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Environmental analysis of servicing centralised and decentralised wastewater treatment for population living in neighbourhoods

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Highlights:

Reclaimed water can achieve 100% tap water savings when used for irrigation.

Decentralized systems can reduce a resident's carbon footprint by 20-23%.

Capital costs are about 98% higher, but operational costs are reduced by 66-77% in decentralised systems.

Decentralised systems are cost-effective provided energy and reclaimed water are valorised.

Environmental analysis of servicing centralised and decentralised wastewater treatment for population living in neighbourhoods

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1 **Abstract**

2 The planning and construction of large-scale wastewater infrastructure, such as
3 sewerage networks and wastewater treatment plants, is undertaken by the public sector or by
4 publicly regulated monopolies. Only on smaller scales can infrastructure be managed by private
5 companies or through local collective initiatives. Within this framework of water cycle
6 management, there is an increasing movement of the population towards cities where economic
7 activity is concentrated. This scenario is particularly pronounced in certain regions of the world
8 and makes it necessary to rethink whether decentralised treatment offers a way of ensuring the
9 servicing of wastewater treatment in new urban developments, alleviating pressure on facilities
10 that are at the limit of their capacity.

11 In this study four systems were evaluated: two centralised and two decentralised
12 configurations, from an environmental and economic perspective, posing as working hypothesis
13 how different wastewater treatment schemes influence the carbon footprint of the population
14 living in a neighbourhood. The analysis of the results identifies that the decentralised systems
15 present a reduction in the carbon footprint of residents of around 20-23% depending on the
16 technology considered. In addition, reclaimed water can meet the water quality requirements
17 for irrigation of the green areas in the neighbourhood. Although decentralised systems have
18 higher construction costs, they can be amortised due to lower energy consumption, so the
19 payback time is estimated to be 8-9 years, lower than that of centralised systems. Considering
20 the problems associated with changing and replacing existing networks, decentralised
21 wastewater treatment systems is especially recommended for new dwelling developments,
22 based on its environmental and economic indicators.

23 **Keywords:** decentralised systems, economic approach, life cycle assessment (LCA), resident
24 carbon footprint, water reuse

25

26 **1. Introduction**

27 Since 1950 the urban population has grown exponentially (Steffen et al., 2015).
28 Currently, more than 55% of the world population lives in cities, and this figure is expected to
29 increase to 60% by 2030 (United Nations, 2018). This means that, from an economic perspective,
30 cities will concentrate more than 80% of the global GDP (World Bank, 2019), although their
31 occupation is only 3% of the world's land area (Wang et al., 2020). It is estimated that human
32 activities, such as transport, food and energy consumed at the households are responsible for
33 about 70% of greenhouse gas (GHG) emissions (Goldstein et al., 2013; González-García and Dias,
34 2019; Kennedy et al., 2009). Given that the population is concentrated in cities, it is necessary
35 to assess the strategies followed to reduce the environmental impacts of residents living in these
36 areas (Lahmouri et al., 2019).

37 In this regard, wastewater treatment plants (WWTPs) have focused on trying to reduce
38 their impact to become carbon neutral (Shen et al., 2015). Clearly, centralised and decentralised
39 options for wastewater treatment present large differences in the process scheme, the
40 equipment deployed and chemicals or energy requirements. Beyond these characteristics,
41 another difference between the two alternatives is attributed to the possibility of reusing
42 resources. While in centralised systems, resource recovery is hampered by the transport and
43 distribution of both streams, decentralised treatment offers the possibility of reusing reclaimed
44 water and biofertilisers in nearby green and agricultural areas (Samuel et al., 2016). While there
45 are indicators of environmental benefits associated with decentralised treatment, it is important
46 to quantify the environmental credits of this approach and its benchmarking with a conventional
47 centralised system.

48 There are several studies that report differences in GHG emissions associated with
49 centralised and decentralised systems using the life cycle assessment (LCA) methodology
50 (Kobayashi et al., 2020; Lahmouri et al., 2019). In this context, Kavvada et al. (2016) compared

51 the carbon footprints of a centralised process in which non-drinking water was obtained for
52 reuse, with a decentralised alternative. Similarly, Lahmouri et al. (2019) assessed a centralised
53 system used in Leh Town (India), and proposed decentralised alternatives to reduce GHG
54 emissions from water treatment. **Additionally, wastewater systems can be improved with the**
55 **addition of food waste. In this regard, Bartocci et al. (2020) reported a reduction of about 42%**
56 **in the carbon footprint when electricity is produced with food waste from food industries.**
57 Finally, LCA was also used to compare the environmental impacts of different types of treatment
58 in decentralised systems (Kobayashi et al., 2020). While the impacts associated with the
59 wastewater treatment facilities were evaluated, the environmental benefits that one system or
60 another has on the impacts of dwellers living in a neighbourhood.

61 For this reason, the main objective of this study is to analyse how conventional or
62 decentralised systems can reduce the total impact of a resident who chooses to live in a building
63 or residential area with centralised or decentralised treatment. The first centralised option is
64 the real case in this city, whereas the other configurations were analysed based on plant-wide
65 simulations. The second option considers a modification of the existing centralised scheme, but
66 with the incorporation of an anaerobic digestion (AD) unit for biogas recovery. The decentralised
67 configurations considered in this study consider the segregation of black and grey water and the
68 use of two types of toilets: conventional or vacuum toilets. Both configurations consist of an up-
69 flow anaerobic sludge blanket unit (UASB) for energy recovery and an aerobic membrane SBR
70 for the treatment of grey water. Not only the environmental but also the economic indicators
71 of the different alternatives will be evaluated, which will make it possible to rank the different
72 options under a combined sustainability perspective.

73 **2. Materials and methods**

74

75 **2.1. Methodology**

76 In this study, the LCA methodology, which can be defined as the evaluation of a product
77 or process during its life cycle, was applied to calculate the environmental impacts. This
78 methodology consists of four main steps: i) goal and scope definition; ii) inventory data (LCI); iii)
79 life cycle impact assessment (LCIA), and finally, iv) interpretation of the results (ISO 14044,
80 2006/AMD 1:2017). These steps will be explained later to understand how the LCA methodology
81 was applied to this case study.

82 **2.2. Goal and scope**

83 The main objective of this study is to benchmark the environmental and economic
84 profiles of a resident living in a neighbourhood with centralised or decentralised wastewater
85 treatment systems according to four different schemes (Figures 1 and 2). The centralised
86 scheme (actual scheme in Santiago de Compostela) consists of a WWTP designed for 220,000
87 equivalent inhabitants with a flow of 75,000 m³/d. The WWTP consists of a pre-treatment unit
88 followed by a coagulation and flocculation process and an activated sludge (AS) process. The
89 treated wastewater is discharged into the aquatic environment. The sludge line consists of a
90 thickening unit and a dewatering unit, prior to composting to be applied as a biofertiliser in
91 agriculture (Scenario 1). In the real scenario, there is no AD unit. A modification including the AD
92 unit in the sludge line and a cogeneration power and heat (CPH) unit for bioenergy production
93 corresponds to Scenario 2.

94 Two decentralised schemes with segregation of streams: black and grey wastewater
95 were designed to treat a flow of about 800 m³/d for 7120 inhabitants. The black wastewater
96 (BW) is treated in an up-flow anaerobic sludge blanket (UASB) unit followed to a membrane
97 bioreactor (MBR). The grey wastewater (GW) is treated in a sequencing batch reactor (SBR).
98 Reclaimed water is used for irrigation. In the UASB, a CPH will transform the biogas into
99 electricity and heat. While electricity will be used in the houses, heat will be used to keep the
100 UASB unit at 35 °C. In case of heat excess, it will be used in the houses. The main difference
101 between the two decentralised systems are the type of toilets: conventional toilets in Scenario

102 3 and vacuum toilets in Scenario 4. Vacuum toilets consume less water and this implies a higher
103 concentration of organic matter to increase the biogas yield (Kujawa-Roeleveld et al., 2006).

104 To apply the LCA methodology, a gate-to-gate perspective is selected. The different
105 wastewater treatment schemes are only compared in terms of operational phase because
106 construction and decommissioning can be considered negligible (Lundin et al., 2000). Therefore,
107 the system boundaries are shown in Figures 1 and 2. The functional unit (FU) that allows to
108 quantify the main inputs and outputs to the different wastewater treatment schemes (ISO
109 14040, 2006) was selected as 1 resident living in the neighbourhood served by centralised or
110 decentralised treatment. The resident is equivalent to 0.125 m³ generated per day, which
111 corresponds to the amount of wastewater generated by one person in one day (Wan et al.,
112 2016).

113 >Figure 1<

114 >Figure 2<

115 **2.3. Life cycle inventory (LCI)**

116 In the LCA methodology, the inventory is the critical and time-consuming step (ISO
117 14044, 2006/AMD 1:2017). In this case, the inventories were made with primary (real data) and
118 secondary data (calculated data or bibliographic data), reported in Tables 1 and 2. The primary
119 data correspond with the real data which are associated with the centralised case. The
120 characteristics of the wastewater, the amount of sludge generated and the consumption of
121 chemicals were obtained from an internal report (PRTR, 2017). Moreover, electricity
122 consumption and biogas production (Scenario 2) were obtained using estimated data. In the
123 decentralised cases, the data were obtained by means of bibliographic information and plant-
124 wide simulation through **modelling software such as Matlab or BioWin (EnviroSim Associated**
125 **Ltd., Canada)**. However, in this case, these methods were not used to perform the analysis. BW,
126 GW, biogas transformation or energy consumption correspond to bibliographical data (Komesli

127 et al., 2007; Zang et al., 2015; Zeeman et al., 2008). Therefore, the inventories were completed
128 with the Ecoinvent 3.5 database (Wernet et al., 2016). Finally, several simplifications were made
129 for background data.

130 Electricity: Spanish electricity country mix was updated for the year 2018 with the data
131 from the annual report (REE, 2018). As regards the consumption of chemical products,
132 polyelectrolyte was implemented as cationic resin taking into account the Ecoinvent 3.5
133 database (Wernet et al., 2016). Biogas composition was considered such as 75% CH₄, 33% CO₂
134 and 1% H₂S (Kujawa-Roeleveld et al., 2006). Finally, the composting emissions to air (CH₄, CO₂,
135 N₂O and NH₃) were estimated through bibliographic data (Boldrin et al., 2009).

136 >Table 1<

137 >Table 2<

138 **2.4. Environmental and economic indicators**

139 The inventory data was implemented in the SimaPro 9.0 software to obtain the most
140 representative impacts to the different configurations. In this case, the most representative
141 categories are climate change (CC) due to electricity production and consumption that can affect
142 the reduction or increase of the resident carbon footprint. The other relevant category in this
143 study is water consumption (WC). As mentioned above, water is used for irrigation. In the
144 centralised case, this water comes from the tap water network, so this tap water has
145 environmental impacts, while in the decentralised case, this water comes from the WWTP.
146 Therefore, it is important to know how this change affects the environmental impacts associated
147 with the residents living in this neighbourhood. These two impact categories were calculated
148 using the ReCiPe midpoint (H) method (Huijbregts et al., 2017). **Moreover, an uncertainty**
149 **analysis was performed for the CC category. The Monte Carlo method was applied with 5,000**
150 **iterations and a significance level of 95%.** Operational and capital costs were calculated as
151 economic indicators. Operating costs were associated with sludge management and chemical

152 and energy consumption, while capital costs considered only the construction of the unit and
153 incorporated into the total value of the WWTP.

154 **3. Results and discussion**

155 **3.1. Carbon footprint for each resident according to the different wastewater scheme**

156 Environmental impacts were only assessed for the CC and WC categories. In this first
157 section, environmental impacts will be studied for CC. For this reason, it is important to know
158 how much energy and water is consumed by the resident in each house. In Spain, energy and
159 heat that is consumed per inhabitant is about 1.581 kWh and 425 kWh in a year (IGE, 2016). The
160 biogas produced in the anaerobic digestion units can be used to supply energy and heat to the
161 houses. In this way, the reduction of the carbon footprint per resident can be estimated.

162 The results of the resident's carbon footprint, depending on the wastewater treatment
163 configuration (centralised or decentralised) are shown in Figure 3. The worst values in terms of
164 heat and electricity are presented for Scenario 1 (centralised case) because there is no AD unit;
165 therefore, there is no generation of these products. Furthermore, when the AD unit is
166 incorporated into the centralised system, the carbon footprint can only be reduced by about 4%
167 in terms of heat and energy. Decentralised cases show better results in reducing the carbon
168 footprint because the production of energy and heat is higher than in centralised systems. The
169 best case is when vacuum toilets are incorporated (Scenario 4) and the reduction is 23% for
170 electricity consumption and 66% for heat production. In Scenario 3 (conventional toilets), the
171 increase is also significant, about 20% for energy and 54% for heat. Thus, these decentralised
172 systems help to decrease the carbon footprint of a resident living in a decentralised wastewater
173 treatment system.

174 **>Figure 3<**

175 In the context of reducing the carbon footprint, it is also important to study the
176 environmental impacts in the CC category for each wastewater treatment scheme. The different
177 wastewater treatment schemes were compared and, in addition, the main impacts for each

178 scheme were analysed. As in the previous analysis, the centralised cases are the worst options
179 because there is no electricity production (Figure 4a). In addition, in terms of CC impacts,
180 Scenario 3 (conventional toilets) is the best scenario, even better than Scenario 4 (vacuum
181 toilets). Energy production is higher in Scenario 4 (about 16% than in Scenario 3), however, the
182 energy consumption of the vacuum toilets implies undesirable impacts. Although, the energy
183 consumption is higher than in Scenario 4, the impacts are better than in the conventional
184 systems.

185 If the subsystems of each system in this category are studied, the main impact is the
186 thickening + homogenisation followed by the CAS unit in centralised systems. In the first unit,
187 the impact is associated with the consumption of polyelectrolyte to ensure good sludge
188 dewatering, while in the CAS unit, the negative effect is related to the consumption of energy
189 for aeration. Moreover, the AD incorporation in Scenario 2 does not represent a significant
190 increase in the impact. In decentralised systems, MBR followed by the SBR represent the worst
191 environmental profile due to energy consumption associated with these units. In addition, the
192 vacuum toilets also have a negative effect of about 10% of the total impact. However, electricity
193 production minimises the total impact of these systems with environmental credits of around
194 50% in both systems (Figure 4b).

195 **>Figure 4<**

196 **3.2. Water consumption and reduction for the different wastewater treatment schemes**

197 In this section, the reduction in the water consumption was evaluated according to the
198 different wastewater treatment configurations. In the city of Santiago de Compostela, the water
199 spent on irrigation is 11.10 m³/inhabitant·year (IGE, 2016). Thus, as in the CC category, the water
200 necessary for irrigation was compared among the different wastewater configurations per
201 inhabitant, in addition, the WC category and the sub-systems affecting to this category were
202 analysed and compared.

203 The total water used in irrigation in this city is 6663 m³/d. This number includes the
204 irrigation of parks, green areas and the provision of water for the fire stations. The
205 neighbourhood studied requires 216 m³/d of irrigation water. In both centralised systems, this
206 number does not decrease because the water in these systems is discharged into the
207 environment. However, in the decentralised cases, water is reused for irrigation. The
208 wastewater generated in Scenario 3 (conventional toilets) is about 788 m³/d because these
209 toilets consume more water than vacuum toilets. In the case of vacuum toilets, the wastewater
210 flow is about 633 m³/d (Scenario 4), which would mean that the reclaimed water would cover
211 the needs for irrigation in both cases. Therefore, the environmental impacts of tap water
212 treatment would be avoided. For the irrigation of green areas only 216 m³/d of water is required,
213 this means that there is an excess of water of about 572 m³/d (conventional toilets) and 418
214 m³/d (vacuum toilets).

215 Thus, in the case of decentralised systems, it is not necessary to purify the tap water for
216 irrigation, which means that only the impacts of the irrigation process itself will be considered.
217 However, in centralised cases there is no water recovery, so in Scenarios 1 and 2 the impacts of
218 irrigation are associated with the treatment of drinking water.

219 If the irrigation process is analysed for the different scenarios, the environmental results
220 for the WC category show that in the case of centralised systems the impact values are 0.12 m³
221 of water per resident, while for centralised cases the negative effect is about 3.03·10⁻³ m³ of
222 water per resident. These results show an improvement of around 99% in the environmental
223 profile because the production and distribution of tap water that is caused by the centralised
224 systems involves large environmental impacts.

225 Figure 5 shows the main results for the WC category for each wastewater treatment
226 scheme considered. In addition, the subsystems that contribute to these impacts are studied.
227 As in the CC category, the best environmental results (including environmental credits)
228 correspond to the decentralised schemes due to energy and water recovery. The conventional

229 toilet scenario (Scenario 3) have a better environmental profile because there is less energy
230 consumption and the energy consumption related to hydropower plants indirectly affects this
231 category. For this reason, the conventional case with an AD unit has a better profile than the
232 conventional case, although the impacts are very similar (2% reduction compared to Scenario
233 1). The main impact of the centralised systems occurs in the thickening + homogenisation unit
234 and is caused by the consumption of polyelectrolyte. As in the CC category, in decentralised
235 systems, the negative effect is associated with the MBR unit followed by the SBR unit. This is
236 due to the high energy of these units compared to the others included in the wastewater
237 scheme. The main reason for these impacts is the indirect emissions associated with
238 hydropower production. In Spain, this energy represents around 15% of the total energy country
239 mix (REE, 2018) (Figure 5).

240 **>Figure 5<**

241 **3.3. Economic results of the different wastewater treatment schemes**

242 In this section, capital and operating costs were calculated for all the wastewater
243 configurations evaluated. The results are shown in Table 3 (FU: 1 resident). In this case,
244 decentralised systems have higher capital costs than centralized systems because the units are
245 more complex. Capital costs can increase by about 98% in these new configurations. In addition,
246 if benefits are not considered in wastewater treatment plans, decentralised systems also have
247 more economic costs. The increase is about 77% for conventional toilets and 82% for vacuum
248 toilets. However, when the benefits of decentralised systems are taken into account, the trend
249 changes. The costs in Scenarios 3 and 4 can decrease by about 67% of total operational costs
250 compared to centralised systems. In addition, if operating and construction costs are linked,
251 decentralised systems are better from an economic point of view. Total costs can be reduced by
252 27% for Scenario 3 and 21% for Scenario 4.

253 Finally, if centralised systems are compared from an economic point of view, operating
254 and construction costs can be reduced by 1%. Thus, a priori, the incorporation of the AD unit
255 can be an advantage, however, the energy production in this unit should be improved.

256 Within this framework, the payback time must be calculated to obtain the different
257 values according to the different wastewater treatment configurations. To obtain this value,
258 Equation [1] was applied to the wastewater schemes.

$$\text{Payback time} = \frac{Ms \times Cd + \Delta E \times Ce + C}{\text{Investment cost}} \quad [1]$$

259 Where **Ms** is the sludge production (ton/year); **Cd** is the sludge management cost
260 (€/ton); **ΔE** represents the relation between energy production and energy consumption in the
261 plant (kWh/year); **Ce** means the electricity costs (€/kWh), **C**: cost of maintenance of the plant
262 (€/year), and, finally, **investment costs** are the total capital costs of the plant.

263 The values of the different configurations are presented in Table 3. The worst result is
264 shown for the conventional case without an AD unit (Scenario 1), the payback time is about 13
265 years followed by Scenario 2 (conventional case with an AD unit). It is true that the time if the
266 AD unit is incorporated can be reduced by 5 years. Decentralised plants, although they have
267 higher investment costs, electricity production is higher, and the payback time is shorter than in
268 centralised cases. In Scenario 3 (conventional toilets), the time is about 5 years, while in Scenario
269 4 (vacuum toilets) it is 4 years.

270 >Table 3<

271

272 **3.4. Sensitivity and uncertainty analysis**

273 In the previous section, the advantages of electricity recovery in decentralised systems
274 were demonstrated. In this framework, it is important to think about what would happen if
275 electricity was not recovered in decentralised systems. Would it make sense to implement these
276 systems? For this analysis, two scenarios were considered: (i) a comparison between centralised

277 and decentralised systems with energy recovery (the case studied in this manuscript) and (ii) a
278 comparison between centralised and decentralised systems without energy recovery. The most
279 affected category in terms of energy is CC category (Stocker et al., 2013). For this reason, only
280 the CC category will be analysed.

281 In addition, to complete this sensitivity analysis, the uncertainty of the data was
282 evaluated (Figure 6). The results of Scenario 1 are the same, because this system has no energy
283 recovery. Although the level of uncertainty may seem high, it is less than 30%, so the results can
284 be considered representative. In the case of Scenario 2, the profile may increase by 5% for this
285 category. For decentralised cases, the increase can be around 99% if energy is not recovered. In
286 addition, when energy is considered, the results have more uncertainty due to the electrical
287 process that incorporates more uncertainty into the data. However, the variation coefficient is
288 lower than 30% for all scenarios, which is indicative of the validity of the data considered. It is
289 interesting to note that if there is no energy recovery, the decentralized cases have very similar
290 impact values to those of the centralized system, even higher for Scenario 4 (vacuum toilets).
291 Therefore, if there is no recovery of energy or water in the decentralized systems, their
292 application will not be appropriate to treat wastewater because the environmental impacts will
293 be higher.

294 >Figure 6<

295 **3.5. Broadening the scope in centralised and decentralised systems to include sewer** 296 **network**

297 As mentioned above, in terms of investment costs, decentralised systems have
298 disadvantages compared to centralised systems. In general, these systems can be more complex
299 due to the construction of the membrane or the aeration equipment. However, centralised
300 systems are more robust and less adaptable to recovering products such as water or nutrients.
301 In addition, decentralised systems are characterised by a lower sewage network compared to

302 centralised systems (Opher and Friedler, 2016). It is estimated that the sewer network has an
303 have a significant contribution to the overall impact of construction of WWTPs (Petit-Boix et al.,
304 2014). Thus, in this case, it was evaluated how the sewerage network affects the environmental
305 profile.

306 In the city of Santiago de Compostela, the extension of sewage network is 647 km, which
307 implies an amount of 5 m/inhabitant. In decentralised systems, this figure is estimated to be
308 about 3.7 m/inhabitant (Kjerstadius et al., 2017). If the environmental profiles are compared, as
309 expected, the centralised system (601 kg CO_{2eq}/resident) has a 99% higher amount than the
310 decentralised systems (4.71 kg CO_{2eq}/resident). These impacts are related to the production of
311 concrete for trenching and pipe material but not only these factors are important, there are
312 taken into account the capacity of the sewer network. The sewer network in Santiago de
313 Compostela has a higher capacity because there is no separation network (wastewater and
314 rainwater), therefore, the capacity of the sewerage has to be high because in this city the rainfall
315 is high. On the contrary, in the decentralised system, although there are two pipes (one for BW
316 and another for GW), the capacity is reduced by 97%. This implies less environmental impacts
317 related to the construction of the pipelines, ditches or even direct emissions related to the
318 construction.

319 It is true that the introduction of a separate network in Santiago is very difficult due to
320 the protection of its old town, so changing the sewage network is not a viable option, but
321 decentralised systems of wastewater and sewage can be a good alternative in new
322 neighbourhoods and can improve the environmental profile of these networks not only in the
323 CC category but in all categories, making the resident have less consumption of carbon and
324 water in terms of irrigation than residents who choose another type of neighbourhood.

325 4. Conclusions

326 In this study, the carbon and water consumption for irrigation of a resident living in a
327 centralised wastewater district was compared to that of a resident who chooses to live in a
328 decentralised wastewater district. The study was carried out in the city of Santiago de
329 Compostela. In this framework, two centralised configurations ((i) conventional system without
330 AD ii) a conventional system with the incorporation of the AD unit) were compared with
331 decentralised options: one with conventional toilets and another with vacuum toilets. The
332 decentralised options show a reduction of the resident carbon footprint by 20-23% due to
333 electricity production. Furthermore, with the reclaimed water, these systems are able to supply
334 water for irrigation of green areas, so no extra consumption of tap water is required. Although
335 these new systems present more construction costs and are more complex, the recovery time
336 is less than in conventional systems due to the recovery of products such as energy or water.
337 However, the incorporation of these systems is not easier due to the robustness of conventional
338 systems. Thus, the option of decentralised cases can be an optimal solution for new buildings or
339 residential areas.

340

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Figure Captions

Figure 1. System boundaries for a neighbourhood with a centralized wastewater treatment system. Acronyms: Scenario 1: without AD unit in the sludge line; Scenario 2: with AD and CPH units in the sludge line.

Figure 2. System boundaries for a neighbourhood with a decentralized wastewater treatment system. Acronyms: Scenario 3: conventional toilets; Scenario 4: vacuum toilets.

Figure 3. Carbon footprint in terms of energy and heat for a resident that lives in a centralized or decentralized wastewater scheme. Acronyms: Scenario 1: conventional system; Scenario 2: conventional system with AD unit; Scenario 3: decentralized system with conventional toilets; Scenario 4: decentralized system with vacuum toilets.

Figure 4. Environmental impacts in CC category for each resident and environmental impacts for each sub-system that conforms the different wastewater treatment schemes. Acronyms: Scenario 1: conventional system; Scenario 2: conventional system with AD unit; Scenario 3: decentralized system with conventional toilets; Scenario 4: decentralized system with vacuum toilets.

Figure 5. Environmental impacts in WC category for each resident and environmental impacts for each sub-system that conforms the different wastewater treatment schemes. Acronyms: Scenario 1: conventional system; Scenario 2: conventional system with AD unit; Scenario 3: decentralized system with conventional toilets; Scenario 4: decentralized system with vacuum toilets.

Figure 6. Climate change profile for the different wastewater treatment configurations (FU: 1 resident). O without energy recovery; Δ with energy recovery. Acronyms: Scenario 1: conventional system; Scenario 2: conventional system with AD unit; Scenario 3: decentralized system with conventional toilets; Scenario 4: decentralized system with vacuum toilets.

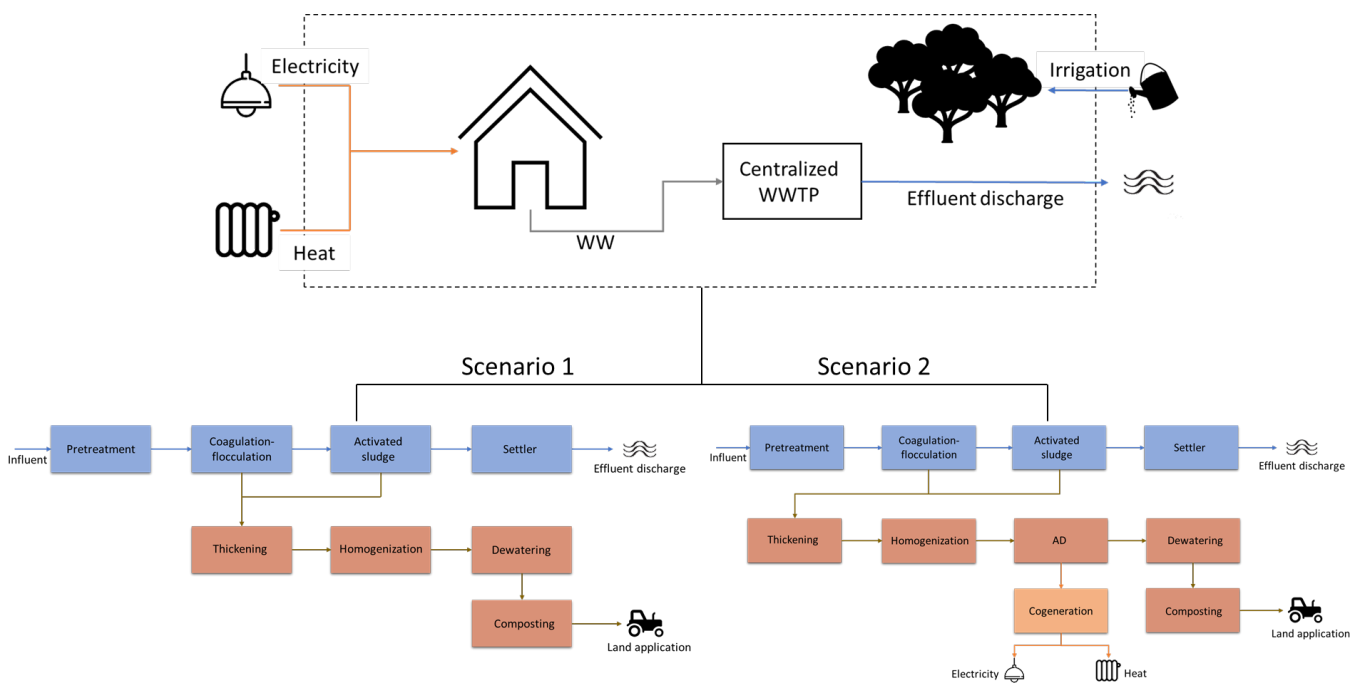


Figure 1

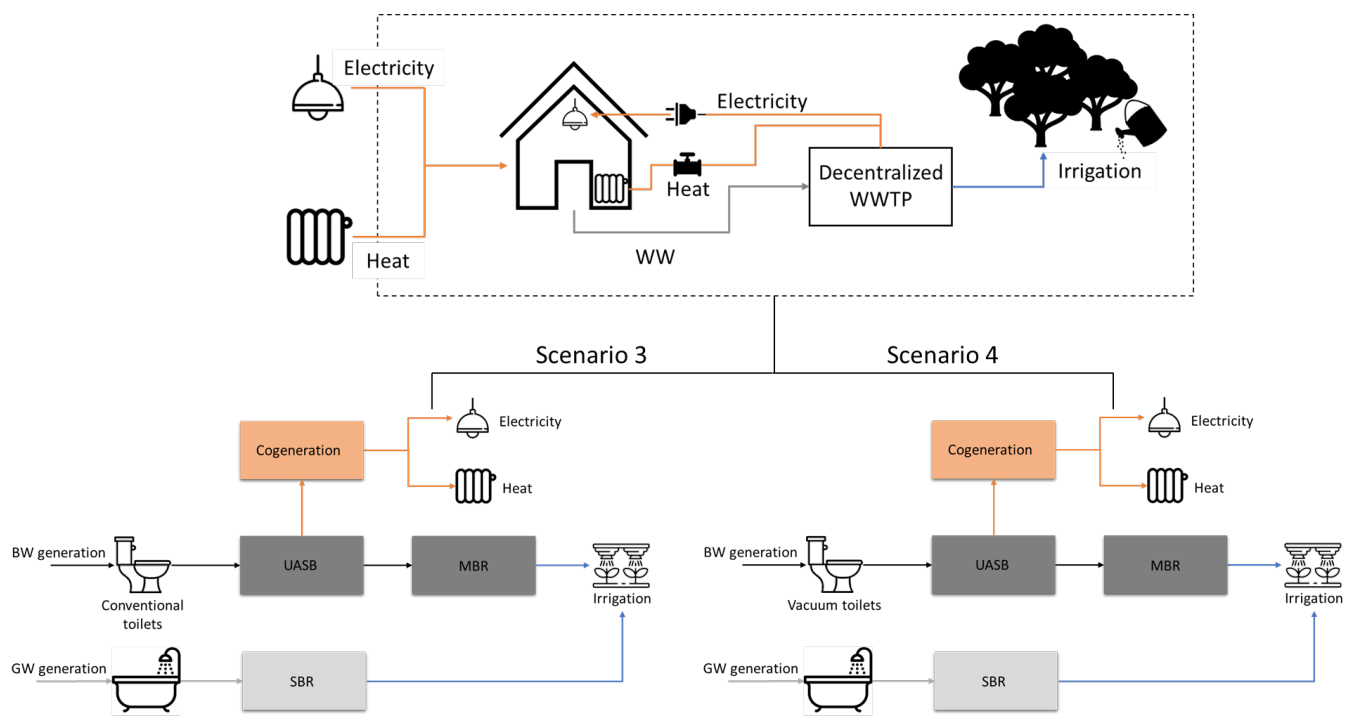


Figure 2

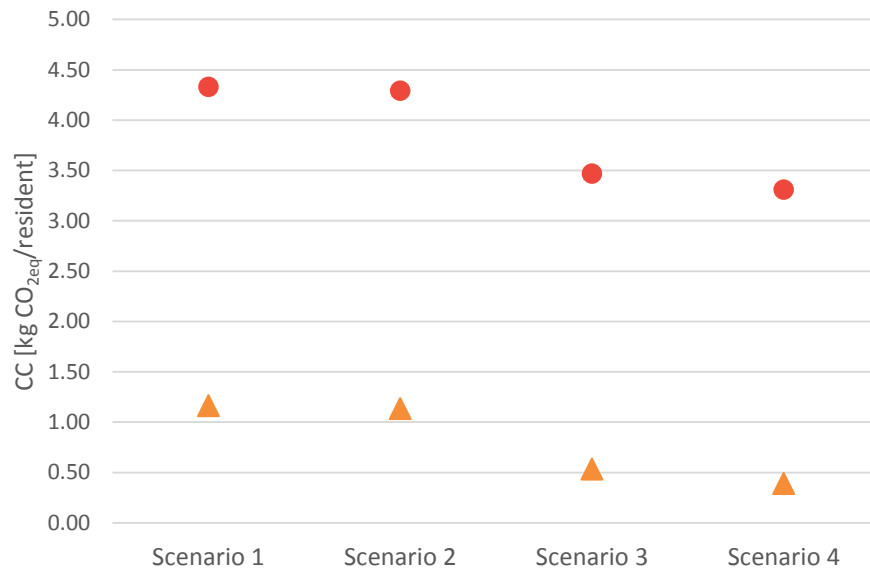


Figure 3

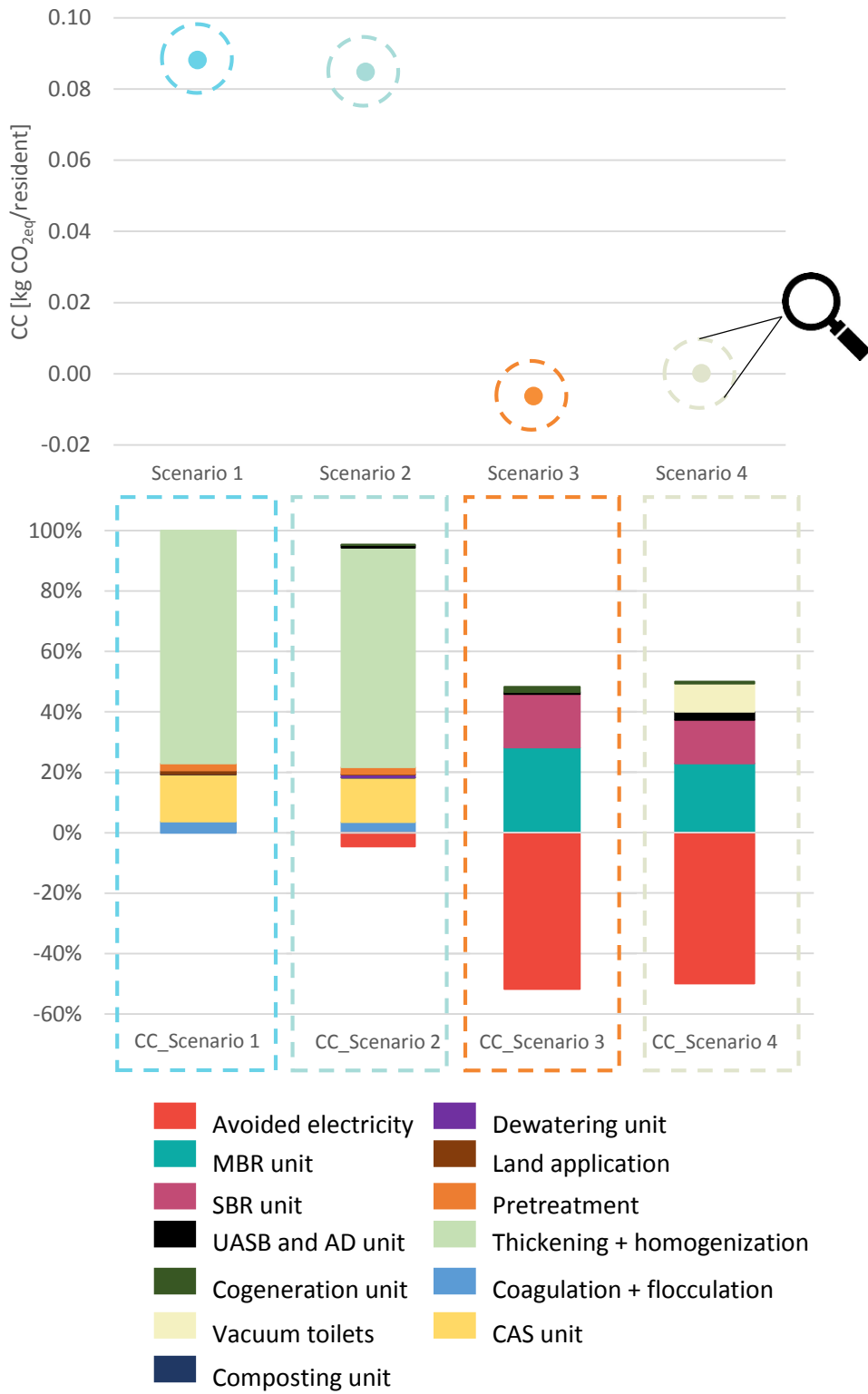


Figure 4

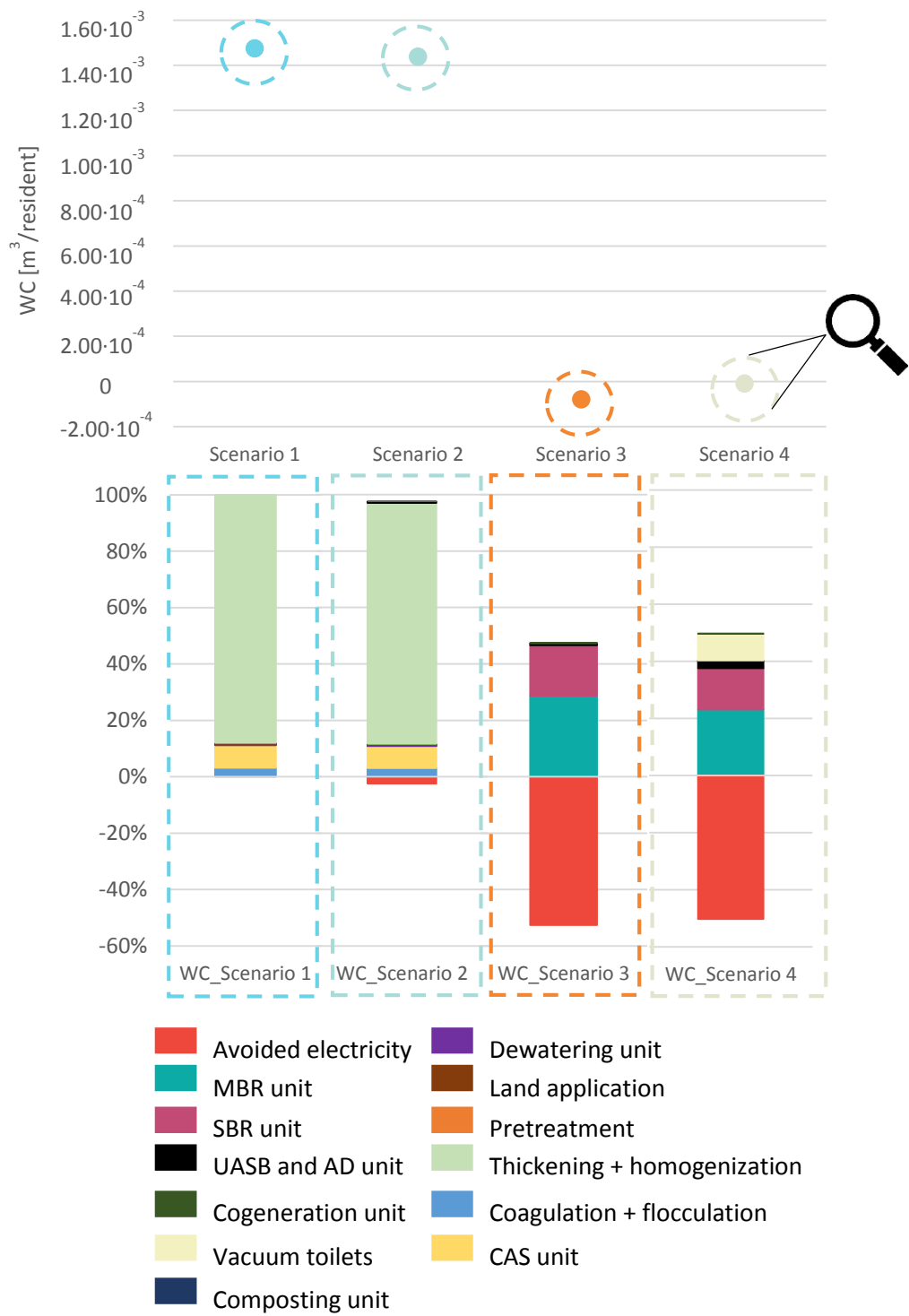


Figure 5

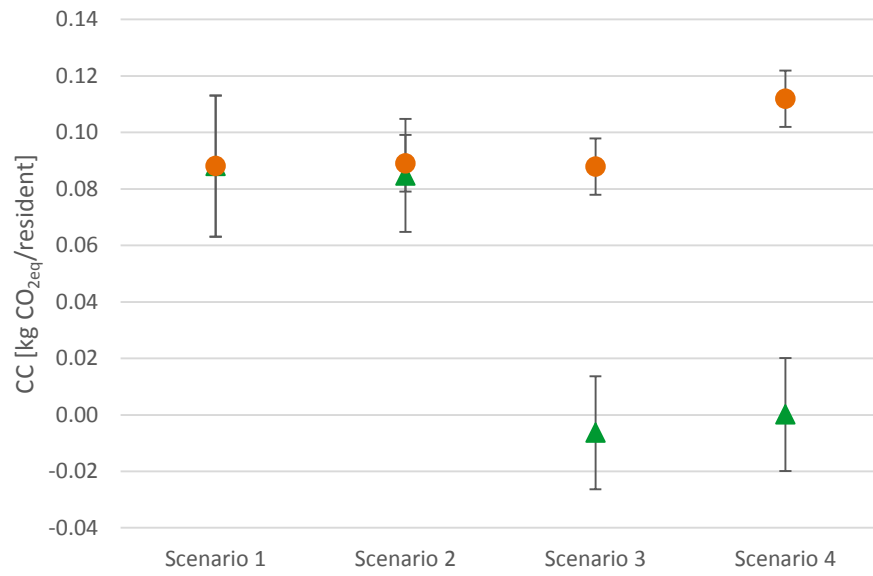


Figure 6

Table 1. Main inputs to the different scenarios considered in this study. FU: 1 resident

		SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
Inputs from the technosphere					
Materials and fuel					
Influent					
COD (g)	BW (g)	42.35	42.35	101.3	101.3
	GW (g)			53.13	53.13
TN (g)	BW (g)	1.31	1.31	175	175
	GW (g)			2.15	2.15
TP (g)	BW (g)	0.51	0.51	21.87	21.87
	GW (g)			0.72	0.72
Electricity consumption					
Pre-treatment (kWh)		$1.57 \cdot 10^{-3}$	$1.57 \cdot 10^{-3}$	-	-
Coagulation-flocculation (kWh)		$5.15 \cdot 10^{-3}$	$5.15 \cdot 10^{-3}$	-	-
CAS (kWh)		$4.03 \cdot 10^{-2}$	$4.03 \cdot 10^{-2}$	-	-
Thickening + homogenization (kWh)		$2.27 \cdot 10^{-4}$	$2.27 \cdot 10^{-4}$	-	-
AD (kWh)		-	$2.91 \cdot 10^{-3}$	-	-
Dewatering (kWh)		$2.27 \cdot 10^{-3}$	$2.27 \cdot 10^{-3}$	-	-
Composting (kWh)		$2.40 \cdot 10^{-4}$	$2.40 \cdot 10^{-4}$	-	-
Toilets (kWh)		-	-	-	0.06
UASB (kWh)		-	-	$3.76 \cdot 10^{-3}$	0.01
MBR (kWh)		-	-	0.15	0.15
SBR (kWh)		-	-	0.10	0.10
Chemical consumption					
Coagulation-flocculation					
FeCl ₃ (kg)		$1.93 \cdot 10^{-3}$	$1.93 \cdot 10^{-3}$	-	-
Thickening + homogenization					
Polyelectrolyte (kg)		$4.51 \cdot 10^{-2}$	$4.51 \cdot 10^{-2}$	-	-
Transport					
FeCl ₃ (kg·km)		0.05	0.05	-	-
Polyelectrolyte (kg·km)		1.13	1.13	-	-
Sludge (kg·km)		0.96	0.96	-	-
Spreading (kg)		0.04	0.04	-	-

Table 2. Main outputs to the different scenarios considered in this study. FU: 1 resident

	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
Outputs to the environment				
Emissions to air				
<i>AD unit</i>				
CH ₄ (kg)	-	4.67·10 ⁻⁴	1.06·10 ⁻²	1.26·10 ⁻²
CO ₂ (kg)	-	5.48·10 ⁻⁴	1.05·10 ⁻²	1.25·10 ⁻²
H ₂ S (kg)	-	9.67·10 ⁻⁶	2.20·10 ⁻⁴	2.60·10 ⁻⁴
<i>Composting unit</i>				
CH ₄ (mg)	4.68·10 ⁻⁴	4.68·10 ⁻⁴	-	-
CO ₂ (mg)	0.13	0.13	-	-
N ₂ O (mg)	2.25·10 ⁻⁴	2.25·10 ⁻⁴	-	-
NH ₃ (mg)	1.87·10 ⁻²	1.87·10 ⁻²	-	-
<i>Land application</i>				
N ₂ O (kg)	1.33·10 ⁻³	1.33·10 ⁻³	-	-
NH ₃ (kg)	1.09·10 ⁻³	1.09·10 ⁻³	-	-
Emissions to water				
NO ₃ ⁻ (kg)	0.02	0.02	-	-
PO ₄ ⁻³ (kg)	1.72·10 ⁻³	1.72·10 ⁻³	-	-
Outputs to the technosphere				
<i>Cogeneration unit</i>				
Electricity production (kWh)	-	0.01	0.28	0.33
Heat production (kWh)	-	0.01	0.25	0.29
Water for irrigation (m ³)	-	-	98.55	79.16

Table 3. Operational and construction costs for the different wastewater schemes considered (FU: 1 resident).

	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
Operational costs (€)				
<i>Electricity consumption</i>				
Pre-treatment	$1.88 \cdot 10^{-4}$	$1.88 \cdot 10^{-4}$	-	-
Coagulation-flocculation	$6.18 \cdot 10^{-4}$	$6.18 \cdot 10^{-4}$	-	-
CAS unit	$4.84 \cdot 10^{-4}$	$4.84 \cdot 10^{-4}$	-	-
Thickening + homogenization	$2.73 \cdot 10^{-5}$	$2.73 \cdot 10^{-5}$	-	-
AD unit	-	$3.49 \cdot 10^{-4}$	-	-
Dewatering	$2.72 \cdot 10^{-4}$	$2.72 \cdot 10^{-4}$	-	-
Composting	$2.76 \cdot 10^{-5}$	$2.76 \cdot 10^{-5}$	-	-
Toilets	-	-	-	$7.39 \cdot 10^{-3}$
UASB	-	-	$4.51 \cdot 10^{-4}$	$2.11 \cdot 10^{-3}$
MBR	-	-	0.02	0.02
SBR	-	-	0.01	0.01
<i>Cogeneration unit</i>				
Lubricant oil	-	$1.98 \cdot 10^{-4}$	0.10	0.12
<i>Chemical consumption</i>				
FeCl ₃	$1.23 \cdot 10^{-7}$	$1.23 \cdot 10^{-7}$	-	-
Polyelectrolyte	0.08	0.08	-	-
<i>Sludge management</i>				
Sludge	0.03	0.03	-	-
<i>Avoided electricity</i>				
Electricity	-	$1.46 \cdot 10^{-3}$	0.10	0.12
TOTAL OPEX (€)	0.10	0.09	0.03	0.04
Construction costs (€)				
Pre-treatment	$9.18 \cdot 10^{-5}$	$9.18 \cdot 10^{-5}$	-	-
Coagulation-flocculation	$9.18 \cdot 10^{-5}$	$9.18 \cdot 10^{-5}$	-	-
CAS unit	$8.17 \cdot 10^{-5}$	$8.17 \cdot 10^{-5}$	-	-
Thickening + homogenization	$6.80 \cdot 10^{-5}$	$6.80 \cdot 10^{-5}$	-	-
AD unit	-	$7.40 \cdot 10^{-5}$	-	-
Dewatering	$4.81 \cdot 10^{-5}$	$4.81 \cdot 10^{-5}$	-	-
Composting	$7.08 \cdot 10^{-5}$	$7.08 \cdot 10^{-5}$	-	-
Cogeneration	$7.10 \cdot 10^{-5}$	$7.10 \cdot 10^{-5}$	0.01	0.01
UASB	-	-	$2.30 \cdot 10^{-3}$	$2.30 \cdot 10^{-3}$
MBR	-	-	0.01	0.01
SBR	-	-	0.01	0.01
TOTAL CAPEX (€)	$4.53 \cdot 10^{-4}$	$5.98 \cdot 10^{-4}$	0.04	0.04
TOTAL COST (€)	0.10	0.09	0.06	0.07
Payback time (y)	13	8	5	4