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Emissions down the drain: Balancing life cycle energy and greenhouse gas savings with resource use for heat recovery from kitchen drains

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Abstract

Although the food service sector is a major user of water, the potential for heat recovery from commercial kitchens' drain water remains largely unexplored. For the first time, we compare the life cycle environmental burdens of producing and installing a heat recovery system with the environmental credits arising from energy savings for a restaurant case study, and for the entire UK food service sector. Life Cycle Assessment was applied to determine the impacts of heat recovery systems made from different materials and comprising a heat exchanger in the shape of a concentric double-walled pipe, pipework and fittings. The design option with the smallest environmental footprint combined a heat exchanger made out of polypropylene-graphite (PP-GR) with polyethylene pipework, exhibiting 80-99% less environmental impact compared with components made out of (35% recycled) copper. Contrasting the environmental impacts of two heat recovery set-ups with energy savings shows that a PP-GR based system pays back all seven assessed environmental impacts within two years, while payback times for the copper-based system vary depending on the replaced energy source, and can exceed the 10 year operational lifetime of the system. When looking at typical flow-rates in UK food outlets, net environmental savings can be realised across all analysed impact categories above a threshold water consumption of 555 L/day, using current technology. Extrapolation to the UK food service sector indicates annual greenhouse gas emission mitigation potential of about 500 Gg CO₂ equivalent.

Keywords

Environmental impact assessment, wastewater heat recovery, energy savings, eco-design, climate change mitigation, recycling

1 Introduction

In the UK, nearly half of the water consumption of the wider food and drink sector occurs in the hospitality and food service sub-sector, with an estimated 143 million m³ water used in 2010 for the preparation of meals in commercial and similarly used kitchens (Bromley-Challenor et al., 2013). Spriet and McNabola (2019a) determined a total wastewater heat

41 recovery potential for the UK food service sector of 1.4 TWh/year, and a financially viable
42 potential of 1.24 TWh/year. The recovered heat is available for direct reuse for pre-heating the
43 cold water supply and can hence directly contribute to the decarbonisation of hot water use.
44 Heating water accounts for a considerable amount of energy consumption across industrial
45 and non-industrial sectors. It is estimated that up to about 90% of the energy requirements
46 and related greenhouse gas (GHG) emissions from the domestic water cycle in industrialised
47 countries derive from heating water (Arpke and Hutzler, 2008; DEFRA, 2008; Fagan et al.,
48 2010; Gerbens-Leenes, 2016; Nair et al., 2014; Siddiqi and Fletcher, 2015). Sanders and
49 Webber (2012) looked into the energy consumption for water use of all sectors in the US, and
50 found that heating for hot water and steam generation dominated water-related energy
51 consumption not only in the residential, but also the commercial and industrial sector.
52 Altogether, 47% of the US primary energy consumption in 2010 was due to water and steam
53 applications (Sanders and Webber, 2012).

54 While heat recovery from wastewater has been intensively studied and applied in the
55 residential sector, this is not the case for the food service sector, although the same appliances
56 can be used. The necessary equipment for heat recovery from drain water on a small-scale
57 includes market-ready low-tech options such as in-line, pipe shaped heat exchangers (Ip et
58 al., 2018; McNabola and Shields, 2013; Schuitema et al., 2005; van der Hoek, 2011). They
59 have been predominantly studied and installed for use in households or similar domestic
60 settings for shower or mixed drain water (Ip et al., 2018; McNabola and Shields, 2013;
61 Schuitema et al., 2005; Słyś and Kordana, 2014; Wong et al., 2010). However, they could also
62 be potentially used with other wastewater types.

63 A bonus of heat recovery from commercial kitchens' drain water is a higher daily water use
64 compared to an average household, which for the UK lies in the range of 360 to 12,500 L/day
65 (Spriet and McNabola, 2019a), versus to 349 L/day in homes (EST, 2013). The heat recovery
66 figures by Spriet and McNabola (2019a) equate to an average yearly saving of about
67 5400 kWh per food outlet. Installation of comparable heat recovery systems with showers
68 have been reported to save 127-1880 kWh/year per six showers in a sports facility (Ip et al.,
69 2018), and 130-508 kWh/year per one shower in a residential building (Wong et al., 2010).
70 The amount of heat energy recovered during the lifetime of the heat recovery system plays an
71 important role not only for financial payback, but also environmental payback for the
72 installation.

73 As with all manufactured products, heat recovery devices carry environmental burdens
74 through their manufacture, installation works, operation and disposal. Significant burdens from
75 manufacture are especially associated with metals such as copper, which is frequently used
76 for plumbing equipment and a preferred material for heat exchangers because of excellent
77 heat conducting properties. It is known that production of copper components generates larger
78 environmental burdens compared to steel (Prek, 2004) or plastic (Asadi et al., 2016; Franklin
79 Associates, 2011), with regard to GHG emissions (Franklin Associates, 2011), human health
80 and eutrophication impacts (Asadi et al., 2016). Hence, to justify the application of heat
81 recovery devices on resource efficiency and wider environmental grounds, the impacts
82 generated during their life cycle have to be considered. However, there is a lack of studies
83 evaluating in-line heat recovery devices for small-scale applications, and providing the
84 complete picture of environmental impacts through full Life Cycle Assessment (LCA). The
85 most comprehensive related study was published by Ip et al. (2018), who conducted an
86 environmental and economic assessment of an in-line heat exchanger from copper recovering
87 heat from shower drains in a university sports facility. Whilst their LCA study comprised all
88 steps, from **cradle to grave** (manufacture, use and end-of-life) of the heat exchanger, it only
89 considered the Global Warming Potential (GWP) burden; i.e. GHG emissions. Other impact

90 categories such as resource depletion with material component manufacture were not
91 included. The study also did not consider the need for additional pipework or fittings that can
92 be necessary to connect the heat recovery device to a boiler, especially when retrofitting an
93 existing plumbing system.

94 Here, we apply LCA methodology to determine for the first time the environmental burdens
95 across seven impact categories arising from the manufacture and retrofit installation of a full
96 drain water heat recovery system suitable for use with kitchen drain water. Besides the
97 essential heat exchanger, the system consists of the pipework required for connecting the
98 heat exchanger to a boiler and cold water supply, of insulation and fittings. Due to important
99 potential environmental trade-offs associated with copper highlighted in aforementioned
100 studies, we explore the use of recycled copper and of a polymer based material as alternative,
101 namely polypropylene-graphite (PP-GR). For pipework, different materials (copper, steel,
102 polyethylene) and different lengths are considered, in order to represent different site-
103 dependent conditions.

104 As the amount of recoverable heat and the benefits derived from avoided water heating
105 significantly influence the environmental sustainability of heat recovery systems, LCA results
106 are compared to energy savings from different sizes of kitchens used for different purposes:
107 the comparison includes savings from a case study restaurant and from commercial kitchens
108 across the UK food service sector. Eventually, extrapolation of the findings to the UK food
109 service sector determines the potential savings on a national level.

110 **2 Materials and methods**

111 **2.1 Goal and Scope**

112 The objective of this study is to provide a comprehensive picture of the environmental burdens
113 of a heat recovery system retrofitted to a commercial kitchen, to identify the steps in the life
114 cycle contributing most to these environmental burdens and to explore the role for alternative
115 materials to mitigate “hotspots” of environmental impacts, and inform eco-design. The LCA
116 approach has been chosen for this purpose, following the guidelines of ISO 14040 (ISO,
117 2006). An LCA accounts for resource use and emissions arising during the life of a product or
118 service, starting with resource extraction and mining, and ending with its disposal or alternative
119 end-of-life (EoL) management. In the case of the copper pipe, it includes for instance the
120 mining of the copper ore, through processing of the copper such as melting and extrusion, to
121 recycling into new copper products.

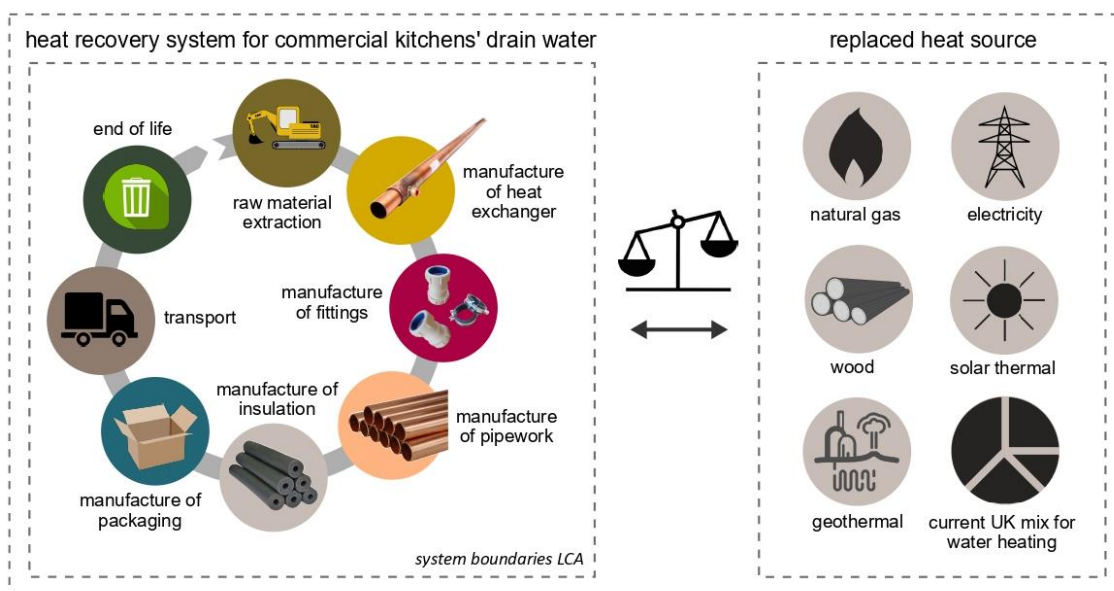
122 Environmental impacts are classified into different impact categories, with Global Warming
123 Potential (GWP) caused by GHG emissions being the most prominent one. We furthermore
124 chose the following environmental impact categories from the set of categories and
125 characterisation methods recommended at midpoint level by the International Reference Life
126 Cycle Data System (ILCD) (EC JRC 2011): Human Toxicity Potential (HTP) and Freshwater
127 Ecotoxicity Potential (FEToxP), as these impacts are associated to mining activities such as
128 copper mining; Mineral, fossil & renewable Resource Depletion Potential (RDP), as nearly all
129 parts of the heat recovery systems assessed are made from finite materials and changes are
130 expected with different recycled material input rates; Freshwater Eutrophication Potential
131 (FEP), Acidification Potential (AP), and Photochemical Ozone Formation Potential (POFP), as
132 they are connected to a variety of industrial processes such as mining, fossil fuel combustion
133 in heat and electricity generation as well as transport. Eutrophication is furthermore associated
134 with energy generation from biomass. HTP is presented as sum of both the cancer and non-

135 cancer toxicity potential. Normalised scores have been obtained in SimaPro, with
136 normalisation factors based on Benini et al. (2014).

137 The life cycles of the heat recovery systems are modelled with the software SimaPro (release
138 9.0) (PRé Sustainability, 2018) and using the Ecoinvent (2018) version 3.5 database for the
139 life cycle inventory for the majority of processes (see Supplementary Material S1 for additional
140 databases used).

141 2.2 System boundaries

142 The LCAs include all stages from cradle-to-grave, i.e. from the extraction of the raw materials
143 incorporated in the processes chosen from the database until the end of life of the products
144 (Figure 1). No environmental burdens are considered to arise during the use phase, as the
145 device itself is passive and not expected to create any emissions. Maintenance (i.e. cleaning)
146 intervals are unknown, and cleaning burdens are estimated to be minor compared to overall
147 lifecycle burdens. Packaging and transport are included. Transport is part of both the
148 foreground system and the background system through choice of appropriate processes from
149 the databases (Supplementary Material S1).



150

151 *Figure 1: System boundaries of the LCAs on the heat recovery system (left, shown for the copper system) and*
152 *extended boundaries for evaluating the savings potential through the replacement of heat energy sources.*

153 2.3 Description of the system and inventory

154 2.3.1 Overview

155 The core part of the heat recovery system is the heat exchanger designed as a concentric
156 double-walled pipe which replaces a part of the wastewater pipe. The warm wastewater flows
157 through the inner pipe, while the cold incoming water flows in the opposite direction through
158 the outer pipe (counter flow principle, Supplementary Material S2). For a fully functional heat
159 exchanger and maximum heat recovery, the warm drain water has to form a falling film along
160 the wall of the inner pipe (Manouchehri et al., 2015). This is enabled through a vertical
161 installation (Manouchehri et al., 2015). The heat exchanger is connected to the existing
162 pipework via plastic fittings (bottom and top connectors) with joint rings, one fitting each end

163 of the pipe (BPD Ltd., 2019a). Screws and brackets made from steel and rubber fix the heat
164 exchanger at the wall (BPD Ltd., 2019a).

165 The pre-heated incoming water is led from the heat exchanger to the conventional heating
166 system, usually a boiler, for further heating. Depending on the layout of the existing plumbing
167 in a building, the heat exchanger cannot be placed in close vicinity to the boiler or the incoming
168 cold water pipe and additional pipework can be required to cross the distance. To minimise
169 heat loss, the pipework is considered to be insulated with a layer of synthetic rubber.

170 An overview of the inventory is provided in the Supplementary Material S1.

171 **2.3.2 Manufacture of the copper heat exchanger**

172 Description: The heat exchanger considered refers to a model which is 1.68 m long, has an
173 inner diameter of 48 mm and weighs 6.1 kg (Q-Blue b.v., 2018). The capacity for the drain
174 water flow is 50 L/min, and the maximum clean water flow is 12 L/min. The clean water void
175 between the inner and outer cylinder has a volume of 0.39 L.

176 Modelling: Starting with primary or recycled copper, the production of a semi-finished copper
177 tube continues with the following steps: melting, casting, extrusion, drawing and finishing steps
178 from the raw pipe to the final heat exchanger (Tikana et al., 2005). As the processes of melting
179 and casting are already included in an Ecoinvent database process for primary copper
180 production, they are only modelled separately for the recycled copper. For melting the
181 secondary copper, we assume the electricity input for an induction furnace, which is the type
182 of furnace predominantly used in the copper industry (CDA Inc., 2019). The energy
183 requirement for melting of copper in an induction furnace is calculated according to basic
184 physical principles and a plant efficiency of 70% (Dötsch, 2017) (Supplementary Material S3).

185 As primary copper production is a resource- and energy-intensive process, responsible for
186 considerable emissions during mining, ore refining and further processing (Althaus and
187 Classen, 2005; Castro Molinare, 2014), adequate assumptions for the share of recycled
188 copper in the heat exchanger are necessary for a realistic picture of its environmental impacts.
189 Two types of recycled or secondary copper can be distinguished: recycled scrap, which
190 originates from low grade copper scrap and which has to be refined electrolytically before
191 reuse; and clean scrap, which can be directly re-melted.

192 Studies from Ciacci et al (2017) and Glöser et al (2013) estimated an average 35% recycling
193 input rate for all types of copper products in Europe and globally, of which 63% is clean scrap.
194 Another study, commissioned by the copper industry and claiming to rely on primary industry
195 data, assumes a share of around 70% of recycled copper as input for the production of
196 European copper pipes, of which about 90% comes from clean scrap (Tikana et al., 2005).

197 **2.3.3 Manufacture of the PP-GR heat exchanger**

198 PP-GR has been chosen in this study as a potential substitute for copper in a wastewater heat
199 exchanger for several reasons. It exhibits a greater fouling and corrosion resistance compared
200 to metals, which is important when conveying media heavily loaded with organic material, such
201 as kitchen wastewater (Chen et al., 2016; Hussain et al., 2017, Glade et al., 2018). As PP-GR
202 has been tested and designed for use in highly corrosive environments such as desalination
203 plants and with higher temperatures than those of kitchen wastewater, we expect the material
204 to be appropriate to handle wastewater (Glade et al., 2018; Technoform, 2014). From an
205 environmental perspective, a great advantage is the smaller amount of energy required for
206 forming polymers, compared with metals.

207 Description: There is no commercially available heat exchanger made from PP-GR to date
208 that is equivalent to the copper model evaluated here. Material requirements are therefore
209 calculated for a hypothetical heat exchanger with the same length and volume for the water
210 leading parts in order to compare the amount of recovered heat. As PP-GR has a considerably
211 lower density than copper, at 1.56 g/cm^3 , only 1.02 kg material is required. The PP-GR
212 composite is made of polypropylene as a matrix with graphite as filler, imparting a thermal
213 conductivity comparable to that of stainless steel (Glade et al., 2018). PP-GR contains 72 wt%
214 graphite, equalling 50 vol% (Glade et al., 2018).

215 Modelling: Information on the material composition and properties were attained from a
216 manufacturer (Technoform, 2014) as well as from a study on its mechanical, chemical and
217 thermal properties (Glade et al., 2018). Virgin polypropylene and battery grade graphite are
218 considered as the inputs for the PP-GR pipe. Battery grade graphite production requires
219 energy intensive steps, comes with a higher environmental burden than that for graphical
220 paper and is therefore selected as a conservative proxy, so as not to underestimate
221 environmental burden (Olson et al., 2016). The tube is produced through an extrusion process.

222 In contrast to the copper device, no field data are available for the heat recovery potential of
223 the PP-GR heat exchanger in the discussed application. But given a heat transfer coefficient
224 of the PP-GR tube of $2523 \text{ W/(m}^2\cdot\text{K)}$ (Technoform, 2014), we can determine an effectiveness
225 of 60.5%, close to that of the copper heat exchanger of 58% on average, according to the
226 manufacturer (Q-Blue b.v. 2018, Spriet and McNabola, 2019a) (Supplementary Material S4).
227 Heat recovery potential by the PP-GR device is therefore conservatively assumed to be equal
228 to that for copper.

229 **2.3.4 Pipework, insulation, fittings and packaging**

230 Pipework required to retrofit the heat exchanger within the existing plumbing network is also
231 accounted for. The outer diameter of this pipework is 28 mm (DN25), and we consider three
232 lengths to represent different retrofit situations: 1 m, 10 m (the length required in the case
233 study), and 30 m. Copper, steel and polyethylene are compared as pipe materials. Information
234 to model the pipework was retrieved from pipe manufacturers for copper (German Pipe, 2019),
235 polyethylene (Pipelife UK, 2019) and stainless steel (Geberit Sales Ltd, 2019). The insulation
236 is modelled using a pipe insulation module from Ecoinvent, which refers to insulation made
237 from the synthetic rubber ethylene propylene diene methylene (EPDM). Information on the
238 quantities and types of material of the fittings were derived from a manufacturer and a supplier
239 (BPD Ltd., 2019b; Q-Blue b.v., 2018). The weights of the parts and packaging were determined
240 directly by the authors.

241 **2.3.5 Transport**

242 The city of Birmingham has been chosen as a representative, central location within the UK
243 for installation of the heat recovery system. The copper heat exchanger and the fittings are
244 considered to be shipped from the Netherlands to the UK by lorry, unless more specific
245 information has been provided by a supplier for particular fittings (Livingston, 2018). Two parts
246 of the top connector are produced in Poland, and the third part is made in the UK along with
247 the entire bottom connector. The PP-GR heat exchanger in contrast is shipped from the
248 production site in Kassel, Germany. The pipework and insulation is assumed to originate from
249 Germany. The transport from the site of use to a recycling facility or landfill site is considered
250 using a generic distance of 100 km.

251 2.3.6 End-of-Life

252 The LCAs regard recycling for parts where a recycling infrastructure exists in the UK, and
253 landfill where recycling is unlikely. Different methodologies exist to allocate burdens for
254 recyclable materials in LCA (Ekvall and Tillman, 1997; Johnson et al., 2013). Here, we opt for
255 the cut-off or recycled content approach (Johnson et al., 2013) and hence do not account for
256 emissions and benefits from recycling in the EoL stage, as the recycling benefits and burdens
257 in the manufacturing stage are already taken into account, where applicable. For copper, we
258 assume recycling of 80%, which is the EoL processing rate for European plumbing equipment
259 as determined by Ruhrberg et al. (2006). The remaining copper is considered to go to landfill.
260 Bottom and top connectors are recycled completely, as their size allows for municipal waste
261 management for hard plastics. Brackets and screws are assumed to go to landfill, as it is
262 unlikely that the user will deconstruct and separate these small components to allow for
263 recycling. For insulation, material is considered to be sent to a landfill for disposal (BIF REP,
264 2013). Pipework: Copper pipework follows the same EoL route as the heat exchanger from
265 copper. Steel is recycled at a rate of 70% (Davis et al., 2006) and polyethylene EoL is split
266 into recycling (16%), incineration (35%) and landfill (49%) (Mudgal et al., 2011) (see
267 Supplementary Material S1 for details).

268 As the PP-GR composite is a relatively new material on the market, we conservatively assume
269 landfill as the most likely fate, accounting for both polypropylene and the inert graphite.

270 2.4 Scenarios and functional unit

271 A range of scenarios has been adopted for the setup of the heat recovery system in order to
272 represent various installation settings and compare different design options. The five
273 scenarios are listed in Table 1. They all include the functional unit of a heat recovery system
274 with one in-line heat exchanger, pipework of 10 m length and fittings. Separate from these
275 scenarios, we assess the design options for the pipework, comparing copper, steel and
276 polyethylene pipework and lengths of 1, 10 and 30 m.

277 *Table 1: Overview of assumptions for scenarios of the LCAs.*

Scenario	Name	Number of heat exchangers	Material heat exchanger	Material pipework	Length pipework
1	Copper (0%)	1	Copper (0% recycled content)	Copper (0% recycled content)	10 m
2	Copper (35%)	1	Copper (35% recycled content)	Copper (35% recycled content)	10 m
3	Copper (70%)	1	Copper (70% recycled content)	Copper (70% recycled content)	10 m
4	Copper (35%) + PE	1	Copper (35% recycled content)	Polyethylene	10 m
5	PP-GR + PE	1	Polypropylene-graphite (PP-GR)	Polyethylene	10 m

278

279 For the operational lifetime, we assume a conservative duration of 10 years. Other studies
280 considered a 50-year lifetime for a copper heat exchanger or copper pipework (Asadi et al.,
281 2016; Ip et al., 2018), but damage through corrosion is likely to occur earlier with kitchen
282 wastewater as it carries a greater load of organic pollutants than shower drain or clean water.
283 The functional unit for the case of an average UK kitchen is 1 kWh of water heating delivered
284 through heat recovery.

285 2.5 Savings potential

286 In order to determine the potential environmental savings associated with use of the heat
287 recovery system, data on recovered heat are required. We look at two different cases:

288 **Case study:** Firstly, LCA results are set into context with data on heat recovery from a case
 289 study on the restaurant kitchen of Penrhyn Castle in Bangor, North Wales, UK, which is open
 290 to visitors as a tourist attraction. Spriet and McNabola (2019b) predicted the amount of
 291 recovered heat during an 8-month monitoring study to be 8.45 kWh per day, taking into
 292 account the following: a copper heat exchanger as described above, a measured average
 293 daily water consumption of 652.5 L, a 90% return rate of the consumed water into the drain, a
 294 retention time of water through kitchen appliances of no longer than 1 hour and measured
 295 average drain water temperatures of 25 to 35 °C (Supplementary Material S4). As the
 296 pipework is insulated and as time between heat recovery and consumption of the pre-heated
 297 water is very short, heat losses in the pipe are considered negligible. We consider the
 298 restaurant to be open 310 days a year. The environmental impacts realised through heat
 299 recovery are compared to the avoided impacts when replacing different conventional and
 300 renewable energy sources for water heating: natural gas, UK grid electricity, woodchips, geo
 301 and solar thermal energy, and the energy mix for water heating in the UK service sector (BEIS,
 302 2018) (Table 2; Supplementary Material S5 for environmental burdens from the energy mix).
 303 Results are presented as payback times for heat recovery when it replaces the mentioned
 304 energy sources.

305 Life cycle burdens of the heat recovery systems as in scenario 2 and 5 are considered.
 306 Scenario 2 represents the actual installations carried out at the case study site where only
 307 copper equipment was used. Scenario 5 has been selected to show potential savings with
 308 polymer-based materials.

309 *Table 2: Types of energy and respective database modules used for determination of environmental savings*
 310 *through heat recovery*

Energy type	Database module	Database	Share in UK water heating mix [%]*
Natural gas	Heat, central or small-scale, natural gas {Europe without Switzerland} market for	Ecoinvent	66
Grid electricity	Electricity, low voltage {GB} market for	Ecoinvent	14
Oil	Heat, central or small-scale, other than natural gas {Europe without Switzerland} heat production, light fuel oil, at boiler 10 kW condensing, non-modulating	Ecoinvent	12
Softwood chips	Heat, central or small-scale, other than natural gas {CH} heat production, softwood chips from forest, at furnace 50 kW, state-of-the-art 2014	Ecoinvent	4
Hardwood chips	Heat, central or small-scale, other than natural gas {CH} heat production, hardwood chips from forest, at furnace 50 kW, state-of-the-art 2014	Ecoinvent	1
Straw	Heat, district or industrial, other than natural gas {GLO} heat production, straw, at furnace 300 kW	Ecoinvent	3
Geothermal	Heat, borehole heat pump {Europe without Switzerland} heat production, borehole heat exchanger, brine-water heat pump 10 kW	Ecoinvent	n.a.
Solar thermal	Heat, central or small-scale, other than natural gas {CH} operation, solar collector system, evacuated tube collector, one-family house	Ecoinvent	n.a.

*current UK energy mix for heating water in the service sector (BEIS, 2018). The category "biomass" was split into softwood chips, hardwood chips and straw in order to best reflect the current use of biomass heat sources (BEIS 2018b, Forest Research 2018, DEFRA 2017). Neglected: bioenergy from (unless included in grid electricity): landfill gas, sewage gas, waste wood, animal biomass, anaerobic digestion and biodegradable energy from waste.

311

312 **UK commercial food outlets:** Secondly, we determine the environmental sustainability of a
 313 heat recovery system when used with typical water consumption rates prevalent in UK
 314 commercial food outlets. The water consumption rates refer to the average rates of different
 315 food outlet categories (Spriet and McNabola, 2019a), ranging from 360 to 12,500 L/day. Heat
 316 recovery data were determined as in Spriet and McNabola (2019a), (Supplementary Material
 317 S4), taking into account the number of heat exchangers optimised for maximum financial
 318 payback with 310 open days a year over a 10 year lifetime i.e. for greater flow-rates, the

319 installation of several heat exchangers in parallel is considered (Supplementary Material S6).
 320 The life cycle burdens taken into account for the heat recovery system refer to scenario 4.

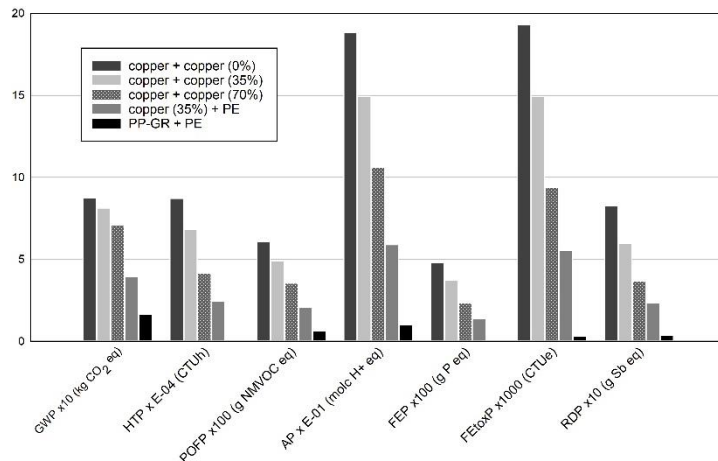
321 Finally, data on the number of served meals, water consumption and the number of outlets in
 322 the hospitality and food service sector serve to extrapolate the environmental savings to a UK
 323 level (Backman, 2018; Bromley-Challenor et al., 2013; Spriet and McNabola, 2019a).

324 3 Results and Discussion

325 3.1 Life Cycle Assessment results

326 Figure 2 shows the characterised LCA results of all scenarios for the drain water heat recovery
 327 system. The different materials used for the scenarios lead to large differences between their
 328 footprints. There are clear benefits from increasing the share of recycled copper or fully
 329 replacing copper with polymer materials. Production, use and end-of-life of the copper systems
 330 emit 87, 81 and 71 kg of CO₂ equivalent, respectively, depending on the recycled material
 331 input. These numbers coincide with the findings of Giurco and Petrie (2007) who found an
 332 increase in recycling rates besides demand reduction the only strategy to meet GHG reduction
 333 targets for copper production as ever lower ore grades constrain the potential to decarbonise
 334 copper ore processing.

335 A combination of a copper heat exchanger with polyethylene pipework has a GWP of 39 kg
 336 CO₂ equivalent. Reductions in burdens of around 45-50% can be achieved for HTP, FEP,
 337 FEtoXP and RDP, when switching from a heat exchanger and pipework of zero percent
 338 recycled copper to one of 70% recycled copper. Replacement of the 35%-copper pipework
 339 through PE can lower the impacts of the whole system by 50-60% considering the heat
 340 exchanger is still made from 35%-copper. Scenario 4 therefore represents the most
 341 environmentally friendly material combination currently available on the market for this set-up.



342 *Figure 2: Environmental burdens arising from the life cycle of drain water heat recovery systems consisting of in-*
 343 *line heat exchanger, 10 m pipework, fittings and insulations. Percentage in brackets stands for the share of*
 344 *recycled copper. PE: polyethylene, PP-GR: Polypropylene-Graphite. GWP: Global Warming Potential; HTP:*
 345 *Human Toxicity Potential; POFP: Photochemical Ozone Formation Potential; AP: Acidification Potential; FEP:*
 346 *Freshwater Eutrophication Potential; FEtoXP: Freshwater Ecotoxicity Potential; RDP: Mineral, fossil & renewable*
 347 *Resource Depletion Potential. All scenarios as described in Table 1.*

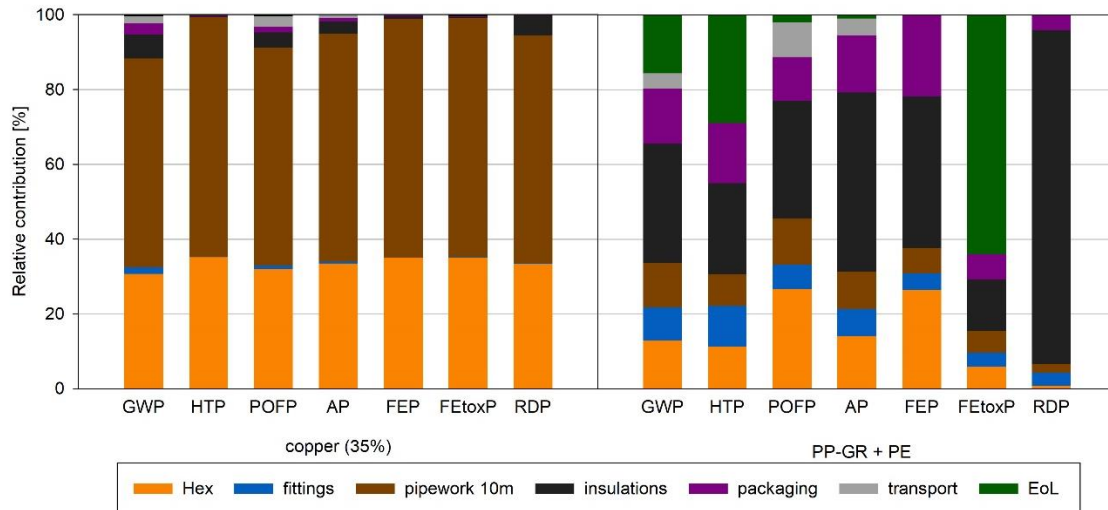
348 Still though, a purely polymer based system with PP-GR performs considerably better with a
 349 GWP of only 16 kg CO₂ equivalent. Depending on the category, it exhibits only 1-20% of the
 350 impacts of the 35%-copper scenario. Supplementary Material S7 shows the scenarios in a

351 relative comparison to each other. The normalised results allow for inter-category comparison
352 and show that the most relevant contributions are those to HTP and FEToxP for both systems
353 (Supplementary Material S8).

354 Ip et al. (2018) determined a GWP of 56 kg CO₂ equivalent for their copper heat exchanger,
355 which would compare to 26, 29 or 32 kg CO₂ equivalent for the life cycle of our copper heat
356 exchanger alone with 70, 35 or 0 % recycled content, respectively (excluding pipework). Their
357 study does not state the recycled copper input, making direct comparison difficult. Even so,
358 one reason for the different results is certainly the different material requirement for the heat
359 exchanger, with about 25 kg copper in Ip's study and about 6 kg in this study.

360 Figure 3 shows the relative contribution of the life cycle stages to the environmental burdens
361 of heat recovery systems under scenario 2 and 5. The majority of burdens of the copper
362 system across all categories originate from manufacture of copper parts (heat exchanger and
363 pipework), ranging from 87% of GWP burdens to 99% of HTP, FEP and FEtoXP burdens. This
364 underlines the pollution associated with the extraction and manufacture of copper products
365 discussed earlier in the introduction (Althaus and Classen, 2005; Castro Molinare, 2014).
366 Indeed, the main burdens from the manufacture of heat exchanger and pipes derive from the
367 generation of primary copper (Ecoinvent, 2018): HTP causing emissions arise mainly during
368 the treatment of sulfidic tailings from primary copper production and comprise groundwater
369 polluting zinc and arsenic (HTP non-cancer), and chromium VI (HTP cancer), amongst others.
370 Similarly, FEToxP is mainly caused by zinc and copper emissions from tailing treatment and
371 FEP predominantly through phosphate released into groundwater during the same process
372 (Ecoinvent, 2018). The main substances responsible for POFP are nitrogen oxides emitted
373 into the air during blasting, which also releases sulphur dioxide, the major cause for AP.
374 Resource depletion is caused especially by use of the sulfidic copper ore and molybdenum
375 during primary copper generation. Other resources contribute less than 1% to the RDP, hence
376 RDP is almost exclusively due to the consumption of abiotic materials. Only for GWP, the
377 finishing process of the heat exchanger and pipes has a greater influence than primary copper
378 production driven by heat and electricity consumption. The impact from the pipework is greater
379 than that from the heat exchanger, which is due to greater material use for the 10 m pipework
380 (11 kg vs. 6 kg copper).

381 In the PP-GR system, the manufacture of the heat exchanger and pipework plays a
382 comparatively smaller role. Apart from transport, all components make significant
383 contributions to the lower overall impacts, depending on the category. Manufacture of the
384 insulation from EPDM rubber accounts for 14-90% of burdens, with the greatest contribution
385 going to RDP. The main resource depleted is indium during the operation of the zinc mine,
386 zinc being an ingredient for the production of EPDM (Ecoinvent, 2018). EoL stage is mainly
387 responsible for impacts in FEToxP (64%), HTP (29%) and GWP (16%). FEToxP causing
388 emissions in the EoL stage are arising from incineration and landfilling of the pipe material PE,
389 both processes releasing vanadium into groundwater (Ecoinvent, 2018). The contribution of
390 the predominantly cardboard packaging ranges from 4% (RDP) to 22% (FEP) across
391 categories.



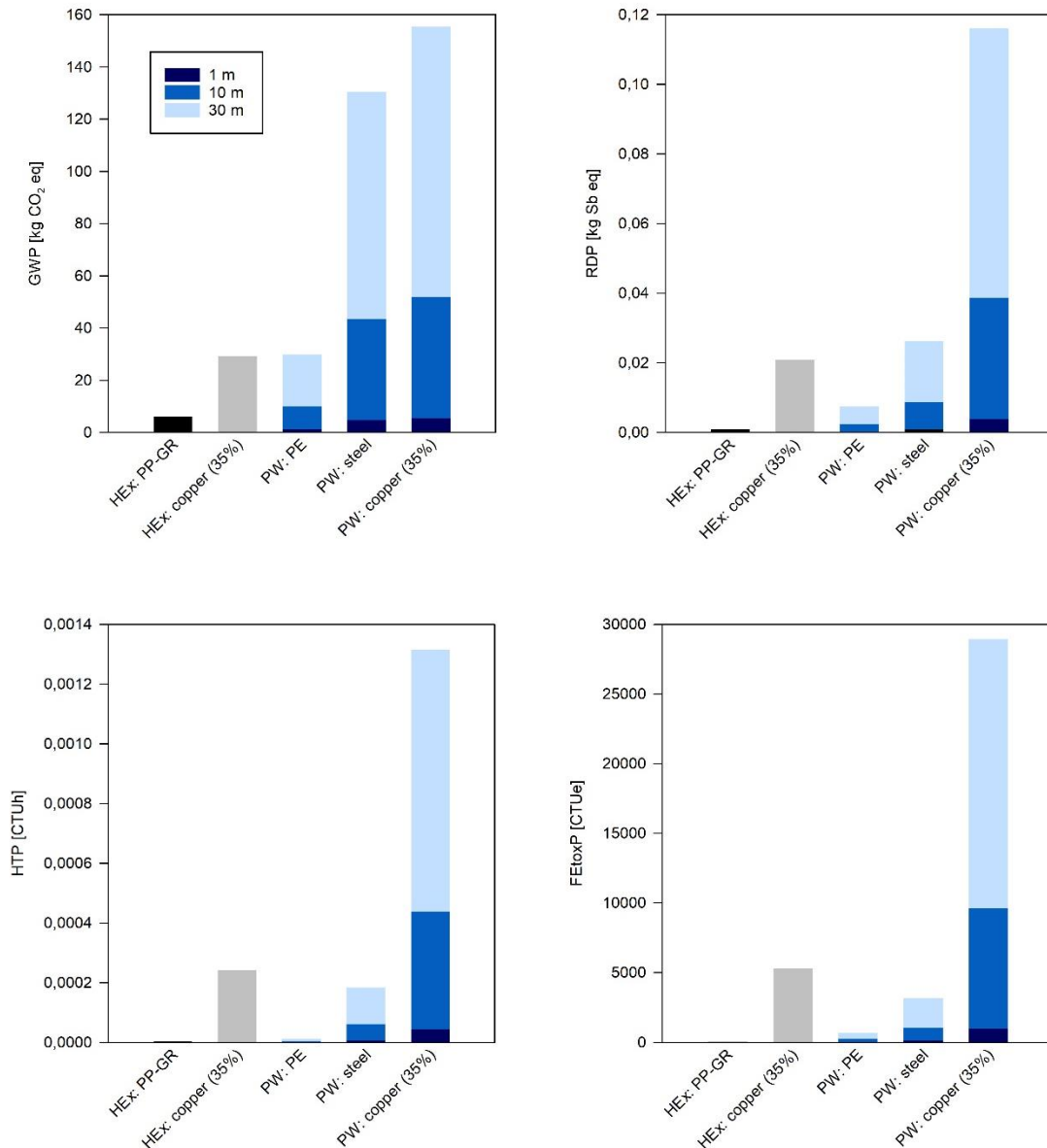
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Figure 3: LCA of heat recovery systems (scenarios 2 and 5): Relative contribution of the life cycle stages to the environmental impacts of the two heat recovery systems including 10 m pipework. Left: scenario 2: copper system with 35% recycled copper input. Right: scenario 5: PP-GR composite system with PP-GR heat exchanger and pipework from PE. GWP: Global Warming Potential; HTP: Human Toxicity Potential; POFP: Photochemical Ozone Formation Potential; AP: Acidification Potential; FEP: Freshwater Eutrophication Potential; FEtoXP: Freshwater Ecotoxicity Potential; RDP: Mineral, fossil & renewable Resource Depletion Potential; Hex: Heat exchanger; EoL: End of Life.

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The length of the pipework greatly influences the overall LCA results. Figure 4 shows the burdens from heat exchanger and pipework separately. Burdens for long and metal based (steel or copper) pipework can be greater than those from the heat exchanger. Steel pipe burdens are considerably lower than copper pipe burdens, ranging from 89% (FEtoXP) to 15% (GWP) of those from copper (see Supplementary Material S9 for more impact categories). These results underline the importance of considering the full equipment necessary for retrofit, and also how on-site conditions influence the environmental sustainability of a retrofit measure. As far as we are aware, this is the first LCA study of a heat recovery system to consider all associated retrofit pipework.



409

410 *Figure 4: Comparison of LCA results for the heat exchanger and pipework for (clockwise from top left): global*
 411 *warming potential (GWP), resource depletion potential (RDP), freshwater ecotoxicity potential (FEToxP) and*
 412 *human toxicity potential (HTP). Left two bars: complete life cycle of a heat exchanger system without pipework.*
 413 *Right three bars: life cycle of pipework from polyethylene (PE), steel and copper (35% recycled content).*

414 3.2 Environmental savings through heat recovery

415 3.2.1 Environmental savings in the case study

416 In the Penrhyn Castle case study, all environmental burdens from the heat recovery system
 417 (scenario 2) will be paid back within 10 years when electricity, geo or solar thermal energy or
 418 the energy mix for water heating is replaced (Table 3). If the recovered heat replaces natural
 419 gas, the impacts of HTP, FEP, FEToxP and RDP from production, installation and EoL of the
 420 heat exchanger and pipework will not be fully paid back in the conservative 10-year lifetime
 421 considered in this study. The low FEToxP and RDP of wood heating also prevent payback in
 422 the FEToxP and RDP categories through heat recovery if wood is used for water heating. For
 423 GWP, relatively short payback times of under 1.6 years compared with all energy alternatives
 424 can be achieved. The payback time for GWP compared to natural gas, the most common

425 water heating source, is only 0.12 years. This is shorter than the 0.55-1.33 year GWP payback
 426 previously calculated for shower heat recovery (Ip et al., 2018). It underpins the suitability of
 427 kitchens for drain water heat recovery due to typically higher wastewater flow-rates than in
 428 showers.

429 As the burdens of the PP-GR heat recovery system are substantially lower, they are paid back
 430 during shorter periods of operation, within 2 years for all impact categories (Table 3).

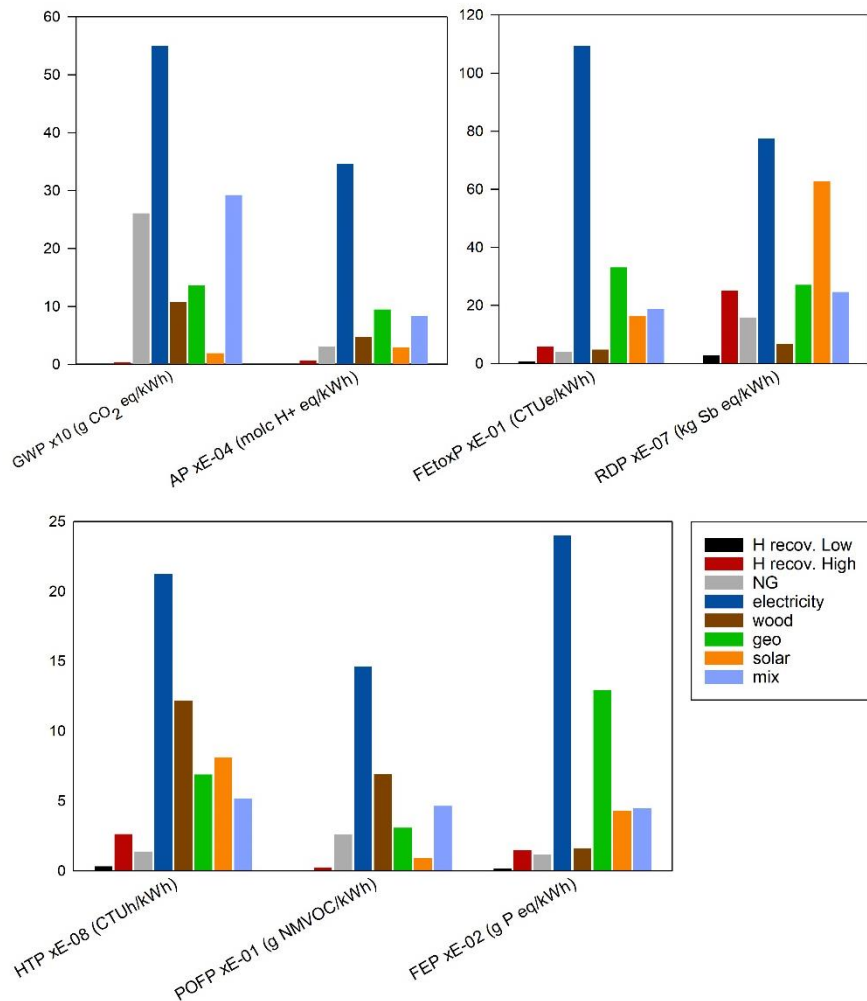
431 *Table 3: Environmental payback times in years for the heat recovery system of the Penrhyn Castle case study.*
 432 *Comparison of the copper (35% recycled content) and the PP-GR systems including 10 m of pipework with*
 433 *different energy sources for water heating. Bold and italic: Impacts are not paid back within a 10-year lifetime. NG*
 434 *= natural gas. Mix: Current UK Energy mix for heating water in the service sector (BEIS, 2018). GWP: Global*
 435 *Warming Potential; HTP: Human Toxicity Potential; POFP: Photochemical Ozone Formation Potential; AP:*
 436 *Acidification Potential; FEP: Freshwater Eutrophication Potential; FEToxP: Freshwater Ecotoxicity Potential;*
 437 *RDP: Mineral, fossil & renewable Resource Depletion Potential. Energy sources as in Table 2.*

Impact category	NG	Electricity	Wood	Geo	Solar	Mix
Copper (35%)	[years]					
GWP	0.12	0.06	0.29	0.23	1.58	0.11
HTP	18.87	1.22	2.13	3.76	3.20	5.04
POFP	0.72	0.13	0.27	0.61	2.05	0.40
AP	1.82	0.16	1.19	0.60	1.90	0.68
FEP	12.20	0.59	8.79	1.10	3.31	3.19
FEToxP	14.16	0.52	11.78	1.72	3.51	3.02
RDP	14.32	2.94	33.49	8.41	3.63	9.23
PP-GR + PE	[years]					
GWP	0.02	0.01	0.05	0.04	0.27	0.02
HTP	0.16	0.01	0.02	0.03	0.03	0.04
POFP	0.08	0.01	0.03	0.07	0.23	0.04
AP	0.10	0.01	0.07	0.03	0.11	0.04
FEP	0.19	0.01	0.13	0.02	0.05	0.05
FEToxP	0.25	0.01	0.21	0.03	0.06	0.05
RDP	0.73	0.15	1.71	0.43	0.19	0.47

438

439 **3.2.2 Environmental savings in UK commercial food outlets**

440 Two different flow-rates, representing the bottom and top end of the flow-rate spectrum in
 441 typical UK food outlets, are taken to show a worst- and best-case scenario for environmental
 442 impacts from heat recovery. The best case refers to kitchens with the highest water flow-rate
 443 typically found in UK food outlets (12,500 L/day), highest heat recovery potential and therefore
 444 the lowest impacts per kWh (“H recov. Low”). The opposite applies to the worst-case scenario
 445 with a flow-rate of 360 L/day (“H recov. High”). The environmental burdens for the heat
 446 recovery system are based on scenario 4 (Table 1), including one heat exchanger for the low-
 447 flow option and four heat exchangers in parallel for the high-flow option.

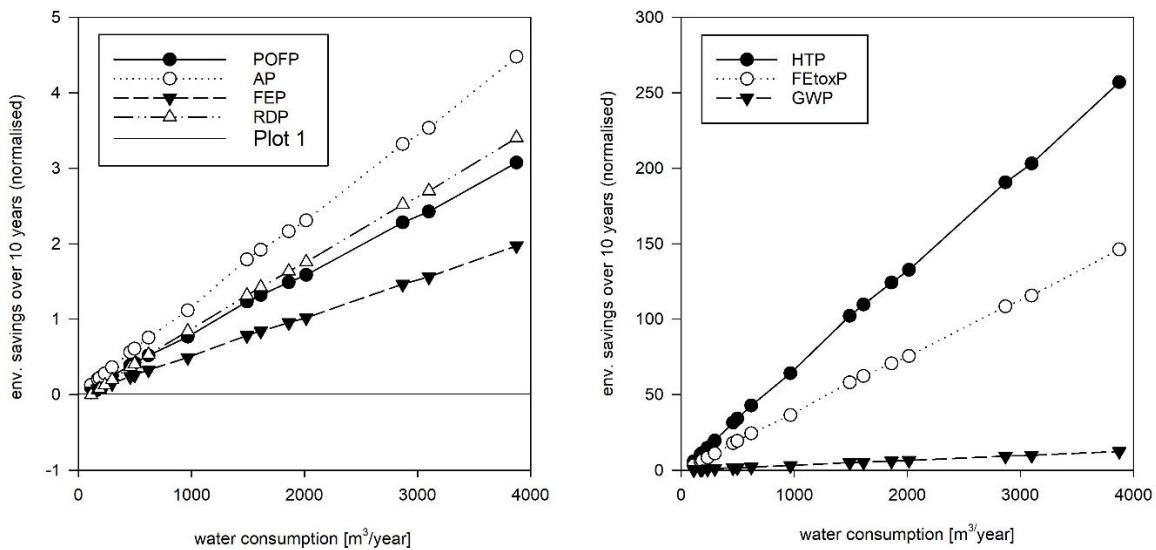


448 *Figure 5: Environmental impacts per kWh for water heating. Comparison of heat recovery from drain water with*
 449 *other renewable and non-renewable heat sources, including the current UK energy mix for water heating (“mix”).*
 450 *Burdens of the heat recovery system as in scenario 4 with two different water flow-rates found in UK commercial*
 451 *food outlets. H recov. Low: low impact case due to higher flow-rate of 12,500 L/day. H recov. High: high impact*
 452 *case due to lower flowrate of 360 L/day. NG: natural gas, electricity: UK grid mix, wood: wood biomass*
 453 *combustion, geo: geothermal, solar: solar thermal. GWP: Global Warming Potential; HTP: Human Toxicity*
 454 *Potential; POFP: Photochemical Ozone Formation Potential; AP: Acidification Potential; FEP: Freshwater*
 455 *Eutrophication Potential; FEToxP: Freshwater Ecotoxicity Potential; RDP: Mineral, fossil & renewable Resource*
 456 *Depletion Potential.*

457 Figure 5 displays the environmental impacts for providing 1 kWh for water heating through
 458 heat recovery versus other energy sources. Considering global warming, heating water
 459 through the use of recovered heat exhibits the lowest emissions with about 0.4 to
 460 4 g CO₂ equivalent/kWh for the low and high impact scenario, respectively. This compares to

461 emissions of 20 to 550 g CO₂ equivalent/kWh for solar thermal and electric water heating –
 462 i.e. even when currently available heat recovery technology replaces renewable energy
 463 sources, GWP can be reduced. Also for ozone formation and acidification, heat recovery at
 464 both flow-rates leads to impact savings compared to all other heat sources. In the other
 465 categories, environmental sustainability of heat recovery depends on the flow-rate or the
 466 heating source replaced. For HTP and FEP, natural gas water heating can have lower
 467 environmental impacts compared to heat recovery at low flow-rates. Here, emission savings
 468 through heat recovery are only achieved from a flow-rate of about 750 L/day onwards (HTP)
 469 and 555 L/day (FEP) (values not shown in graph). Similarly, FETOX and RDP can be reduced
 470 through heat recovery at higher flow-rates only, when replacing natural gas or wood biomass.
 471 With these results a recommendation for drain water heat recovery can be given from a daily
 472 flow-rate of 750 L when natural gas is replaced, the most common source for water heating in
 473 the UK.

474 Figure 6 shows the environmental savings that can be achieved during 10 years of heat
 475 recovery depending on the flow-rate and replacing the water heating energy mix. Values are
 476 shown as normalised scores. The net environmental savings increase with water
 477 consumption, although the number of heat exchangers and with them the environmental
 478 footprint of the installations augments, too. Apart from RDP, environmental payback is reached
 479 within 10 years for all impact categories starting from the lowest average daily water
 480 consumption considered (360 L/day) (Spriet and McNabola, 2019a). For RDP, environmental
 481 payback within 10 years is only achieved at water consumption rates above approximately
 482 555 L/day or 300 m³/year. The greatest normalised savings are achieved in HTP and FETOX P,
 483 followed by GWP, AP, RDP, POFP and FEP in descending order.



484

485 *Figure 6: Normalised net environmental savings (positive values) through heat recovery from a commercial*
 486 *kitchen after 10 years depending on the yearly water consumption. GWP: Global Warming Potential; HTP:*
 487 *Human Toxicity Potential; POFP: Photochemical Ozone Formation Potential; AP: Acidification Potential; FEP:*
 488 *Freshwater Eutrophication Potential; FETOXP: Freshwater Ecotoxicity Potential; RDP: Mineral, fossil & renewable*
 489 *Resource Depletion Potential.*

490 Extrapolation of the savings using average daily water consumption rates for the circa 258,000
 491 food outlets in the UK (Backman, 2018; Bromley-Challenor et al., 2013; Spriet and McNabola,
 492 2019a) gives the potential annual environmental savings for the UK (Table 4). Annual GHG
 493 emission mitigation of 490 Gg (kilo-tonnes) CO₂ equivalent could be avoided if heat from

494 wastewater was recovered across all UK commercial food outlets. These environmental
 495 savings equate to 30% of thermal energy needed for water heating in the hospitality and food
 496 service sector, based on the share of hot water consumed in the Penrhyn Castle restaurant
 497 case study.

498 The results show that even with the currently available copper heat exchanger and especially
 499 at high water consumption rates, there is strong evidence for environmental savings. It can
 500 therefore be recommended as a viable measure to de-carbonise water heating in commercial
 501 kitchens.

502 *Table 4: Yearly net environmental savings potential for the UK through heat recovery from wastewater in all*
 503 *commercial food outlets. eq = equivalent*

Impact category	GWP	HTP	POFP	AP	FEP	FEtoXP	RDP
Unit	[kt CO ₂ eq]	[CTUh]	[t NMVOC eq]	[1000 molc H+ eq]	[t P eq]	[10 ⁶ CTUe]	[kg Sb eq]
All outlets	490	78	772	1390	70	2979	3370

504

505 Although an economic evaluation of the heat recovery system is out of scope of this study, it
 506 is worth mentioning that heat recovery is not only beneficial from an environmental point of
 507 view, but also pays back financially from water consumption rates of 960 L/day (Spriet and
 508 McNabola, 2019a).

509 A study by McNabola and Shields (2013) estimated the heat recovery potential from shower
 510 drain water in Ireland to be 808 GWh per year, averaging 577 kWh per year for a 3-person
 511 household. Taking into account the population of the UK of 66M (ONS, 2019) and the UK
 512 domestic energy mix for water heating (BEIS, 2018), this would translate to yearly savings of
 513 13 TWh or 3600 Gg CO₂ equivalent. Based on the heat recovery system evaluated in this
 514 study, the aforementioned annual heat recovery at a household scale would not be financially
 515 viable, nor environmentally responsible from a resource depletion perspective.

516 3.3 Outlook

517 3.3.1 Expected changes with a changing energy mix

518 With a change in the future energy mix towards more renewable sources, the benefit of saving
 519 energy through heat recovery is likely to shift from avoiding GHG emissions, to avoiding the
 520 depletion of metal and mineral resources. GHG emission savings through heat recovery will
 521 be lower as water heating from renewable energy sources emits less GHGs, for both direct
 522 electric water heating and thermal water heating with solar collectors or air and ground-source
 523 heat pumps (Clarke et al., 2008). Although of course, the GHG emissions of producing the
 524 heat recovery system and pipework are also expected to decrease owing to decarbonisation
 525 of energy supplies.

526 Resource depletion burdens are higher for renewable electricity generation (namely wind,
 527 solar and hydro power) compared to energy supply from fossil resources owing to large
 528 quantities of abiotic resources, especially metals (e.g. manganese, copper, iron, nickel,
 529 chrome) required in renewable energy infrastructure (Berrill et al., 2016; Gallagher et al.,
 530 2019). The trade-offs between resource depletion and GHG emission savings which currently
 531 exist for heat recovery at low flow-rates are therefore likely to disappear.

532 Another important indirect and long-term benefit of heat recovery lies in increasing the
 533 efficiency in which energy is used and thus supporting a transformation to a sustainable
 534 energy economy through reducing energy demand – a strategy that has been adopted as part

535 of European and UK policies for future low-carbon energy supply (Clarke et al., 2008; da Graça
536 Carvalho, 2012; Ekins and Lees, 2008; Rosenow, 2012).

537 **3.3.2 Recommendation for further research**

538 As neither the copper nor the PP-GR heat exchanger have been in use with kitchen drain
539 water for significant periods of time, there is room for further research and need for empirical
540 data on real performance. In addition to environmental savings during manufacture, PP-GR
541 and similar composites can offer other potential advantages such as the reduction of scaling
542 in the pipe and thus reduced build-up of an insulating layer inhibiting heat transfer. The
543 behaviour of new materials for this application, but also the behaviour of the conventional
544 copper heat exchanger when used with heavily polluted wastewater such as that from
545 kitchens, requires long-term experimental studies. This will provide more reliable data on heat
546 transfer performance and on required maintenance interventions such as cleaning to remove
547 scaling or fouling. It will also allow more accurate determination of the useful lifetime of the
548 heat exchangers, which will be important for both economic and environmental performance.
549 The lack of accurate data sets and reliance on manufacturer data for modelling the PP-GR
550 material are aspects which should improve with increasing use of such materials.

551 **4 Conclusions**

552 The presented LCA study is the first to evaluate the environmental sustainability of a heat
553 recovery system for harvesting the heat of commercial kitchens' drain water, based on case
554 study data. Different sets of materials are studied for the system, comparing components from
555 conventional copper with alternatives from polypropylene and graphite, as well as
556 polyethylene. The results support the following conclusions:

- 557 • The environmental impacts from the copper system, predominantly arising from the
558 production of primary copper, can be reduced substantially through increasing the
559 share of recycled copper as input material.
- 560 • A critical factor influencing the material requirement and environmental footprint of any
561 retrofitted (or new) heat recovery system is the length of pipework necessary for
562 connecting the heat exchanger with boiler and cold water supply. We therefore
563 recommend to design the system as compact as possible.
- 564 • It is strongly encouraged to consider material choice during the design phase of such
565 installations, including the use of recycled material or new functional materials, such
566 as the polypropylene-graphite composite.
- 567 • Heat recovery shows environmental trade-offs with other water heating sources only
568 for flowrates at the lower end of the spectrum of typical water consumption rates in UK
569 food outlets, mainly for resource depletion.
- 570 • The amount of recovered heat and with it the environmental savings increase with the
571 water consumption rate, even when environmental capital costs are increased through
572 the installation of several heat exchangers in parallel. Environmental savings across
573 all seven impact categories analysed is achieved for water consumption above
574 555 L/day when replacing the heating energy mix.
- 575 • Heat recovery from wastewater from food outlets offer a potential solution for saving
576 energy and emissions across the food service sector. When applied across all UK food
577 outlets, GHG emission savings can amount 490 Gg CO₂ equivalent per year.

578
579

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584

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754

755 **Figure and Table Captions:**

756 *Figure 1: System boundaries of the LCAs on the heat recovery system (left, shown for the copper system) and*
757 *extended boundaries for evaluating the savings potential through the replacement of heat energy sources.*

758 *Figure 2: Environmental burdens arising from the life cycle of drain water heat recovery systems consisting of in-*
759 *line heat exchanger, 10 m pipework, fittings and insulations. Percentage in brackets stands for the share of*
760 *recycled copper. PE: polyethylene, PP-GR: Polypropylene-Graphite. GWP: Global Warming Potential; HTP:*
761 *Human Toxicity Potential; POFP: Photochemical Ozone Formation Potential; AP: Acidification Potential; FEP:*
762 *Freshwater Eutrophication Potential; FEToxP: Freshwater Ecotoxicity Potential; RDP: Mineral, fossil & renewable*
763 *Resource Depletion Potential. All scenarios as described in Table 1.*

764 *Figure 3: LCA of heat recovery systems (scenarios 2 and 5): Relative contribution of the life cycle stages to the*
765 *environmental impacts of the two heat recovery systems including 10 m pipework. Left: scenario 2: copper system*
766 *with 35% recycled copper input. Right: scenario 5: PP-GR composite system with PP-GR heat exchanger and*
767 *pipework from PE. GWP: Global Warming Potential; HTP: Human Toxicity Potential; POFP: Photochemical Ozone*
768 *Formation Potential; AP: Acidification Potential; FEP: Freshwater Eutrophication Potential; FEToxP: Freshwater*
769 *Ecotoxicity Potential; RDP: Mineral, fossil & renewable Resource Depletion Potential; Hex: Heat exchanger; EoL:*
770 *End of Life.*

771 *Figure 4: Comparison of LCA results for the heat exchanger and pipework for (clockwise from top left): global*
772 *warming potential (GWP), resource depletion potential (RDP), freshwater ecotoxicity potential (FEToxP) and*
773 *human toxicity potential (HTP). Left two bars: complete life cycle of a heat exchanger system without pipework.*
774 *Right three bars: life cycle of pipework from polyethylene (PE), steel and copper (35% recycled content).*

775 *Figure 5: Environmental impacts per kWh for water heating. Comparison of heat recovery from drain water with*
776 *other renewable and non-renewable heat sources, including the current UK energy mix for water heating ("mix").*
777 *Burdens of the heat recovery system as in scenario 4 with two different water flow-rates found in UK commercial*
778 *food outlets. H recov. Low: low impact case due to higher flow-rate of 12,500 L/day. H recov. High: high impact*
779 *case due to lower flowrate of 360 L/day. NG: natural gas, electricity: UK grid mix, wood: wood biomass*
780 *combustion, geo: geothermal, solar: solar thermal. GWP: Global Warming Potential; HTP: Human Toxicity*
781 *Potential; POFP: Photochemical Ozone Formation Potential; AP: Acidification Potential; FEP: Freshwater*
782 *Eutrophication Potential; FEToxP: Freshwater Ecotoxicity Potential; RDP: Mineral, fossil & renewable Resource*
783 *Depletion Potential*

784 *Figure 6: Normalised net environmental savings (positive values) through heat recovery from a commercial kitchen*
785 *after 10 years depending on the yearly water consumption. GWP: Global Warming Potential; HTP: Human Toxicity*
786 *Potential; POFP: Photochemical Ozone Formation Potential; AP: Acidification Potential; FEP: Freshwater*
787 *Eutrophication Potential; FEToxP: Freshwater Ecotoxicity Potential; RDP: Mineral, fossil & renewable Resource*
788 *Depletion Potential.*

789 *Table 1: Overview of assumptions for scenarios of the LCAs.*

790 *Table 2: Types of energy and respective database modules used for determination of environmental savings*
791 *through heat recovery*

792 *Table 3: Environmental payback times in years for the heat recovery system of the Penrhyn Castle case study.*
793 *Comparison of the copper (35% recycled content) and the PP-GR systems including 10 m of pipework with different*
794 *energy sources for water heating. Bold and italic: Impacts are not paid back within a 10-year lifetime. NG = natural*
795 *gas. Mix: Current UK Energy mix for heating water in the service sector (BEIS, 2018). GWP: Global Warming*
796 *Potential; HTP: Human Toxicity Potential; POFP: Photochemical Ozone Formation Potential; AP: Acidification*
797 *Potential; FEP: Freshwater Eutrophication Potential; FEToxP: Freshwater Ecotoxicity Potential; RDP: Mineral,*
798 *fossil & renewable Resource Depletion Potential. Energy sources as in Table 2.*

799 *Table 4: Yearly net environmental savings potential for the UK through heat recovery from wastewater in all*
800 *commercial food outlets. eq = equivalent*