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Energy saving from small-sized urban contexts: integrated application into the domestic water cycle

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13 Abstract

14 A novel approach is investigated, based on an integrated solution aiming at exploiting the energy 15 harvestable from both drinking water reaching a municipality (or district) and wastewater flowing 16 out from households. Global costs are also analyzed under several macroeconomic scenarios. A first 17 experimental set was carried out using a supply system, where the mechanical power was generated 18 using a pump as turbine (PAT). The biogas production, especially from black water discharged in a 19 separated sewage system, was analyzed during a second set, to evaluate the anaerobic valorization 20 of carbon sources. Several scenarios were built for small-scale urban applications, varying 21 parameters like population and macroeconomic conditions. The produced energy changes among 22 the scenarios: the PAT is optimized when hydraulic regulation is used, while the anaerobic digestion 23 is optimized for decentralized system coupled to toilet operation without urine separation. 24 Differences in energy production and costs exist between the analyzed technologies, the PAT 25 requiring small investments for a small production, the anaerobic digestion requiring high costs for 26 a large production. Hence, the application to urban contexts depends on the local means/needs and 27 the size of the exploitable territory. The work also draws a potential methodology for urban planning 28 in developing or developed countries.

29 Keywords: pump as turbine; biogas production; energy recovery; life-cycle costing

30

31 Nomenclature

- 32 BMP: Biochemical Methane Potential
- 33 BW: Black Water

- 34 CAPEX: CAPital EXpenditure
- 35 CP: Calculation Period
- 36 DWBT: Domestic Water-Based Technology

- 37 FF: Feces+Flushing water (urine diverting 73 Edw: electrical energy production from 38 toilet) 74 drinking water 39 FU: Feces+Urine (dry toilet without urine 75 *E_{ww}*: net energy production from wastewater 40 separation) 76 source 41 GC: Global Cost 77 Effheat: fraction of heat available after losses 42 GDP: Gross Domestic Product 78 from vessel and heat exchanger 43 GHG: Greenhouse Gas 79 H: total head 80 KqCOD_{fed}: amount of the COD which was 44 GLS: Gas-Liquid-Solid 81 inserted in the batch volume at the beginning 45 HR: hydraulic regulation 46 HRT: Hydraulic Retention Time 82 of the test 47 KW: Kitchen Waste 83 M: braking force 48 LCC: Life Cycle Costing 84 n: number of served inhabitants 49 O&M: Operation and Maintenance 85 N: rotation speed 50 OLR: Organic Loading Rate 86 *P_H*: hydraulic power 51 OPEX: Operative Costs 87 *P_M*: mechanical power 52 PAT: Pump As Turbine 88 *P_{M,mean}*: daily mean mechanical power 53 PLC: Programmable Logic Controller 89 $P_{M,max}$: daily maximum mechanical power 54 PRV: Pressure Reducing Valves 90 Q: flow rate 55 RES: Renewable Energy Source 91 Q(t): hourly average flow rate 56 SSP: single-serial-parallel 92 Q_{ww}: influent wastewater 57 UASB: Upflow Anaerobic Sludge Blanket 93 Y_{biogas}: specific biogas 58 WDN: Water Distribution Network 94 *Y*_{CH4}: specific biomethane 59 WWTP: WasteWater Treatment Plants 95 α : ratio between daily mean water demand 60 %CH4(t): percentage of methane in the biogas 96 and annual mean consumption 97 *∆H:* head drop 61 produced at the duration test t 62 *Biogas(t)*: biogas produced at the duration 98 ΔH_{mean} : daily mean head drop 63 test t 99 ΔH_{max} : daily maximum head drop 64 C_d : water consumption variability during the 100 ΔT : temperature increase for influent 65 day 101 wastewater 66 CI: cost of initial investment 102 γ :water specific weight 67 *CM_t*: cost for annual O&M 103 μ_a : daily mean water demand 68 *CE_t*: annual gain of energy 104 η: PAT efficiency 69 R_t^{disc} : discount factor 105 η_{best} : best PAT efficiency 70 R_t^L , R_t^E : price development rates 106 η_q : generator efficiency for either HR 71 CODrem: COD removed 107 regulation ($\eta_{q,HR}$) or SSP regulation ($\eta_{q,SSP}$) 72 *d*: per-capita water demand 108
- 109

110 **1** Introduction

- 111 The present work originates from the need to mitigate environmental issues related to pollution
- and resources depletion, recovering energy and optimizing the exploitation of available natural
- sources. A non-conventional approach is thus proposed based on the domestic water cycle as adirect system for energy production.
- 115 Many progresses in producing equipment and low-emission technologies for buildings heating and 116 cooling based on renewable energy sources (RESs) have been made in the last decades. However,
- 116 cooling based on renewable energy sources (RESs) have been made in the last decades. However, 117 the transition towards the integration of RES in the building sector began by considering buildings
- as stand-alone energy consuming units of a wider grid. Currently, this conception is changing and
- 119 the urban energy system is more and more intended as a distributed network of "prosumers", to be

designed and managed considering different levels of building clusters, districts and cities [1]. According to this challenging vision, energy planning at higher scales than building level, would provide huge advantages in terms of sustainability and cost optimality [2,3]. In this context, the energy exploitation potential of urban water networks remains a rather unexplored field.

124 International community policies have underlined the need to increase the efficiency of all those 125 systems which are energy consuming [4]. The European guideline for greenhouse gas (GHG) 126 reduction aims to decrement the carbon footprint by 2050 from 80% to 95% compared to 1990 127 levels (Energy Roadmap 2050), evidencing the need to cut the use of fossil fuels and reduce energy 128 consumption. The Directive 2009/125/EC [5] is another example of the policies undertaken by the 129 European Union, addressing the importance of some technical changes in the industrial design of 130 water pumps [6].

- Moreover, the whole concept of water-energy nexus in urban contexts needs to undergo a profound rethinking in the light of drivers such as climate change, population growth and technological development and addressing the growing need for an effective economy circularity application in the sector [7]. Energy and water flows should be not considered isolated cycles, but conceived more and more in a holistic way, including their interactions. For this reason, also the importance of topics like water value and leakages in traditional water distribution networks (WDNs) is increasing, as
- 137 confirmed by international initiatives concerning the sustainable use of water.
- 138 The domestic water cycle can be defined as the water cycle involving all water flows that typically 139 exist in a household (building scale), that can also be extended to a whole residential area 140 (neighborhood scale). Such water cycle starts from drinking water supplied for people usual needs, 141 and ends with wastewater flows usually discharged in mixed sewage system and treated in big 142 centralized wastewater treatment plants (WWTPs). Hence, the domestic water cycle is ruled by two 143 main elements, i.e. the WDN and the WWTP, and both systems can be exploited for 144 environmental/energetic targets. To date, several new approaches at building scale try to recover 145 potential thermal energy from greywater or to optimize the specific hydric consumption to improve 146 the indirect energy savings [8–10]. However, the recovery of energy directly from the main water 147 streams (not related to the dissipated heat) represents a valid alternative. Currently, several 148 solutions have been tested and validated such purpose, although an integrated perspective at 149 building/neighborhood scale is still missing.
- 150 In this sense, the present work aims at investigating an innovative integrated approach for the 151 energy harvesting, exploiting the whole domestic water cycle, i.e. both WDN and WWTP systems. A 152 further goal is that of finding convenient and efficient solutions for energy recovery in small-sized 153 urban contexts, through dedicated cost analyses based on innovative stochastic approaches able to 154 assess the robustness of the results under alternative macro-economic scenarios.
- 155 Specifically, hydropower generation in traditional WDNs can be attained by exploiting localized 156 excess water pressures which are typically damped. Different strategies exist for this purpose, as well as to reduce energy consumptions [11] and water leakages [12], such as the application of 157 158 pressure control through pressure reducing valves (PRVs) or within pressure break tanks [13–16]. 159 Specifically, to reduce leakages and avoid damages to appliances, a potential energy is dissipated 160 into heat when PRVs are used, although this could be converted into electric power using hydraulic 161 turbines. Recovering this kind of energy along the pipelines is possible, through application of micro-162 turbines that harvest power while adjusting pressure level to those required by users, by converting 163 dissipation nodes into energy production nodes [17,18].
- However, the use and optimization of classical turbines is hard and costly in WDNs, especially in small urban agglomerates or districts, due to the large variability of water demand during the day [19]. Hence, a smart solution is represented by Pumps As Turbines (PATs), i.e. classical pumps

167 working in reverse mode. Such hydraulic machineries are typically centrifugal pumps and can be applied to a traditional supply system, like a WDN, where the water flow forces the pump impeller 168 169 to run. The application of an electric generator to the pump shaft allows the conversion of the water 170 power into mechanical power, which is, in turn, converted into electric energy. The relatively small 171 heads and flow rates of operation lead to a power generation of the order of kilowatts, the PAT 172 application being thus classified as a micro- or pico-hydropower [20]. As already proved, PAT 173 applications for small-scale hydropower generation lead to many advantages, being these (i) 174 cheaper and (ii) easy to find on the market, as well as because of their capability (iii) to better 175 manage flow variations and (iv) to lead to substantial savings in the invested capital [17].

176 Pico-hydro schemes have been already proposed to provide electricity in remote regions of the 177 world [21], but PAT fitting in WDNs is still an unusual application which requires accurate 178 preliminary analysis to guarantee optimal choice of the machine, accounting for daily and seasonal 179 patterns of demand and pressures, which dramatically modify turbine operation [22]. An additional 180 obstacle to PAT application and design concerns PAT characteristic curves, that are typically not 181 provided by manufacturers in off-design conditions, although some analytical approaches exist to 182 predict PAT performances based on the curves of the pump working in classical/direct mode [23,24]. In terms of PAT functioning, the combination with a PRV can improve the PAT performances, 183 184 especially during low consumption hours [20]. The PAT-PRV-system is particularly suitable in WDNs 185 with high differences in altitude, high operational pressures and high demand variability, as 186 demonstrated by recent numerical and laboratory tests [25]. Connected to the use of a PRV is also 187 the PAT regulation, which is typically represented by three schemes: i) hydraulic or mechanical 188 regulation (fixed rotational speed of the PAT, using PRVs); ii) electrical regulation (variable speed, 189 using an inverter); iii) dual regulation (variable speed, using both PRVs and inverter) [26]. 190 Considering that each scheme provides specific benefits and is related to specific investment costs, 191 PAT optimization plays a major role and potentially leads to significant improvements in terms of 192 effectiveness, i.e. capability, flexibility, and reliability [27].

193 Recent investigations suggest the potential use of axial flow pumps in reverse mode [28,29]. 194 Compared to traditional centrifugal pumps, axial pumps provide higher flow rates at low heads, this 195 facilitating their application in, e.g., low mountainous areas. Consequently, axial PATs are typically 196 applied when/where the flow rate is larger and the head is much smaller than those expected for 197 the application of centrifugal PATs [30]. Technical shortcomings also exist for axial flow PATs, like 198 the loss of efficiency, ascribed to blade tip clearance, and their performance is linked to mechanical 199 factors, like the orientation of guide vanes [28,31,32]. Experiments and numerical tests are currently 200 devoted to study such issues, and aim at making axial PATs a viable alternative to centrifugal PATs. 201

202 Concerning the WWTP system, different anaerobic treatment schemes were investigated for the 203 valorization of wastewater flows. As an example, anaerobic co-digestion could be implemented for 204 the simultaneous treatment of kitchen waste (KW) and black water (BW) [33] for biogas production. 205 Moreover, a combination of vacuum toilet, food waste collection system and Upflow Anaerobic 206 Sludge Blanket (UASB) system can be considered for maximizing the energy recovery also in 207 decentralized contexts (e.g., at household level) [34]. Other applications at household level includes 208 the possibility to couple UASB reactor with struvite precipitation system to recover Mg, N and P to 209 be reused in agriculture [35,36]. Nowadays, UASB technology is mostly applied in the industrial 210 sector¹ and its implementation at small-scale level (e.g., household and district) is still relatively new 211 [37]. The great potential of anaerobic treatments can also be exploited for closing the water loops

¹ <u>https://www.hydrousa.org/innovations/</u>

- in small communities, as these solutions can provide the possibility not only to treat municipal
- greywater but also to recover water, biogas for further reuses² and nutrients after the co-treatment of the anaerobic sludge [38].
- Based on the above, appropriate and efficient solutions for energy production from domestic water
- 216 cycle, referred to as Domestic Water-Based Technologies (hereinafter DWBTs), are here proposed
- for a small-sized urban context, representing a district or a decentralized area. However, the
- 218 presented methodology can be replicated and applied to urban environments of different size.
- The main findings of laboratory tests on PAT and WWTPs applications have been used to evaluate their potential in a typical ideal scenario of a small urban context where water demand profiles are set.
- To assess the economic performance of the proposed solutions, their energy production and global costs in a Life Cycle Costing (LCC) perspective are evaluated. The economic dimension is just one of
- the three main components of sustainability assessment. However, this constitutes an important aspect to be scrutinized together with the technical feasibility. Indeed, the financial aspect is a typical barrier to an effective implementation of renewable solutions.
- Hence, the present research provides a further contribution to the field of urban energy-water
 cycles, pursuing the following objectives: (i) investigating an integrated approach for the energy
 harvesting, through the exploitation of the domestic water cycle and based on DWBTs; (ii) providing
- an added value to supply and sanitary systems in small-sized urban areas, based on experimental
- tests covering flow rates that are consistent with the water demand in small-sized urban areas; (iii) providing a feasibility assessment based on a "stochastic" LCC, able to take into account the intrinsic uncertainties due to future economic scenarios. The application of a "stochastic" LCC is a novelty of this work compared to the conventional approaches adopted in most of the literature, which disregard the long-term uncertainty and interdependence affecting the macroeconomic variables
- and, consequently, misrepresent the impact of the associated risk.
- In other words, the proposed integrated solution for the energy exploitation from the domestic
 water cycle leads to a circular approach which is a novelty for small urban contexts, while the
 analyzed macroeconomic scenarios provide a guideline for the urban planning in such areas, to face
 the economic barriers for feasibility.
- The paper is divided as follows. Section 2 reports the experimental tests carried out using the two defined technologies, as well as the definition of both the real-world scenarios and the LCC based on the energy production. Section 0 describes the main results of the chosen applications in terms of energy and global costs. Section 4 discusses the main results, while Section 5 presents the final remarks.
- 247 2 Material and methods

- The present work aims at finding appropriate and efficient solutions to produce energy from the water source in different urban contexts and at different scales, also considering the LCC aspect. This could be obtained using PAT technologies and producing biogas from WWTPs, especially in areas where the excess water pressure needs to be significantly dissipated in the local WDN and a specific sewage treatment can be applied, like remote villages or decentralized districts.
- To this purpose, ideal urban scenarios have been built with the aim to represent either small rural contexts or decentralized area, often found in Italy and in many other countries worldwide. In a scarcely populated zone like this, peaks of water demand can be significantly variable, due to the different users' habits. Further, such contexts are of great interest due to the lack of information in

² <u>https://www.hydrousa.org</u>

- terms of both water demand (e.g., daily coefficients cannot be easily obtained for residential areas with less than 5,000 inhabitants) and sewage treatment (e.g., specific limit legislation for WWTP are not available for served territory below 2,000 inhabitants). Hence, although the existence of international policies related to energy harvesting from small water sources, a detailed analysis of energy production and recovery in such contexts has not been provided so far.
- The work is made up of two areas of interest, which represent the two main water sources in urban context: drinking water and wastewater. The following sections describe the experimental setup used for both sources (Section 2.1) and their application to ideal scenarios (Section 2.2).

266 2.1 Experimental tests

- Energy generation from a typical WDN was investigated through dedicated laboratory tests, focused
 on the characterization of a PAT, while biogas production and its methane content were monitored
 both at laboratory scale and pilot scale for valorization in terms of energy production.
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271 2.1.1 Drinking water and supply system

- Energy generation through a PAT-based system was investigated in a series of experimental tests conducted in the Laboratory of Hydraulics and Maritime Constructions of the Università Politecnica delle Marche (Ancona, Italy), where an old centrifugal pump was installed in an existing facility resembling a traditional supply system, and tested in reverse mode [39] (Figure 1).
- To both identify the most efficient PAT configurations and provide useful hints for possible realworld applications, several tests were carried out. The hydrodynamic conditions (pressure and flow rate) of the plant were varied by adjusting the frequency of a feed pump, with the aim to get the performance curve of the PAT. The tested flow rates were in the range Q = (5-9) L/s, while the pressure heads were in the range H = (4.8-33.9) m. Head drops ΔH were recorded using two pressure sensors located, respectively, upstream and downstream of the PAT. The mechanical
- behavior of the PAT was investigated by means of a test bench that allowed the regulation of the
- impeller rotation *N* by imposing a braking force *M* to the PAT shaft.





Figure 1. Schematic of the supply system, with the insets showing some of the system details.

286

287 2.1.2 Evaluation of mechanical power

Tests with specific flow rates Q and rotation speeds N, respectively ranging between (5-9)L/sand (650 - 1250)rpm, led to the performance characteristic curves, each one related to a specific N value (Figure 2). The evaluation of both induced hydraulic power $P_H = \gamma Q \Delta H$ (with γ being the water specific weight) and produced mechanical power $P_M = MN$ led to the definition of the PAT efficiency η . It has been observed that: (i) the larger is N, the larger is the flow rate at which the maximum efficiency occurs; (ii) the maximum efficiency is significantly larger at higher N values, i.e. $\eta_{max} = 43\%$ when N = 650 rpm, while $\eta_{max} > 60\%$ when N = 1250 rpm. Conversely, if small



295 flow rates are considered ($Q \le 6 L/s$), larger efficiencies are obtained at small speeds, i.e. $\eta_{max} =$ 296 37% when N = 650 rpm, while $\eta_{max} = 25\%$ when N = 1250 rpm.

Figure 2. Characteristic curves of the PAT, each referring to a specific speed N (colored lines). The curve referring to the pump working in classical mode at N = 1450 rpm is also shown (black line).

301 Similarly, the mechanical power P_M increases with both flow rate and rotational speed (Figure 3). The following step concerns the conversion of mechanical power into electricity exploiting a classical 302 303 electric generator [40]. Further details about the experimental setup and main findings are 304 illustrated in [39].



Figure 3. Mechanical power vs. flow rate through the PAT, each referring to a specific speed N.

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308 2.1.3 <u>Black undiluted wastewater and municipal wastewater</u>

309 Synthetic feces and urines were made and used to simulate concentrated domestic wastewater as

310 influent matrix to be anaerobically treated for biogas production in batch scale tests. Specifically,

according to literature assessment [41], the recipes reported in Table 1 were used to simulate the

312 mentioned matrices.

313

Table 1. Recipes of	of synthetic feces and urines used	for experimental tests	accordina to literature.

COMPONENTS	AMOUNTS [G]		REFERENCE
FECES			
HUMIDITY CONTENT (%TS)	80% (S80)	65% (S65)	
	SB80 (g)	SB65 (g)	
YIEST EXTRACT	72.29	126.51	
BIER YIEST	0	0	
MICROCRYSTALLINE			
CELLULOSE	24.1	42.17	
PSILLIUM	42.17	73.8	Donn at al [11]
MISO PASTE	42.17	73.8	Penn et al. [41]
VEGETAL OIL	48.19	84.34	
NACL	4.82	8.43	
KCL	4.82	8.43	
CACL ₂ ·H ₂ O	2.41	4.81	
WATER	758.7	577.72	
1 KG FINAL FECES	1000	1000	
URINES			
NACL	3.6		
КСІ	3.4		
KHCO₃	1.1		Udart & Wächtar [42]
Na ₂ SO ₄	2.3		Ouert & Wachter [42]
NaH ₂ PO ₄ ·2H ₂ O	2.7		
NH4NO3	19.2		

314

315 Feces and urines were used in the batch tests as external carbon source and substrate to keep the

inoculum to substrate (I:S) ratio constant at value of 2 (VSS basis) [43]. The substrate was added to
 obtain an Organic Loading Rate (OLR) equal to 1 kgCOD/m3/d.

318 Lab test reactors for anaerobic digestion were fed with different matrices to simulate two main 319 toilet operation mode: "urine diverting toilet" (Feces+Flushing water) and "dry toilet" without urine 320 separation (Feces+Urine). In the first mode, a blend of feces (F) and flushing water (FI) was 321 performed to simulate the effect of flushing toilet (F+FI) into the sewage. Moreover, the effect of 322 urines (U) was evaluated by the addition of synthetic urines to the feces F. Specifically, for the two 323 tests the amounts of matrices were added as according to the average values derived from literature 324 studies [44] and equal to: volume of feces 0.12 L/p/d, volume of urines 1.38 L/p/d and volume of 325 flushing water 20 L/p/d. Thus, the total black water supply was estimated equal to 21.5 L/p/d.

326 Performed tests allowed to both estimate the biogas production yields and collect biogas samples

for further chromatography analysis for determination of methane production (see Section 2.1.4).

328 Moreover, in Section 2.1.4 analytical method was used to estimate the methane production yield

to be considered for energy production in decentralized scenarios. Finally, rates obtained with black

330 water (F+Fl and F+U) were compared with biogas production derived by the anaerobic digestion of

331 municipal wastewater at pilot scale.

Municipal wastewater is treated in the Pilot Hall of the Università Politecnica delle Marche through a UASB reactor, heated at 30°C. The influent from Falconara WWTP is the preliminary treated by means of screening, degritting and oils removal before being sent to the pilot-scale UASB. Influent is fed with a peristaltic pump (Watson-Marlow, UK) to guarantee an influent flow rate of about 3 L/h. Moreover, a pump for recycle is installed to ensure a flow rate of 12 L/h.

337 The cylindrical Plexiglas UASB reactor has a volume of 16 L, an internal diameter of 15 cm and a total 338 height of 136 cm. The reactor was filled with an initial inoculum of sludge taken from a paper mill 339 WWTP of Castelfranco Veneto (Italy) and it is internally divided in two parts. Specifically, the first is 340 the bottom reaction chamber (85 cm, 12.4 L) while the second at the top is dedicated to the tree-341 phase Gas-Liquid-Solid (GLS) separator, 21.9 cm height. Moreover, the GLS separator is connected 342 to a hydraulic guard which creates the appropriate backpressure for the release of biogas [45]. The 343 produced biogas is measured by means of a milligas counter (RITTER). Hydraulic Retention Time 344 (HRT) was set at 6 hours and the up-flow velocity of the reactor was kept at 1 m/h.

Pilot scale experimental test was performed to evaluate the biogas and methane productions yield
 which derive from the treatment of grey water in centralized scenario.

347

348 2.1.4 Evaluation of biogas production

349 At lab scale, Biochemical Methane Potential (BMP) tests were performed to determine expected 350 biogas and methane productions when undiluted flows such as black domestic wastewater was 351 added as substrate to the sludge. Specifically, the biogas, mainly composed of methane and carbon 352 dioxide, is produced by methanogenic bacteria during the test due to the anaerobic degradation of 353 the organic compounds in the substrate. Experimental tests were conducted in glass reactors of 250 354 mL of total capacity and with working volume equal to 200 mL. Tests were performed by using as 355 biomass the anaerobic granular sludge (TS% averagely equal to 2.6 % and TVS/TS% averagely equal 356 to 57.8 %) from the full-scale anaerobic digestion reactor.

The BMP tests were conducted according to van Loosdrecht et al. [43] and in a thermostatic bath at temperature-controlled conditions at 30°C with an overall HRT of 15 days. Specific biogas production was daily registered (in mL) and biogas samples were collected to determine methane content in the biogas by means of gas chromatography "Bruel and Kjaer Multi-gas Monitor Type 1302" based on photoacoustic spectroscopy. Biogas and biomethane production rates were calculated and expressed as mL of biogas or biomethane per kg of COD removed or fed.

Specific trends of the biogas and biomethane production were plotted to analyze the effect of the substrate on the methanogenic activity. For each test the production curves were built through graphs with duration time values on the x-axis and the cumulative produced biogas and biomethane values on the y-axis.

Furthermore, specific biogas (Y_{biogas}) and biomethane (Y_{CH4}) yields were calculated with the following equations 1 and 2:

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 $Y_{biogas} \left[\frac{m^3 biogas}{kgCOD_{fed}} \right] = \frac{Biogas(t)}{kgCOD_{fed}},$ (1)

$$Y_{CH_4} \left[\frac{m^3 CH_4}{kgCOD_{fed}} \right] = \frac{Biogas(t)}{kgCOD_{fed}} \cdot \frac{\% CH_4(t)}{100},$$
 (2)

- 371 where:
 - *Biogas(t)* is the biogas produced at the duration test *t* (m³);
- *KgCOD_{fed}* is the amount of the COD which was inserted in the batch volume at the beginning of the test (kg/m³);
 - *%CH4(t)* is the percentage of methane in the biogas produced at the duration test *t* (%).
- 375 376
- 377

378 2.2 Exemplary case application

379 Different populations are analyzed in the present work, based on a relatively small community 380 characterized by a water demand consistent with tested flow-rate ranges [39]. Since the legislation 381 requires the presence of a treatment plant for population centers with more than 2,000 inhabitants, 382 we here refer to a population of, respectively, 3,000 (case 1), 4,000 (case 2) and 5,000 (case 3) 383 inhabitants, with one WDN ensuring the water supply to the whole area and two hypotheses of 384 WWTP for the sewage treatment. Specifically, in the first hypothesis, the implementation of several 385 decentralized systems was evaluated, while in a second hypothesis, a centralized plant was 386 considered.

The selected population cases, consistent with the configurations investigated in [39], are considered in the following sections for both drinking-water framework/PAT system (Section 2.2.1) and wastewater framework/biogas (Section 2.2.2), as well as for the definition of the LCC (Section 2.3).

391

392 2.2.1 Definition of drinking water scenarios

393 Since a PAT-based plant exploits the hydraulic power in the WDN to generate mechanical power, 394 the potential energy production can be assessed with reference to the water flowing in the network.

In the present cases, the reference flow rate is the daily mean water demand required by users μ_q , estimated through the classical formulation

397 398 where:

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$$\mu_q = \alpha \cdot n \cdot d \tag{3}$$

• *n* is the number of served inhabitants, i.e. either 3,000, 4,000 or 5,000;

- *d* is the per-capita water demand, assumed as 160 *lpd* (maximum water required in little communities [46]);
- 402 *α* is the ratio between the daily mean water demand and the annual mean consumption,
 403 here assumed as 1.04, as in [39] for a small community with no tourist flow.

Hence, the daily mean water demand μ_q is, respectively, 5.78 L/s, 7.70 L/s, 9.63 L/s. Further, the hourly average flow rate Q(t) can be obtained multiplying the daily average flow rate μ_q by an hourly coefficient accounting for the water consumption variability during the day C_d , i.e.

$$Q(t) = \mu_a \cdot C_d(t) \tag{4}$$

408 Relevant C_d values are available in the literature for residential areas of 10,000 to 50,000 inhabitants 409 [47], but these are not consistent with the present scenario. Hence, coefficients retrieved from a 410 similarly sized urban context are required. For this reason, values of the coefficient C_d are extracted 411 from the data recorded in July 2008 in the small municipality of Servigliano (Marche Region, Italy), 412 characterized by a population of almost 2,400 inhabitants [39]. The daily distribution of such C_d 413 values are thus retained as valid for a population up to 5,000 inhabitants [47].

The trend of C_d illustrated in Figure 4 is thus typical of relatively small urban areas. Specifically, while areas with larger population (over 10,000 people) are identified by C_d distributions characterized by a smoothed trend and only one peak [47–49], smaller areas are identified by two or more peaks [19], that correspond to hours of larger demand. In the present case, a clear increase of water demand occurs between 5:00 and 8:00 am. Further, the demand is large between 8:00 (first peak) and 21:00 (second peak), with a minimum around 16:00-17:00.

Values of the hourly-averaged flow rate Q(t) during the day are calculated using eq. (4). Figure 4 shows the time evolution of Q(t) for case 1 (blue columns), case 2 (orange) and case 3 (gray). It can

422 be observed that a portion of the day, mainly daytime, can be exploited to harvest energy, and this 423 depends on users' water demand, while the water demand is small during the night. Hence, due to 424 the significantly low efficiency at low flow rates and according to [39], it is supposed to operate the 425 PAT only when Q > 5 L/s.

426 Suitable design strategies for PAT integration into an existing WDN have been selected, in terms of

- 427 both PAT regulation and control valves configuration. Specifically, the design may deal with the 428 addition of specific devices, able to improve the PAT efficiency under variable flow-rate and pressure 429 conditions [50–52].
- A first solution, suitable for a real-world application, is the use of a hydraulic regulation (HR) realized by combining PAT with PRVs, that allow to reduce the upstream pressure and make the PAT work in almost optimal way [16,26]. In fact, with the HR approach, two regulating valves are combined to the PAT system: one upstream, in series with the pump, dissipates some of the excess pressure, when power generation is important during the day. On the other hand, the second valve is integrated into a bypass in parallel with the PAT, providing greater dissipation when the pump is not working, i.e. during the nighttime. Such combination allows the PAT to work properly, in terms of
- 437 both head drop and flow rate.





441



442 The second solution here investigated is evaluated as the most convenient way to harvest energy 443 from small-sized water distribution networks, e.g. where water demand is significantly variable due 444 to the both reduced scale and number of inhabitants [16]. This solution, based on a single-serial-445 parallel (SSP) regulation mode, consists of two identical PATs piped with three on-off valves: two of 446 them are located, respectively, downstream of each PAT, while the third valve is installed in a bypass 447 pipe. This configuration allows one to set the plant work in three working conditions: single, series 448 and parallel modes. The first condition involves only a single PAT and its downstream valve, to 449 produce energy in case of moderate flow rates; the second condition concerns the activation of 450 both pumps, working in series thanks to the opening of the bypass valve and the valve located 451 downstream of the second PAT, in case of a higher available head; in the third working condition, 452 the valve located in the bypass pipe is closed and the two PATs are activated, together with both downstream valves, with the aim to make the PATs work in parallel in case of much higher flow 453 454 rates. Developing a list of set points necessary to activate valves and PATs according to the different 455 working conditions, and with the aid of a Programmable Logic Controller (PLC), the power plant can 456 adapt to the WDN context by switching from one mode to another when the pressure drop 457 decreases [53]. Other types of PAT regulations are also available and have been applied to real contexts, as described by several works [16,26,39,52]. Details on the costs relevant to both 458 459 regulations are provided in Appendix A.

460

Scenario	n	μ_q [L/s]	η_{best} [%]	N [rpm]	HR/SSP
1a	3,000	5.78	33	750	HR
1b	3,000	5.78	33	750	SSP
2a	4,000	7.70	54	950	HR
2b	4,000	7.70	54	950	SSP
3a	5,000	9.63	63	1250	HR
3b	5,000	9.63	63	1250	SSP

Table 2. Tested scenarios for the drinking-water source.

461

462 Six technological solutions are considered, each related to a specific combination between 463 regulation mode and rotational speed of the PAT. Specifically, the above-described cases (see also 464 Figure 4) suggest the use of well-defined rotational speeds, depending on the best efficiency η_{best} . 465 Such efficiency is related to the selected values of the daily mean water demand μ_q and is estimated 466 from the $\eta - Q$ curves [39]. Table 2 summarizes the analyzed scenarios: three of them are based on 467 an HR regulation, three on an SSP regulation; the best efficiency is provided by a rotational speed 468 that varies between 750 and 1250 rpm, directly depending on the considered population *n*.

469

470 2.2.2 Definition of wastewater scenarios

471 For the determination of the case studies, a literature assessment was conducted to preliminary 472 assess the economic and operative feasibility of anaerobic systems both for centralized and 473 decentralized UASB application. In this perspective, two main scenarios were considered: the first 474 one considers the implementation of UASB technology at small and decentralized scale (e.g. at 475 household level) for black water treatment, while the second one involves the UASB application 476 with small centralized approach for mixed wastewater. For all the scenarios, capacities of 3,000, 477 4,000 and 5,000 inhabitants were considered to treat the whole wastewater produced by the 478 community which is going to be served.

Further, according to literature assessment [54], predictive equations were used to estimate and
compare the Capital Costs (CAPEX), Operative Costs (OPEX) and Land Requirement of the UASB of
both Scenarios. Specifically, equations used are reported in the following:

482
$$Capital Cost \left[\frac{\$}{\frac{m^3}{d}}\right] = 494 \cdot Q_{ww}^{-0.2}, \tag{5}$$

483
$$Operative Cost\left[\frac{\$}{\frac{m^3}{d}}\right] = 457 \cdot Q_{ww}^{-0.49}, \tag{6}$$

484
$$Land Requirement\left[\frac{m^2}{\frac{m^3}{d}}\right] = 10.4 \cdot Q_{ww}^{-0.12}, \tag{7}$$

- 485 where Q_{ww} is the influent wastewater (m³/d).
- 486 The data which were obtained from equations above were used to deliver a Life Cycle Assessment
- 487 of the anaerobic treatments applied to both decentralized and centralized levels. Moreover, for an

estimation of the biogas and biomethane production for the considered scenarios, preliminary
design data were calculated and considered according to the flow rate to be treated. Specifically,
black water supply was estimated according to Section 2.1.3, while sewage water supply was
calculated considering a daily water supply of 160 L/PE/d and a flow coefficient in the sewer of 0.9.
Finally, the obtained biogas and biomethane production yields were used to preliminary evaluate
the UASB performance in terms of energy production for all the scenarios (see Table 3).

494

Scenario	n	Description	Toilet operation
1 FF	3,000	Decentralized	F+F
1 FU	3,000	Decentralized	FU
2 FF	4,000	Decentralized	F+F
2 FU	4,000	Decentralized	FU
3 FF	5,000	Decentralized	F+F
3 FU	5,000	Decentralized	F+U
1 C	3,000	Small Centralized WWTP	-
2 C	4,000	Small Centralized WWTP	-
3 C	5,000	Small Centralized WWTP	-

Table 3. Tested scenarios for the wastewater source.

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For each scenario, an energy assessment was delivered to detect the net energy production (E_{ww} , in kWh/d) from each UASB operative condition. E_{ww} is calculated according to the following equation (Metcalf & Eddy, 2014):

499
$$E_{ww} = \left[Q_{ww} \cdot COD_{rem} \cdot \left(\frac{0.35 \ m^3 CH_4}{kg \ COD_{rem}} \right) \cdot \left(\frac{35,864 \ kJ}{m^3 CH_4} \right) - Q_{ww} \cdot \Delta T \cdot C_p \cdot \left(\frac{10^3 kg}{m^3 H_2 O} \right) \cdot \left(\frac{1}{Eff_{heat}} \right) \right] \cdot \frac{3600 \ kJ}{kWh}$$
(8)
500 where:

- 500 where 501
- *COD_{rem}*: COD removed (kg/m³)
- Δ*T*: temperature increase for influent wastewater (°C)
- C_p=4.2 kJ/°C·kg: specific heat of water
- *Eff*_{heat}: fraction of heat available after losses from vessel and heat exchanger.

505 Moreover, both summer and winter seasons are considered for each scenario, to evaluate the effect 506 of temperature in UASB energy consumption for heating the reactor.

508 2.3 Life Cycle Costing based on estimated DWBTs' energy production

509 The economic affordability of the proposed DWBTs has been evaluated considering a life cycle 510 perspective. Global Costs are calculated in a time horizon of 20 years (equal to the considered 511 service life of the DWBTs, according to [22,52,55–59]), based on the procedure of the European 512 Standard EN 15459-1:2017 [60]. The cost categories included in the assessment are the initial 513 investment costs and the Operation and Maintenance (O&M) costs, while the annual produced 514 energy is considered as a gain. For each DWBT, the alternative technological solutions (identified in 515 previous Sections 2.2.1 and 2.2.2) are assessed to evaluate the most affordable ones.

516 The Global Cost (GC) of each solution, at the end of the Calculation Period (CP) and referred to the 517 starting year, is then calculated as follows:

$$GC=CI+\sum_{t=1}^{CP} (CM_t R_t^{disc} R_t^{L}-CE_t R_t^{disc} R_t^{E})$$
(9)

519 where:

518

520

- CI is the cost of initial investment;
- CMt is the cost for annual O&M (assumed constant);

- CE_t is the annual gain of energy (assumed constant);
- Rt^{disc} is the discount factor;
 - R_t^L and R_t^E are the price development rates (respectively for human operation and for energy).
- 525 526

524

527 According to EN 15459-1:2017 [60], the LCC calculation here performed is expressed in real terms 528 and "dynamic", i.e. the discount factor (depending on inflation rate and nominal interest rate) and 529 the price development rates vary over time.

530 Moreover, in order to consider the inherent uncertainty of LCC assessments, which are projected 531 over many years into the future, a Monte Carlo-based stochastic approach is used, which considers 532 the interdependent stochastic nature of these macro-economic variables. This stochastic LCC 533 method was previously developed and applied in the context of energy efficiency projects [61–63]. For each Monte-Carlo iteration, a draw from the macro-economic variables' distributions is realized, 534 535 thus propagating the stochastic nature of the calculation into the statistical distribution of the output Global Cost. Consequently, the economic evaluation of the proposed DWBT solutions is itself 536 537 stochastic and represented by a probability density function, thus expressing both its expected 538 mean value and its inherent uncertainty.

539

540Table 4. Summary statistics (Mean and SD= Standard Deviation of distribution, in %) and characterization of the alternative541macroeconomic scenarios for the LCC evaluation: the "regular growth" scenario is the baseline case, \uparrow means higher than the542baseline, \checkmark means lower than the baseline.

Variable:	Inflation rate		Interest rate		GD	P
Macro-economic scenario:	Mean	SD	Mean	SD	Mean	SD
Regular growth (RG) -Baseline	2.25	0.97	2.77	0.78	2.54	1.64
	=		=		=	
	2.55	0.63	3.45	0.73	3.31	1.19
Intense growth (IG)	\uparrow		\uparrow		\uparrow	
	8.41	3.35	4.81	0.32	0.34	3.21
Stagflation (SF)	\uparrow		\uparrow		\downarrow	
	0.46	1.11	1.50	0.63	1.34	1.62
Deflation (DF)	1	,	\downarrow	,	\downarrow	,

543

The stochastic LCC is performed considering four alternative macro-economic scenarios, characterized by different distributions of the macro-economic variables entering eq. (9), in order to evaluate the outcomes' robustness in possible different economic conditions. These scenarios are extensively described in [63] and their main features here summarized in Table 4.

548 The "regular growth" scenario represents the baseline case and the actual economic condition in 549 EU (with an inflation rate around 2% and slight real interest rates and Gross Domestic Product (GDP)

550 growth). GDP proxies the growth rate of prices for human operation.

551 Beside the macroeconomic variables, the inputs of the LCC calculation in eq. (9) have been 552 estimated for all variants of DWBTs according to the following assumptions.

553 Concerning the drinking water, the CI includes all the purchase, construction and installation costs

of the PATs systems in the urban network. The price of the pumps has been estimated based on a

555 survey among hydraulic machines manufacturers, considering pumps with power comparable to that tested during the experimental laboratory phase (i.e. \approx 1 kW). The price of valves has been 556 557 assessed on the basis of a literature research on similar systems [13]. The civil and installation works 558 have been assumed at 30% of the total purchase costs (according to [22,55,58,59]), while the total 559 CMt for the whole CP at 15% of the CI [22,55,58,59]. Table 5 summarizes CI and CMt for the 560 technological variants of the PAT systems. It can be noticed that the HR solutions have very high 561 investment costs, more than three times as those of the SSP solution. Hence, SSP systems result more economically convenient at the time of investment, especially in case of small-sized 562 563 hydropower plants where the production is limited.

564 In scenarios "b", the PAT works at the same rotational speed characterizing scenarios "a", but in SSP 565 regulation mode and not in HR mode. The production in scenarios "b" is thus not maximized as in 566 scenarios "a", but initial investment costs are clearly reduced. Further details on the cost estimation 567 are provided in Appendix A.

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 Table 5 Summary of the purchase and installation costs of the technological variants considered in the PAT systems evaluation.

 Total CI and CMt for the LCC assessments are also reported.

Scenario	enario <i>n</i> μ _q [l/s]		CI [€]	CMt [€]
1a	3,000	5.78	19,539.00	146.54
1b	3,000	5.78	6,318.00	47.39
2a	4,000	7.7	19,539.00	146.54
2b 4,000		7.7	6,318.00	47.39
3a	5,000	9.63	19,539.00	146.54
3b	5,000	9.63	6,318.00	47.39

571

572 Concerning the WWTP, CI has been estimated based on the unit cost per reactor and the number 573 of units needed to treat the whole capacity of (3,000, 4,000 and 5,000 inhabitants). Specifically, unit 574 cost per reactor was calculated based on equation 5 and assuming that the water supplied (in 575 m^{3}/d /reactor unit) is the amount of black water produced and the municipal wastewater discharged into the sewage network for decentralized and centralized case, respectively. Furthermore, a total 576 577 black water production of averagely 21 L/p/d was considered as according to Section 2.1.3, while 578 for the municipal wastewater a value of 144 L/p/d was calculated based on assumptions in Section 579 2.2.2. Moreover, for decentralized cases, the number of UASB reactors needed was calculated 580 assuming that 1 unit can treat wastewater from 10 houses with averagely 5 people per house.

581 582 583

Concerning CMt, costs were calculated based on the annual cost per reactor (according to eq.(6)) and the numbers or units needed. Specifically, annual costs were calculated with the same flow rates considered for CI and the annual operative cost expressed in €/m³/d.

584

585 Table 6 summarizes the CI and CMt for the technological variants of the WWTP systems.

The annual energy gains are calculated multiplying the annual energy production for the energy selling price related to the specific energy carrier in Italy: at 0.186 €/kWh for electricity (in the case of PAT) and 0.075 €/kWh for natural gas (in the case of WWTP), as in [13].

589 10,000 Monte-Carlo iterations were run for each of the 24 case studies of PAT (6 technological 590 variants x 4 macro-economic scenarios) and of the 36 case studies of WWTP (9 technological 591 variants x 4 macro-economic scenarios).

593 594

Table 6 Summary of the CI and CM_t of the technological variants considered in the WWTP systems for the LCC assessments.

			Total investment Cost (purchase +	Annual O&M Cost	
Scenario	n	Description	installation) [€/m3/d]	[€/m3]	
1 FF	3,000	Decentralized system	29,207	26,459	
1 FU	3,000	Decentralized system	29,207	26,459	
2 FF	4,000	Decentralized system	38,943	35,278	
2 FU	4,000	Decentralized system	38,943	35,278	
3 FF	5,000	Decentralized system	48,678	44,098	
3 FU	5,000	Decentralized system	48,678	44,098	
1 C	C 3,000 Small WWTP		58,965	9,386	
2 C	4,000	Small Centralized WWTP	74,225	10,870	
3 C	5,000	Small Centralized WWTP	88,731	12,180	

595

596 **3 Results**

597 **3.1** Energy and Global costs from drinking water

598 Based on the performances of the chosen PAT system and on the scenarios illustrated in Table 2, 599 the mechanical power has been evaluated with the aim to calculate the energy that the PAT system 600 is able at providing within each scenario. Specifically, Figure 5 shows the daily distribution of the 601 mechanical power for the three HR scenarios, under the assumption that the head drop provided 602 by the PAT system is smaller than the available net head within the WDN at the PAT location (e.g., 603 [16]).

Figure 6 illustrates the time evolution of the head drop generated by the PAT, which reaches significantly large values (up to 33.4 m) in the scenario 3a (gray line), i.e. in the case of the highest flow rate and rotational speed. Under this condition, the mechanical power is thus significantly high, almost reaching 3 kW during the first peak (8:00-9:00), but care should be taken in the choice of the installation site. For instance, the location considered in [39] is characterized by a maximum available net head smaller than 18 m and is clearly unsuitable for scenarios 2a and 3a, which require larger head drops (Figure 6, orange and gray lines).



Figure 5. Daily distribution of mechanical power for the three HR scenarios (see also Table 2): scenario 1a (blue line), scenario 2a (orange line), scenario 3a (gray line).

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In terms of functioning (i.e. for Q > 5 L/s, as stated above), the system would work during most of the day, i.e. for 16 hours (time range 7:00-23:00) in scenario 1a, and for 19 hours and 20 hours in scenarios 2a and 3a, respectively. In general, all scenarios show similar trends in terms of both P_M and *△H*, replicating the Q distribution (Figure 4) and identified by the following crucial conditions: i)
increase starting at 6:00, ii) first peak between 8:00 and 9:00, iii) local minimum at 4:00-5:00, iv)
second peak at 20:00-21:00.

625 Other interesting features concern the change in the mechanical power when passing from a scenario to another (Table 7). Specifically, passing from 3,000 to 4,000 to 5,000 inhabitants, the 626 627 mean mechanical power P_{M,mean} becomes about 2 times and 5 times larger, i.e. the three HR 628 scenarios are in a ratio 1:2.3:5.5, while the increase in the flow rate Q is relatively small, i.e. 1:1.3:1.7. 629 In terms of power peak $P_{M,max}$, the ratio is 1:2.5:6.3. Moving to the head drop, the ratios related to 630 the mean (ΔH_{mean}) and maximum (ΔH_{max}) values are, respectively, 1:1.6:2.3 and 1:1.8:2.4. This 631 means that a little increase in the flow rate provides a larger increase in the head loss, but also a 632 much larger improvement in the generated mechanical power. This must be carefully taken into 633 account when choosing the optimal location for the PAT installation.

634

 Table 7. Summary of relevant outputs from the three HR scenarios.

Scenario	n	μ_q [L/s]	P _{M,mean} [W]	P _{M,max} [W]	<i>∆H_{mean}</i> [m]	<i>∆H_{max}</i> [m]
1a	3,000	5.78	309.86	463.05	10.63	13.95
2a	4,000	7.70	721.06	1139.96	17.38	25.22
3a	5,000	9.63	1705.72	2932.18	24.03	33.36

635

The total amount of mechanical energy produced during the day is equal to 4.96 kWh, 13.70 kWh and 34.11 kWh for scenarios 1, 2 and 3, respectively. The yearly production is also calculated and then used for the estimate of the electrical energy through an efficiency of the generator which is different for HR and SSP approaches. For the classical HR regulation, it is assumed $\eta_{g,HR} = 0.8$, while for the SSP regulation, in agreement with the difference in plant capability between such regulation modes [16,64,65], it is assumed $\eta_{g,SSP} = 0.46$. Finally, the yearly produced electrical energy is evaluated integrating in time the mechanical power:

643

$$E_{dw} = \eta_{g} \cdot 365 \cdot \sum_{h=1}^{24} P_{M}$$
 (10)

The final outputs are illustrated in Table 8, showing large variability among the considered scenarios,
with the scenario 3a providing the largest energy production (9,961.38 kWh), while the scenario 1b
provides the smallest value (832.41 kWh).

647

Table 8. Mechanical and electrical energy from all scenarios.

Technological approach		HR			SSP	
Scenario	1a	2a	3a	1b	2b	3b
Daily mechanical energy [kWh/day]	4.96	13.70	34.11	4.96	13.70	34.11
Yearly mechanical energy [kWh/year]	1,809.60	5,000.57	12,451.73	1,809.60	5,000.57	12,451.73
η_g		0.8			0.46	
<i>E_{dw}</i> [kWh/year]	1,447.68	4,000.46	9,961.38	832.41	2,300.26	5,727.80

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The above results suggest that some of the proposed scenarios provide a significantly low energy saving and the PAT operation falls close to the lower limit of applicability [66]. However, to properly analyze the feasibility of each scenario, the results of the LCC evaluation are reported, also bearing in mind that the present work only proposes a methodology to be applied to a decentralized context, hence the PAT here used can be substituted with another one that best suites the area/WDN of interest [66,67]. 655 Figure 7 shows the boxplots of the Global Costs for the analyzed PAT scenarios (named in the x-

- 656 axis), considering the four alternative macroeconomics conditions (represented by different colors).
- 657 It should be reminded that Global Costs are represented by distributions given the stochastic nature 658 of the macro-economic variables entering the LCC assessments.

659 Global Costs have positive values where in 20 years the energy produced is not sufficient to

- 660 compensate for the initial investment, negative values in case of an economic gain. In general, the
- 661 highest GCs for all PAT scenarios are obtained in the Stagflation scenario, while the lowest ones in
- 662 the Deflation scenario.



663

664Figure 7 Global Costs for the analyzed PAT scenarios in the four alternative macroeconomic conditions (RG = Regular Growth,
G65665IG = Intense Growth, SG = Stagflation, DF = Deflation).

In all macroeconomic conditions, scenarios 1a and 1b result not affordable. For solution 1a, GC
median value ranges from a minimum of about 11,200 € (in the Deflation scenario) to a maximum
of about 17,400 € (in the Stagflation scenario), while the range of GC median value for solution 1b
is included between 1,040 € (in the Deflation scenario) and 4,700 € (in the Stagflation scenario).
Indeed, these scenarios entail quite high investment costs (19,539 € for 1a as all HR systems and
6,318 € for 1b as all SSP systems) and the lowest energy production.

672 Conversely, in all macroeconomic conditions, scenarios 3a and 3b entail the highest economic gains.

673 Under the Regular Growth macroeconomic condition, the median value of the GC for solution 3a is
674 about -29,300 €, while that of solution 3b is about -22,200 €. These values are quite close, as the
675 higher investment cost of the HR solution 3a is offset by the highest energy gain ever.

The economic performance of scenarios 2a and 2b is strictly related to the macroeconomic environment where the LCC assessment is performed. Solution 2b can always be economically convenient (albeit to a limited extent, with average GCs between -3,700 \in and -9,400 \in), except in the Stagflation condition, while scenario 2a is affordable only under a Deflation condition (where the median value of GC is 6,800 \in).

Figure 7 exhibits another interesting information provided by the stochastic LCC assessment, i.e. the uncertainty expressed by GC variability. Indeed, the interquartile range growths as the value of 683 negative GC increases and as energy gains grow. This is clearly showed in scenarios 3a, 3b and 2a, 684 and reveal that macroeconomic variables affecting the energy prices are the main source of 685 uncertainty. For the same reason, for these solutions, the computed GC is greatly influenced by the 686 macroeconomic scenario.

688 3.2 Energy and Global costs from wastewater

As first result, a preliminary literature study was assessed to evaluate the performance and main parameters which characterized the existing case study application of anaerobic digestion of wastewater. A summary of the analyzed case studies is reported in Appendix B.

The literature assessment showed that wastewater treatment via UASB anaerobic digestion is already implemented both at small case for decentralized application and at full scale in centralized WWTP. However, no clear picture of the benefits in terms of costs and performance according to the system scale is detected. From the literature analysis, the overall costs were estimated, by using equations (4), (5) and (6). As result, scenarios assessment is summarized in Table 9.

Table 9 . Summary of Scenarios Economic Assessment	
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Scenarios	min_dec	min_centr	mean_dec	mean_centr	max_dec	max_centr
Type of wastewater	Black (feces+urine+ flushing)	Sewage wastewater	Black (feces+urine+ flushing)	Sewage wastewater	Black (feces+urine+ flushing)	Sewage wastewater
Total served PE	3000	3000	4000	4000	5000	5000
Houses served for each UASB reactor(unit)	10	600	10	800	10	1000
Persons per house	5		5	1	5	
PE served per UASB reactor	50	3000	50	4000	50	5000
n°of UASB to be constructed to treat all PE	60	1	80	1	100	1
Water (Black or Sewage) supply [m3/p/d]	0.022	0.144	0.022	0.144	0.022	0.144
Water supplied [m3/d]/unit	1.075	432	1.075	576	1.075	720
Water supplied [m3/y]/unit	392	157680	392	210240	392	262800
Total flow rate [m3/d] for all PE	65	432	86	576	108	720
Total flow rate [m3/y] for all PE	23543	157680	31390	210240	39238	262800
Capital Costs [€/m3/d]	453	136	453	129	453	123
Cost per reactor [€/unit]	487	58965	487	74225	487	88731
Total Capital Cost [€]	29207	58965	38943	74225	48678	88731
Annual Operative Costs [€/m3/d]	410	22	410	19	410	17
Annual Cost per reactor [€/unit]	441	9386	441	10870	441	12180
Total Annual Operative Cost [€/y]	26459	9386	35278	10870	44098	12180
Total Annual Operative Cost [€/PE]	9	3	9	3	9	2
Land requirement [m2/m3/d]	10	5	10	5	10	5

⁶⁹⁷

698 From the assessment it was evident that, although the specific CAPEX [€/m3/d] are overall higher 699 for decentralized scenario, the total plant construction cost is globally lower than that estimated for 700 centralized scenario, due to and increase more than proportionately with system capacity (m3/d). 701 Moreover, when considering a centralized implementation, specific CAPEX was found to decrease 702 with the treatment capacity, passing from 136 €/m3/d to 123 €/m3/d. When considering OPEX, 703 total annual costs are higher for decentralized systems than for centralized ones also for Land 704 Requirement. In fact, land optimization, from 10 to 5 m2/m3wastewater treated/d, was detected 705 when centralized system is considered. When analyzing the performance of anaerobic system in 706 terms of biogas production, the type of the influent substrate (e.g., black water of municipal 707 wastewater) should be taken into consideration as it might influence the biogas production yields 708 (e.g., expressed as m3 of biogas or methane produced / kg COD fed or removed) [68]. Moreover, 709 also the Organic Loading Rate and Temperature were considered for gas production as they are 710 considered key parameters for the anaerobic treatments [69]. Thus, a preliminary literature 711 research was assessed and main parameters and performance of UASB reactors are summarized in 712 Appendix B.

From the assessment a higher methane production was detected when concentrated wastewater (e.g., black water/domestic water) is treated rather than diluted wastewater (e.g., grey+black water/urban wastewater), at same reactor temperature. Averagely, for concentrated wastewater methane yield was estimated equal to +17% m3CH4/kgCODfed and +70% m3CH4/kgCODremoved respect to municipal wastewater treatment. However, a slight decrease was detected in the biogas production. This could be due to a higher CH4 percentage in the produced biogas when a concentrated wastewater is treated.

Biogas and methane productions from anaerobic process were also evaluated within experimental
 activities and preliminary results for the full-scale implementation scenarios were achieved. Results
 in terms of performance and expectations are summarized in Table 10.

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Expected	Expected full-scale performance								
Scenario	OLR	т	HRT	Biogas Yield	CH4 Yield	%CH4/ biogas	CODfed	Biogas	CH4
-	kgCOD/m3/d	°C	h	m3biogas/kgCODfed	m3CH4/ kgCODfed	%	kgCOD/d	m3/d	m3/d
1FF	1	30	360	1.13	0.44	39	968	1093	426
1FU	1	30	360	0.94	0.44	47	968	909	427
2FF	1	30	360	1.13	0.44	39	1290	1458	569
2FU	1	30	360	0.94	0.44	47	1290	1213	570
3FF	1	30	360	1.13	0.44	39	1613	1822	711
3FU	1	30	360	0.94	0.44	47	1613	1516	712
1C	1	30	6	0.09	0.03	34	108	10	3
2C	1	30	6	0.09	0.03	34	144	13	4
3C	1	30	6	0.09	0.03	34	180	16	5

 Table 10. Summary of experimental tests results

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725 Results from the laboratory activities with F+F substrate indicated that anaerobic digestion at HRT 726 of 15 days and 30°C led to a specific biogas production equal to 1.13 m3biogas/kgCODfed with an 727 average CH4 content of 39% (i.e. 0.44 m3CH4/kgCODfed). Thus, when considering a full-scale UASB 728 reactor for decentralized "diverting toilet" effluent treatment (e.g., scenarios FF) biogas and 729 methane production could reach values up to 1822 and 711 m3/d, respectively, for 5,000 730 inhabitants. For lower capacities (e.g., 3,000 and 4,000 inhabitants) yields were 1,093 and 1,458 731 m3/d of biogas and 426 and 569 m3/d of methane, respectively. Whereas if a "dry toilet" is 732 implemented (e.g., scenarios FU), biogas and methane yields could reach values up to 1,516 and 733 712 m3/d for 5,000 inhabitants, while lower yields down to 909 m3biogas/d and 427 m3CH4/d could 734 be achieved for 3,000 inhabitants. This could be due to the positive effect of urine in breeding the 735 methanogenic bacteria and improving the bacteria culture for methane production [70]. It can be 736 concluded that urine addition to feces led minimum decrease in biogas production and slight 737 optimization of methane in biogas together with a water saving of 21 L/p/d. Finally, from pilot UASB 738 operation average biogas and methane production reached values equal to 0.09 and 0.03 739 m3/kgCODfed, respectively. These values led to considerable low expected yields of biogas and 740 methane in the range of (10-16) and (3-5) m3/d respectively, calculated for the full-scale scenario 741 (e.g., scenario 1C, 2C and 3C).

- 742 Thus, considering the expected yields estimated for all the scenarios, energy assessment was 743 delivered, and the net energy production was calculated according to eq. (7). Results are 744 summarized in Table 11, considering: a temperature inside the reactor equal to 30°C; an energy 745 conversion factor of 3,600 kJ/kWh; an energy content of CH4 at standard conditions equal to 746 35,846 kJ/m3CH4; the heat capacity of water of 4.2 kJ/°C kg; a percentage of heat available after 747 losses from vessel and heat exchanger equal to 90%. Moreover, it was calculated that the average 748 temperature of wastewater in winter is averagely equal to 13°C, while in summer about 25°C. For 749 what concerns the temperature inside the reactor: 30°C was considered for decentralized scenario, 750 while 25°C is defined for the centralized one.
- As a result, on one side all the decentralized scenarios resulted in a positive energy consumption with a gross energy production higher than the energy consumed. Specifically, thanks to the biodegradation process, scenario FU resulted the most optimized system in terms of energy efficiency when compared to scenarios FF. For the analyzed capacities and considering a gas tariff equal to $0.075 \notin$ /kWh, possible revenues for F+U+F systems are in the range of (105,731-176,219) \notin /y.
- On the other side, centralized scenarios could be considered as the less energy-efficient cases, as in winter season the biogas produced is not sufficient to provide the amount of energy needed to heat the digester. Thus, although in summer positive results could be achieved, the overall yearly energy balance highlights further energy required in the range of (1,217,131-2,028,552) kWh/y. This implies costs for energy demand from 90,841 to 151,402 €/y, respectively. Possible implementation of further phase of Anaerobic Membrane after the UASB could improve the biogas recovery and the related energetic scenario.
- 764 The distributions of the Global Costs for the analyzed WWTP scenarios are reported in the box-plots 765 graph in Figure 8, under the four considered alternative macroeconomics conditions. Considerations 766 similar to those made for the PAT system (Figure 7) can be drawn. It is noteworthy that the 767 investment and O&M costs in all WWTP cases are of a similar order of magnitude, so that the 768 difference in the resulting Global Costs is almost exclusively given by the different amount of energy 769 produced (FU and FF cases) or consumed (C cases). In particular, the separation between 770 economically inconvenient or advantageous solutions is very clear. FF and FU cases generally 771 provide an economic gain, represented by negative Global Costs in 20 years in all macroeconomic 772 circumstances. The most affordable cases are FU solutions, and especially 3FU case, with a median 773 Global Cost of about 3.9 M€ in the baseline economic scenario (until 5.8 M€ in the Deflation 774 scenario). Conversely, and as expected, 1C, 2C and 3C solutions provide positive and high Global 775 Cost, given that they waste energy during their life cycle.
- Finally, as already shown for drinking water, the interquartile range of boxplots, representing the
 uncertainty associated with the calculated stochastic Global Costs, growths as the value of GC
 increases, and especially in Stagflation and Deflation Scenarios, confirming that the macroeconomic
- variables affecting the energy prices are the main source of uncertainty.



Figure 8 Global Costs for the analyzed WWTP scenarios in the four alternative macroeconomics conditions (RG = Regular Growth, RG = Intense Growth SG = Stagflation, DF = Deflation).

						Table 11	. Summar	y of UASB	performa	nce in ter	ms of ene	rgy recove	ry							
Parame ters	Unit	Decentralized system(F+F)							Decentralized system (F+U+F)						Small Centralized WWTP (F+U+F)					
Scenari o		1FF 2FF 3FF		16	1FU 2FU			3FU		1C		2C		3C						
CH4 prod.*	m3CH4/ kgCOD	0.4	44	0.	44	0.	44	0.4	44	0.	44	0.4	14	0.0	03	0.0	03	0.0	03	
CH4 yield	m3CH4/ d	42	426 569		711		427		570		712		3		4		5			
Flow rate	m3/d	65		86		108		65		86		108		432		576		720		
Season	-	w	S	w	S	W	S	W	S	W	S	w	S	W	S	w	S	w	S	
Workin g time	h/d	10	10	10	10	10	10	10	10	10	10	10	10	24	24	24	24	24	24	
_	kJ/d	6.4 E+06	6.4 E+06	8.5 E+06	8.5 E+06	1.1 E+07	1.1 E+07	1.5 E+07	1.5 E+07	2.0E+ 07	2.0 E+07	2.6 E+07	2.6 E+07	1.2 E+05	1.2 E+05	1.6 E+05	1.6 E+05	2.0 E+05	2.0 E+05	
Energy Product ion	kWh/d	1769	11769	2359	2359	2948	2948	4256	4256	5675	5675	7094	7094	33	33	43	43	54	54	
	kW/m3	27	27	27	27	27	27	66	66	66	66	66	66	0.08	0.08	0.08	0.08	0.08	0.08	
	kJ/d	2.1 E+06	6.3 E+05	2.8 E+06	8.4 E+05	3.6 E+06	1.0 E+06	2.1 E+06	6.3 E+05	2.8 E+06	8.4 E+05	3.6 E+06	1.0 E+06	2.4 E+07	0	3.2 E+07	0	4.0 E+07	0	
Energy Request	kWh/d	592	174	790	232	987	290	592	174	790	232	987	290	6720	0	8960	0	11200	0	
	kWh/ m³	9.18	2.70	9.18	2.70	9.18	2.70	9.18	2.70	9.18	2.70	9.18	2.70	15.56	0	15.56	0	15.56	0	
	kJ/d	4.2 E+06	5.7 E+06	5.6 E+06	7.7 E+06	7.1 E+06	9.6 E+06	1.3 E+07	1.5 E+07	1.8 E+07	2.0 E+07	2.2 E+07	2.4 E+07	-2.4 E+07	1.2 E+05	-3.2 E+07	1.6 E+05	-4.0 E+07	2.0 E+05	
	kWh/d	1177	1595	1569	2126	1961	2658	3664	4082	4885	5443	6107	6803	-6688	33	-8917	43	- 11146	54	
Net	kWh/ m³	18.2	24.7	18.2	24.7	18.2	24.7	56.8	63.3	56.8	63.3	56.8	63.3	-15.5	0.1	-15.5	0.1	-15.5	0.1	
Energy	kWh/ season	2.1 E+05	2.9 E+05	2. 9E+05	3.9 E+05	3.6 E+05	4.8 E+05	6.7 E+05	7.4 E+05	8.9 E+05	9.9 E+05	1.1 E+06	1.2 E+06	-1.2 E+06	5.9 E+03	-1.6 E+06	7.9 E+03	-2.0 E+06	9.9 E+03	
	kWh/y	5	.04 E+05	6	6.73 E+05		8.41 E+05		1.41 E+06		1.88 E+06		2.35 E+06		-1.21 E+0		1.61 E+06		-2.02 E+06	
	kWh/d/ house	2.0	2.7	2.0	2.7	2.0	2.7	6.1	6.8	6.1	6.8	6.1	6.8	-	-	-	-	-	-	

*at standard condition

W = Winter; S = Summer

783

W = Wi

785 4 Discussion on the combined system

In the perspective of a domestic water cycle, an energy production analysis is possible by combining 786 787 the energy harvested from drinking water and that produced from wastewater. At the scale of a 788 small municipality with a population ranging between 3,000 and 5,000 inhabitants, an investigation 789 has been undertaken through specific laboratory tests. The mechanical power generated by drinking 790 water flowing inside a supply system and through a PAT has been measured for different mechanical 791 and hydraulic conditions, also assuming two different system regulations. On the other hand, the 792 biogas and biomethane produced from wastewater have been evaluated for two different toilet 793 operation modes and for decentralized or centralized contexts.

- 794 The hypothesized scenarios for both energy sources have been analyzed in terms of four alternative 795 macroeconomic conditions (Regular Growth, Intense Growth, Stagflation, Deflation). Depending on 796 the considered scenario, the Global Costs provide either positive or negative values in 20 years. In 797 particular, the drinking water source provides the highest economic gains (up to about 50k€) in all 798 macroeconomic conditions if a larger population (5,000 inhabitants) is considered (scenarios 3a and 799 3b), this being due to the larger mechanical power produced at larger flow rates. Comparing with 800 the recent literature, installation of PAT working in similar conditions, i.e. similar flow rate and head 801 drop ranges, produce comparable (if not smaller) energy (e.g., see [16]). Larger incomes may derive 802 from machines with different characteristics. An example is Carravetta et al. [53], who worked with 803 flow rates which were one order of magnitude larger than those used in the present work, i.e. 804 $Q \approx (30-80)$ L/s VS (5-10) L/s, and obtained a produced daily energy that is also one order of 805 magnitude larger than that obtained in the present work, i.e. $E \approx (90-280)$ kWh/day VS (4-806 27) kWh/day.
- 807 The wastewater source provides very good gains (up to 6M€) under all macroeconomic scenarios, 808 considering a decentralized framework (scenarios 1 FF, 1 FU, 2 FF, 2 FU, 3 FF, 3 FU), and especially 809 when the population is the largest (5,000 inhabitants). Conversely, the small centralized approaches 810 lead to important economic losses especially related to the not optimized biogas production 811 working at environmental temperature during the process [71-73]. Specifically, concerning the 812 UASB performance, it can be found that biogas generation (m3biogas/m3 reactor/d) at 813 decentralized level was 1.8 and 1.4 times higher than the average value of 0.4 detected in the 814 literature experience [74] for F+F and F+U+F, respectively. It has to be noticed that despite the greater biogas production in the F+F scenario, the methane content is higher in the F+U+F probably 815 816 thank to the positive effect of urine in improving the bacteria culture for methane production [70]. 817 In order to close the energetic loop, the recovered biogas can be reused in different household 818 applications such as cooking, heating or lighting. In this case, gas turbines, combustion engines, 819 cogeneration or combined heat and power (CHP) can be used to generate electricity (and 820 simultaneous thermal energy in the case of CHP) from biogas [75]. Also, Micro cogeneration 821 (distributed energy resource DER) can be implemented as easily adaptable system at the 822 household/community level for cutting the energy losses and reducing the costs. Within this 823 strategy bills could lower by the 25-34% and up to the 25% of primary energy could be saved [76].
- Although the order of magnitude of the two energy sources is quite different, the present configuration suggests that the integrated presented solutions may be applied to a small-sized municipality or urban area, with particular attention to the most appropriate and convenient solutions for the involved stakeholders (e.g., utility, municipality).
- Hence, if a relevant economic effort might be exerted and a significant budget is available, the realization of a decentralized wastewater treatment could be designed and realized, bearing in mind that this is a suitable choice for population ranging between 3,000 and 5,000 inhabitants. In such a condition, a PAT system could also be installed, as it deals with small investment if compared to the
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investment for the decentralized WWTP, but the small energy harvesting from WDN would affectonly slightly the overall economic gain.

834 On the other hand, the installation of the only PAT system guarantees an economic gain when the population is around 5,000 inhabitants. Such solution might be applied whether a wastewater 835 836 system is already operating in the area of interest, or only a small economic effort can be afforded 837 by the stakeholders, as it might occur in villages marginalized from grid-based electricity supply (e.g., 838 see [40,77,78]). Specifically, little rural communities with relatively small energy demand could 839 benefit from the energy generated by a PAT system, whose production is in line with the 840 consumption of some community services (e.g., electricity for schools, kindergartens, churches, 841 hospitals), as evaluated for rural areas of developing and least developed countries [79,80].

842

843 **5 Conclusions**

The present work has shown the possibility to exploit the domestic water cycle in small-sized urban contexts for energy harvesting purposes. The main conclusions are:

- Experimental tests on DWBTs and the related data analysis have provided insights on the potential energy production under several scenarios, which have been built on the variation of both population (ranging between 3,000 and 5,000) and technological approach (hydraulic or single-series-parallel approach, for the PAT system; urine diverting toilet or dry toilet, for the wastewater treatment).
- The analyzed scenarios have led to a yearly electrical energy, provided by the PAT system, in the range ~(0.9-10) MWh, while the daily production of biogas (between ~900 and ~1800 m³) and methane (between ~400 and ~700 m³) have provided a yearly energy production in the range ~(500-2,000) MWh.
- The LCC assessment has highlighted that, under several potential macroeconomic scenarios,
 the Global Costs after 20 years may reach important gains for both PAT and UASB systems,
 especially in case of a large population, i.e. up to ~50 k€ and ~6 M€, respectively.
- Although the valorization of domestic wastewater source may lead to an amount of energy significantly larger than the electrical energy produced exploiting a PAT, the different economic gain/loss provided by the two investigated technologies translates into a different economic investment, which could make the difference for little municipalities or rural communities located in developing or developed countries.
- Finally, the work demonstrates that a novel approach is possible, based on energy exploitation from the whole domestic water cycle. The novelty comes from the integration of the investigated technologies in small-sized decentralized urban contexts, such integration being rarely considered in the literature, and from the analyzed macroeconomic scenarios, which provide a guideline for the urban planning in least developed, developing and developed countries.
- 868 Future works should aim to assess the environmental performance of the solutions proposed in a 869 Life-Cycle perspective and according to a wider Circular Economy vision. Moreover, further research 870 is needed to apply this integrated application of energy-harvesting technologies from the domestic 871 water cycles at larger scales (i.e. larger population and water demand) and in environments with 872 different features (e.g., low mountainous areas), in order to validate the possible new solutions and 873 to optimize the obtained provisional performances, also exploiting different technologies (e.g., axial 874 PATs). In this sense, strict interdisciplinary future work with building and plant engineering sectors 875 are necessary to integrate new sustainable approaches in the conventional constructions. 876
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889 Data Availability

890 А dataset related to this article be found https://univpmcan at: 891 my.sharepoint.com/:x:/g/personal/p005420 staff univpm it/ERMwQsmBtbVKgJh-7mulhWgBBPQMm6q0csJ6SHth-8llcA?e=t50B1J 892

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1169 Appendix A

1170 The costs associated with the PAT installation within the studied WDN are provided for both HR 1171 (Table A. 1) and SSP (Table A. 2) regulations.

1172

Table A. 1. Preliminary costs evaluation in the case of an HR regulation mode.

Ν	Components	EGE (€)	CW (€)	TC (€)	MC (€/year)
1	РАТ	1030.00	30%		0.75%
2	Control valves	14000.00			
	Tot.	15030.00	4509.00	19539.00	146.54

1173

1174

Table A. 2. Preliminary costs evaluation in the case of an SSP regulation mode.

N	Components	EGE (€)	CW (€)	TC (€)	MC (€/year)
2	РАТ	2060.00	30%		0.75%
3	On-off valves	2100.00			
1	PLC controller	500.00			
2	Pressure transducer	200.00			
	Tot.	4860.00	1458.00	6318.00	47.39

1176 Appendix B

1177 The present section summarizes the existing case studies on anaerobic digestion (Table B. 1), as well as the main parameters and performance of 1178 UASB reactors (Table B. 2).

1179

Table B. 1. Summary of existing case studies

Reference	Unit	Daud et al. [81]	Lohani et al. [82]	Lens et al. [83]	Rose [84]	Blanken et al. [85]	Kujawa- Roeleveld et al. [35]	Khalil et al. [86]	Von Sperling [87]	Von Sperling [88]	AVERAGE
Wastewater (WW) type		Domestic WW	Domestic WW	Domestic WW	Domestic WW	Excrements, Kitchen waste	Concentrated black water	Municipal WW	Municipal WW	Municipal WW	
Flow rate	mld	-	0.00005	0.009	-	-	-	50	-	-	
Inhabitants	n°	-	-	50***	160000***	550 up to 1200)	-	-	9733	
CODtot rem	%	70 - 80	51 - 83	80	-	-	61 - 74	80 - 85	55 - 70	59	
BOD rem	%	75 - 83	-	-	-	-	-	80 - 88	60 - 75	72	
TSS rem	%	70 - 80	57 - 88	-	-	-	-	80 - 85	65 - 80	67	
Piegos Droduction	m3/kg COD rem d	0.05 - 0.25	0.17	-	-	-	0.13-0.16	0.08-0.11	-	-	
Biogas Production	m3/kg COD fed d	0.07 – 0.3	0.11	-	-	-	0.1	0.1 - 0.13	-	-	
Footprint	kgCO2/kg COD rem	0.5 - 1	-	-	-	-	-	-	-	-	
Area Required	m2/mld	1450	-	-	-	-	-	1800	-	-	
OLR for sewage treatmen	t kgCOD/m3d	1 - 2.0	0.23 – 0.96	-	-	-	-	1.15-1.25	-	-	
Economic Life	У	30	-	-	-	-	-	30	-	-	
Annual Power Cost	€/у	-	-	-	-	-	-	15588	-	-	
Total Investment Costs	€/inhab.	10.7 - 18	-	11.8	15.28	36.7	-	-	10.7 - 18	29.2	18.3
Total annual O&M Costs	€/inhab. y	0.9 - 1.34	-	-	1.35	73	-	-	0.9 – 1.35	-	1.1

^aData for this column are referred to UASB + Final Polishing Unit

Table B. 2. Summary of parameters and performance

Ref.	WW Type	Vol	Qin	CODin	CODre m	OLR	т	HRT	Biogas	CH4	Biogas Yield	CH4 Yield		
-	-	m3	m3/d	mg/l	%	kgCOD /m3/d	°C	h	m3/d	m3/d	m3/kg COD fed	m3/kgCO D rem	m3/kgCOD fed	m3/kgCOD rem
	Black water*	0.0047	0.003	1050	73	0.76	35	34	-	0.0003	-	-	0.09	0.34
Gao et al. [89]	Black water**	0.0047	0.0004	9492	83	0.81	35	288	-	-	-	-	0.14	1.15
Lohani et al. [82]	Domestic Wastewater	0.55	0.81	324	67	0.48	0-30	24	0.030	-	0.11	0.17	-	-
de Graaff et al. [90]	Concentrate d Black water	0.05	0.01	8750	71	1	25	209	-	0.018	-	-	0.21	0.29
Kujawa-Roeleveld et al. [35]	Feces + Urine	0.2	0.01	9503	61	0.33	15	696	0.006	-	0.01	0.16	-	-
	Feces + Urine	0.2	0.01	12311	77	0.42	25	696	0.008	-	0.1	0.13	-	-
Nnaji [91]	Domestic Wastewater	Lab Scale	-	-	81	0.4	-	-	-	0.004	-		-	
Zeeman and Roeleveld [92]	Domestic Wastewater	-	-	-	-	-	-	-	0.027	-	-	0.25	-	
AVERAGE	-	-	-	-	75	0.6	-	-	-	-	0.10	0.18	0.15	0.59
ST.DEV	-	-	-	-	9.3	0.3	-	-	-	-	0.01	0.05	0.06	0.48
	Sewage wastewater	64000	-	267	50-75	-	25.2	4-6	-	-	-	-	-	0.19
	Sewage wastewater	4	-	1000	94	3	27.9	8	-	-	-	0.49	-	-
Stazi and Tomei [93]	Sewage wastewater	6.5	-	-	80	1.6	10	8.2	-	-	-	0.14	-	-
	Sewage wastewater	140	-	721	44	2.88	15	24	-	-	-	-	-	0.09
	Sewage wastewater	15.7	-	312	64-70	1.6	13-25	6	-	-	-	-	-	0.16-0.26
Salazar-Larrota et al. [94]	Municipal wastewater	3300	10800	766	52	2.5	26	6.9-7.7	1234	1017	0.15	0.3	0.12	0.24
AVERAGE	-	-	-	-	67	2.3	-	-	-	-	0.15	0.31	0.12	0.18
ST.DEV	-	-	-	-	18.3	0.7	-	-	-	-	-	0.18	-	0.08

1182 *Conventional toilet with 9 L of flushing water/use

1183 **Vacuum toilet with 1 L of flushing water/use