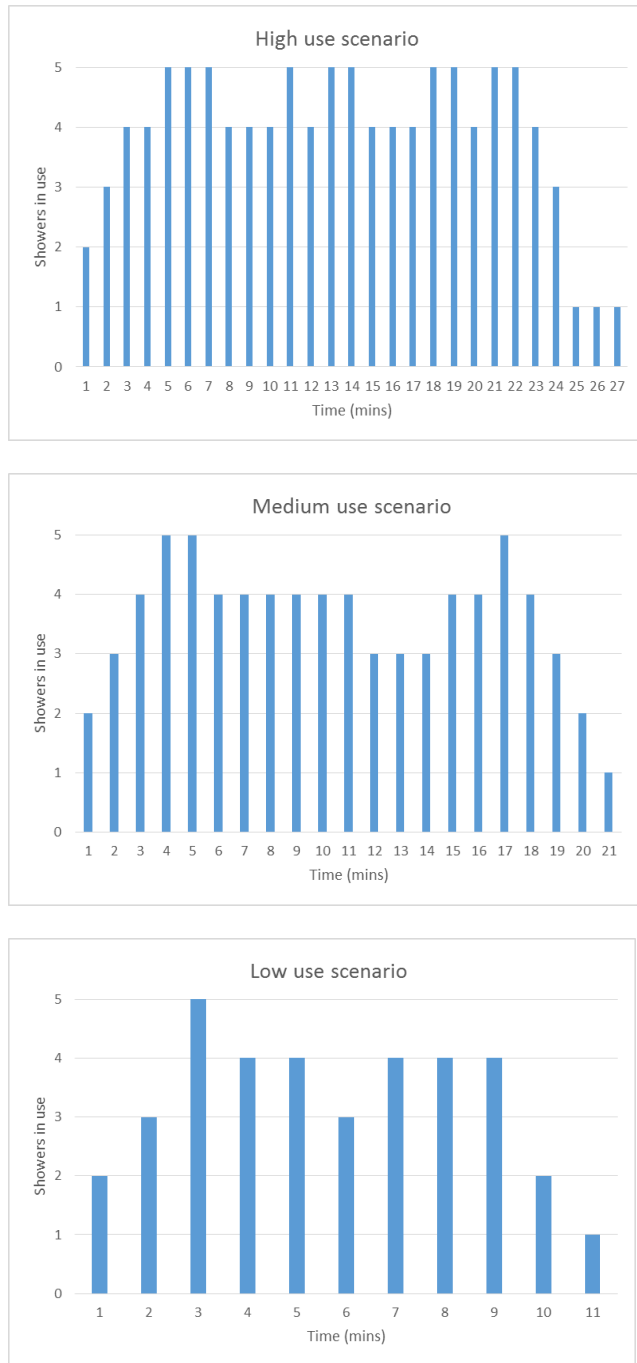
Figure 3 Usage scenarios

3.2 Life cycle assessments

3.2.1 Goal and functional unit

The goal of the life cycle environmental assessment (LCEA) is to assess the environmental life cycle performance of a waste heat recovery heat exchanger (WWHX) and contrast against a PVC-u non heat recovering pipe. The functional unit replicates the device installed at the Sport Pavilion, which is a 2.13 m long vertical pipe heat exchanger, with a nominal internal diameter of 110 mm; it transfers heat from shower waste water to the incoming mains cold water supply, designed in use for 50 years without loss of performance. This heat recovery device has a total

weight of 24.8 kg and consists of an inner copper pipe to ASTM B306 standard for sanitary drainage with 1.47mm wall thickness. The outer tube coil consists of 6 numbers of 6.1m tubes of copper to ASTM B88 standard, type K for water supply with 9.525mm nominal internal diameter and 1.25mm wall thickness. The reference unit used for comparison is a PVC-u pipe of the same diameter and length in use for 50 years without loss of performance.
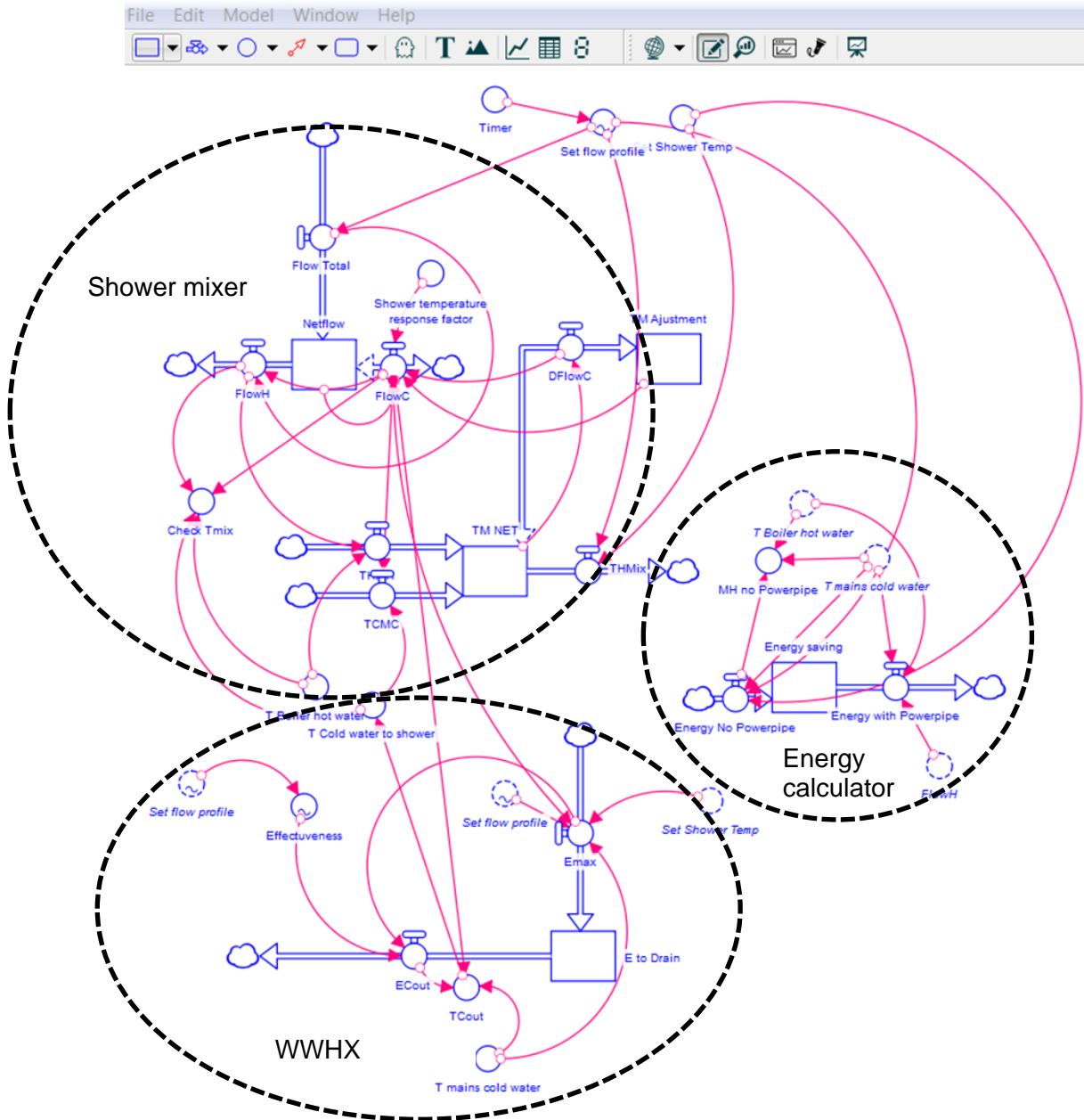

Figure 4 System model

3.2.2 *System, process and inventory*

The pipe is manufactured in Canada and transported to the site in the UK. Impact for Installation is negligible as it is mainly by hand tools. The functional unit is assumed maintenance free during operation and is 100% recyclable (CDA 2016, Folkman 2014). Figure 5 is the process map established for the functional unit and Table 1 is a summary of the materials and energy input (RenewABILITY 2015).

Process, material or energy input		Quantity
Material inputs		
Copper tubing		**24.7 kg**
Braising gas: acetylene		**0.371kg**
Braising gas: liquid oxygen		**0.415kg**
'Silfos 6' braising alloy	copper	***85.2 g***
	silver	***5.9 g***
	phosphorous	***7.1 g***
Tap water for pressure testing		**13.5 l**
Cardboard packaging		**3.71 kg**
Energy inputs		
Electricity		**13.28 kWh**
Natural gas		**1.629 kg**

Table 1 Summary of the WWHX functional unit production input

3.2.3   Life cycle environmental assessment

The life cycle processes of the functional unit and details of the input/output items shown in Figure 5 are processed and analysed using the SimaPro LCA software (PRé 2010). Data for life cycle modelling are selected from European Reference Life Cycle Database 3.1 (ILCD 2010) and Ecoinvent 3.1 (EcoInvent 2015). When specific data is not available, such as percentage of recycling content in copper pipe, European or global average values would be adopted. The single issue method following the IPCC 2013 Global Warming Potential 100a (IPCC 2014) recommendations to demonstrate the impact on the climate change was selected as the impact assessment category.

3.2.4   Life cycle cost assessment

The life cycle cost assessment (LCCA) process follows the principles in BS ISO 15685-5 (BSI 2008b) and procedure proposed by Churcher (Churcher 2008). The cost data for the installation and fuel supply rates are obtained from the Facility Management Team. Other materials and installation costs are taken from industry price books (AECOM 2015).
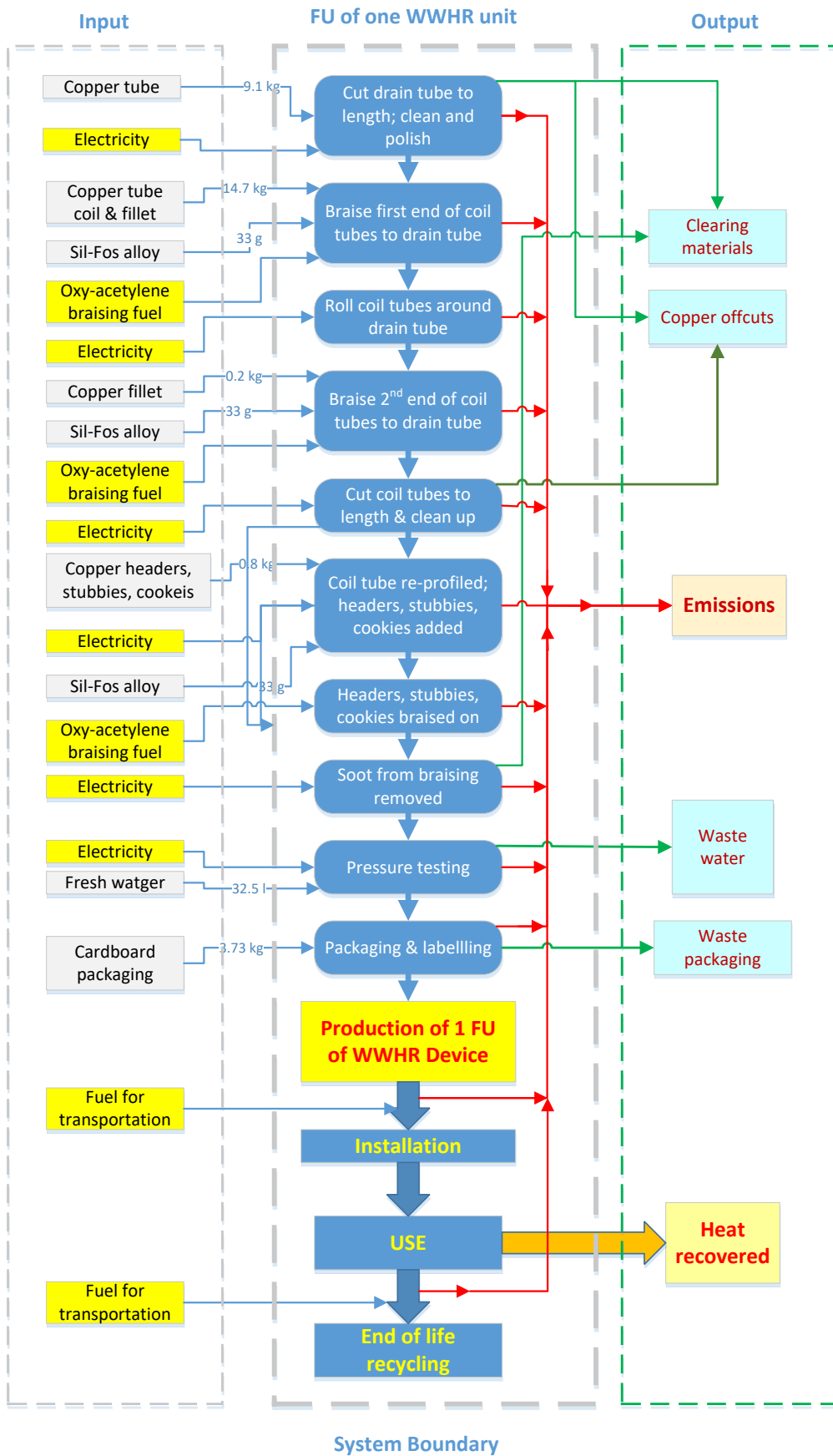
Figure 5 Process map of a waste water heat exchanger (WWHX) functional unit

4   RESULTS AND DISCUSSION

4.1 Effectiveness of WWHX

Measurements on the effectiveness of the vertical WWHX units installed at Falmer Pavilion were conducted and recorded over a period between November 2015 and August 2016. There is no access to alter the temperature and control settings of the mixing valves which were already tested and commissioned by the installer. Both hot and cold water pressures were consistently maintained by the pneumatic pressurisation units in the system. The measured incoming cold water temperatures were fairly stable between 10.4°C to 12.5°C. Data gathered from the measurements were processed to calculate the effectiveness after checking for any errors. Average results from two WWHX units and measurements over several days were used to establish representative performance data for use in the simulation modelling in the next stage. The results of the effectiveness over the monitoring period are shown in Figure 6 which indicates a range of between 0.5 and 0.6 - depending on the waste water flow rates. Data for direct comparison of results of similar site measurements are not available. However, some published laboratory based results can be used for indirect comparisons. For example, the experimental measurements of effectiveness by Zaloum et al (2007), the Oak Ridge National Laboratory (Tomlinson 2001) and Beentjes et al. (2014) under controlled steady state conditions indicated comparable performance of the WWHX within the range of between 0.4 to 0.7. In an attempt to use heat pump to boost the output of WWHX, Wallin and Claesson (2014) found no significant improvement to the effectiveness which, lower than the theoretical prediction, was between 0.4 and 0.6 as measured in their experiments. WWHXs were also tested by Tanha et al. (2015) in two solar hot water systems and reported to have an overall effectiveness of about 50%. There is a general consensus from the published results and the measurements from this study that if the 'falling film' effect is correctly applied to the vertical WWHXs, it is viable to achieve effectiveness in the region between 0.4 and 0.6.
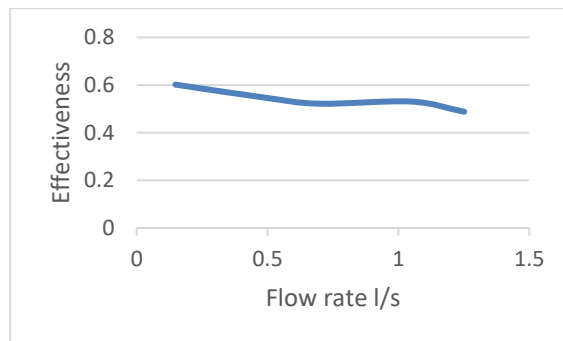

Figure 6 Average effectiveness of WWHX

4.2 Life cycle environmental assessment

The results from the assessment are summarized in Table 2 which shows the greenhouse gas (GHG) emissions, in $kgCO_{2eq}$, from the WWHX unit is three times more than the reference PVC-u pipe unit. However, the negative emissions as a result of WWHX installation indicate system reduction in GHG emissions due to the fuel savings for heating the water during the operation phase of the WWHX. The GHG payback time required to compensate for the extra greenhouse gas associated with the WWHX is short, between 0.55 and 1.33 years, for high and medium use scenarios but even for low use, requires nearly 10 years, it is still a very positive worthwhile option.

Scenario	Lifetime [kg CO2 eq]	Annual Saving [kg CO2 eq]	Pay back [Years]
PVC-u reference pipe	11.42		
WWHX after installation (pre use)	56.27		
WWHX 'low use'	-223.8	4.48	10.02
WWHX 'medium use'	-1,702.00	33.81	1.33
WWHX 'high use'	-4,064.00	81.05	0.55

Table 2 IPCC 2013 GWP 100a method results

4.3 Life cycle cost assessment

Costs of WWHX and PVC-u units are itemized in Table 3. The cost of the 110mm PVC-u pipe supply and inclusive of fixing was taken from the PSA Schedule of Rates for Building Works (AECOM 2015b) is around £40. Hence a significant capital cost difference of nearly £951.

Item		Quantity	Rate (£)	Cost (£)
WWHX	**Materials** - WWHX unit, fittings & delivery	1	800.00 each	800.00
	Labour - Mechanical services installer	1	13.53 / hr**	13.53
	Plant - Not required	-	-	-
	Incidentals, overhead & profit Mark-up on materials, labour & plant to provide 20% gross profit margin	1	25%	203.38
	Total			1016.01
PVC-u	110mm pipe - supply and fix, inc. fittings	2.13	19.03 / m*	40.53

Table 3 Cost of the WWHX unit and PVC-u pipe

To determine the operating costs, three scenarios representing low, medium and high usage profiles were considered in the analysis based on the fuel costs at 0.0172 £/kWh (Baker 2016) for the showers served by the WWHX unit and the reference PVC-u pipe. Results of lifetime fuel costs are summarized in Table 4 which shows significant fuel cost savings especially at higher usage of water.

When considering the net present value of the life cycle costs based on a 5% discount rate and taking into account both the capital and operating costs, the WWHX is clearly more expensive and the additional cost of incorporating the WWHX costing nearly £724 will not be recovered. Even when taking the fuel cost increase of 10% for every 5 years, the difference is still significantly higher by, as much as £641, as shown by the results for the 'medium use' scenario in Table 5. Even in the case of scenario for 'high use' the total life cycle cost for the WWHX and PVC-u pipe are £1869.46 and 1484.57 respectively. These results indicate the additional cost of WWHX will not be recovered by the energy savings alone, which largely attributed to the much cheaper gas price the university was able to acquire from the market as a big energy consumer. These findings are consistent with the comprehensive financial study by (Słyś and Kordana 2014) which demonstrated the most favourable payback was 2.5 years but could exceed the technical life of the device in the worst case.

With conventional PVC-u pipe	kWh used	Total cost (£)
Very low use	15,727.5	271.21
Medium use	98,297.5	1,695.09
High use	229,361.0	3,955.22
With WWHX unit		
Very low use	9,342.5	161.11
Medium use	58,202.0	1,003.66
High use	135,408.5	2,335.05

Table 4 Lifetime fuel costs

However, if WWHXs were operated in locations where fuel costs are not discounted and more expensive fuels were used, such as in electric water heating, the payback back will be much shorter with periods of between 2 to 5 years (DOE 2005). Similarly the study on domestic dwellings by (Kordana et al. 2014) which shows discounted payback, depends on assumed usage profiles and number of occupants, is on average of 3-4 years. Even in the case of less effective horizontal WWHXs, the potential payback is around 10 year but only 5 years if there are government incentives (McNabola and Shields 2013)

	Power-Pipe (£)		PVC-u reference pipe (£)	
	5% discount rate	Fuel rise 10% every 5 years	5% discount rate	Fuel rise 10% every 5 years
NPV of lump sums	1,016.91		40.53	
NPV of recurring costs (energy use – natural gas)	366.40	486.77	618.88	822.27
NPV of total lifetime cost	**1383.31**	**1503.68**	**659.41**	**862.80**

Table 5 NPV of lifetime costs: 'medium use' scenario

5 CONCLUSIONS

This study has evaluated the whole life environmental and financial impacts of a waste water heat recovery technology in a sport facility where a high simultaneous usage of hot water for showers was expected. Measurements on performance on different flow rates based on the number of showers in operation showed that over 50% of the heat in the waste water could be recovered. Applying these performance data to the system simulation to the low, medium and high usage profiles have enabled the projections of the annual energy demands for use in the life cycle environmental and cost assessments.

The LCEA shows the WWHX could be a very effective means to reduce the environmental impact as the payback periods to compensate the GHG emissions due to the use of WWHX are between 0.55 to 10 years with a period of 1.33 in the medium use case. On the other hand, the additional life cycle cost of the WWHX, taking into account of the financial savings from the heat recovery, is higher than that of a conventional PVC-u pipe installation even under the high usage scenario. With a low fuel cost in this particular case, the full cost of a system with WWHX will not be recovered within the life cycle period of 50 years in this study.

Within the limitations of the experimental measurements and assumptions made, the vertical WWHX, which virtually consumes no resources during operation but instead contributes to the reduction of fuel demand for heating the hot water, is able to rapidly 'pay for itself' environmentally but fails to do so financially over its lifetime. This study has developed a methodology which can be adopted for comparative studies of environmental and financial impacts of similar or other

types of waste water heat exchangers. Future work will consider the life cycle social impact enabling a holistic sustainability evaluation of the WWHX.

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