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

Matteo Postacchini<sup>1,\*</sup>, Elisa Di Giuseppe<sup>1</sup>, Anna Laura Eusebi<sup>2</sup>, Leonardo Pelagalli<sup>3</sup>, Giovanna Darvini<sup>1</sup>, Giulia Cipolletta<sup>2</sup>, Francesco Fatone<sup>2</sup>

<sup>1</sup>*Dipartimento di Ingegneria Civile, Edile e Architettura (DICEA), Università Politecnica delle Marche, Ancona (Italy)*

<sup>2</sup>*Dipartimento di Scienze e Ingegneria della Materia, dell'Ambiente ed Urbanistica (SIMAU), Università Politecnica delle Marche, Ancona (Italy)*

<sup>3</sup>*Dipartimento di Ingegneria Industriale e Scienze Matematiche (DIISM), Università Politecnica delle Marche, Ancona (Italy)*

\* Corresponding: [m.postacchini@staff.univpm.it](mailto:m.postacchini@staff.univpm.it)

## Abstract

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

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

**Nomenclature**

BMP: Biochemical Methane Potential

BW: Black Water

CAPEX: CAPital EXpenditure

CP: Calculation Period

DWBT: Domestic Water-Based Technology

37	FF: Feces+Flushing water (urine diverting	73	$E_{dw}$ : 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	$Eff_{heat}$ : 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
44	GLS: Gas-Liquid-Solid	80	$KgCOD_{fed}$ : amount of the COD which was
45	HR: hydraulic regulation	81	inserted in the batch volume at the beginning
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	$Y_{CH_4}$ : specific biomethane
59	WWTP: WasteWater Treatment Plants	95	$\alpha$ : ratio between daily mean water demand
60	$\%CH_4(t)$ : percentage of methane in the biogas	96	and annual mean consumption
61	produced at the duration test $t$	97	$\Delta H$ : head drop
62	$Biogas(t)$ : biogas produced at the duration	98	$\Delta H_{mean}$ : daily mean head drop
63	test $t$	99	$\Delta H_{max}$ : daily maximum head drop
64	$C_d$ : water consumption variability during the	100	$\Delta T$ : temperature increase for influent
65	day	101	wastewater
66	$CI$ : cost of initial investment	102	$\gamma$ : water specific weight
67	$CM_t$ : cost for annual O&M	103	$\mu_q$ : daily mean water demand
68	$CE_t$ : annual gain of energy	104	$\eta$ : PAT efficiency
69	$R_t^{disc}$ : discount factor	105	$\eta_{best}$ : best PAT efficiency
70	$R_t^I, R_t^E$ : price development rates	106	$\eta_g$ : generator efficiency for either HR
71	$COD_{rem}$ : COD removed	107	regulation ( $\eta_{g,HR}$ ) or SSP regulation ( $\eta_{g,SSP}$ )
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  
112 and resources depletion, recovering energy and optimizing the exploitation of available natural  
113 sources. A non-conventional approach is thus proposed based on the domestic water cycle as a  
114 direct 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,  
117 the transition towards the integration of RES in the building sector began by considering buildings  
118 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

120 designed and managed considering different levels of building clusters, districts and cities [1].  
121 According to this challenging vision, energy planning at higher scales than building level, would  
122 provide huge advantages in terms of sustainability and cost optimality [2,3]. In this context, the  
123 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].

131 Moreover, the whole concept of water-energy nexus in urban contexts needs to undergo a profound  
132 rethinking in the light of drivers such as climate change, population growth and technological  
133 development and addressing the growing need for an effective economy circularity application in  
134 the sector [7]. Energy and water flows should be not considered isolated cycles, but conceived more  
135 and more in a holistic way, including their interactions. For this reason, also the importance of topics  
136 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  
157 well as to reduce energy consumptions [11] and water leakages [12], such as the application of  
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].

164 However, the use and optimization of classical turbines is hard and costly in WDNs, especially in  
165 small urban agglomerates or districts, due to the large variability of water demand during the day  
166 [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  
168 applied to a traditional supply system, like a WDN, where the water flow forces the pump impeller  
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].  
183 In terms of PAT functioning, the combination with a PRV can improve the PAT performances,  
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 sector<sup>1</sup> 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

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

212 in small communities, as these solutions can provide the possibility not only to treat municipal  
213 greywater but also to recover water, biogas for further reuses<sup>2</sup> and nutrients after the co-treatment  
214 of the anaerobic sludge [38].

215 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  
217 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.

219 The main findings of laboratory tests on PAT and WWTPs applications have been used to evaluate  
220 their potential in a typical ideal scenario of a small urban context where water demand profiles are  
221 set.

222 To assess the economic performance of the proposed solutions, their energy production and global  
223 costs in a Life Cycle Costing (LCC) perspective are evaluated. The economic dimension is just one of  
224 the three main components of sustainability assessment. However, this constitutes an important  
225 aspect to be scrutinized together with the technical feasibility. Indeed, the financial aspect is a  
226 typical barrier to an effective implementation of renewable solutions.

227 Hence, the present research provides a further contribution to the field of urban energy-water  
228 cycles, pursuing the following objectives: (i) investigating an integrated approach for the energy  
229 harvesting, through the exploitation of the domestic water cycle and based on DWBTs; (ii) providing  
230 an added value to supply and sanitary systems in small-sized urban areas, based on experimental  
231 tests covering flow rates that are consistent with the water demand in small-sized urban areas; (iii)  
232 providing a feasibility assessment based on a “stochastic” LCC, able to take into account the intrinsic  
233 uncertainties due to future economic scenarios. The application of a “stochastic” LCC is a novelty of  
234 this work compared to the conventional approaches adopted in most of the literature, which  
235 disregard the long-term uncertainty and interdependence affecting the macroeconomic variables  
236 and, consequently, misrepresent the impact of the associated risk.

237 In other words, the proposed integrated solution for the energy exploitation from the domestic  
238 water cycle leads to a circular approach which is a novelty for small urban contexts, while the  
239 analyzed macroeconomic scenarios provide a guideline for the urban planning in such areas, to face  
240 the economic barriers for feasibility.

241 The paper is divided as follows. Section 2 reports the experimental tests carried out using the two  
242 defined technologies, as well as the definition of both the real-world scenarios and the LCC based  
243 on the energy production. Section 3 describes the main results of the chosen applications in terms  
244 of energy and global costs. Section 4 discusses the main results, while Section 5 presents the final  
245 remarks.

246

## 247 **2 Material and methods**

248 The present work aims at finding appropriate and efficient solutions to produce energy from the  
249 water source in different urban contexts and at different scales, also considering the LCC aspect.  
250 This could be obtained using PAT technologies and producing biogas from WWTPs, especially in  
251 areas where the excess water pressure needs to be significantly dissipated in the local WDN and a  
252 specific sewage treatment can be applied, like remote villages or decentralized districts.

253 To this purpose, ideal urban scenarios have been built with the aim to represent either small rural  
254 contexts or decentralized area, often found in Italy and in many other countries worldwide. In a  
255 scarcely populated zone like this, peaks of water demand can be significantly variable, due to the  
256 different users’ habits. Further, such contexts are of great interest due to the lack of information in

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<sup>2</sup> <https://www.hydrousa.org>

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

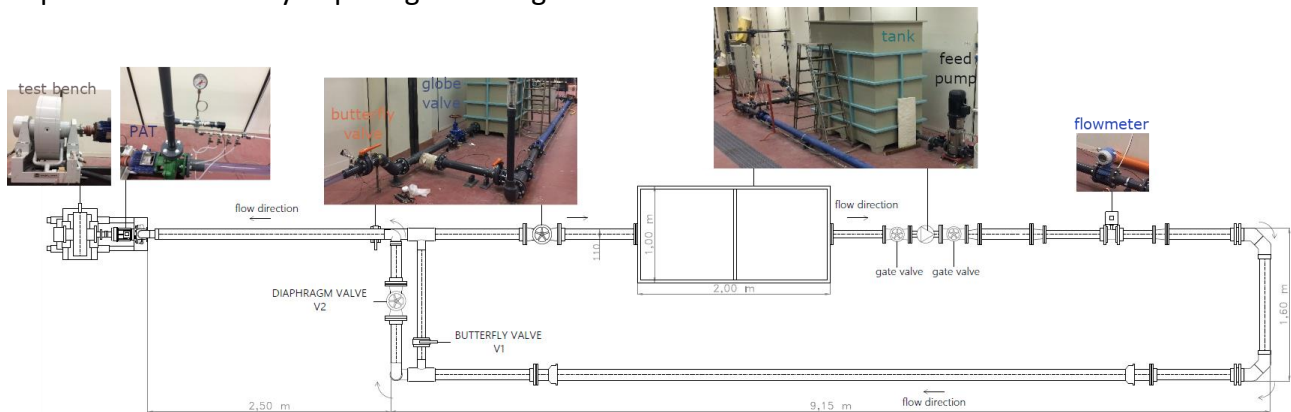
## 266 2.1 Experimental tests

267 Energy generation from a typical WDN was investigated through dedicated laboratory tests, focused  
 268 on the characterization of a PAT, while biogas production and its methane content were monitored  
 269 both at laboratory scale and pilot scale for valorization in terms of energy production.

### 271 2.1.1 Drinking water and supply system

272 Energy generation through a PAT-based system was investigated in a series of experimental tests  
 273 conducted in the Laboratory of Hydraulics and Maritime Constructions of the Università Politecnica  
 274 delle Marche (Ancona, Italy), where an old centrifugal pump was installed in an existing facility  
 275 resembling a traditional supply system, and tested in reverse mode [39] (Figure 1).

276 To both identify the most efficient PAT configurations and provide useful hints for possible real-  
 277 world applications, several tests were carried out. The hydrodynamic conditions (pressure and flow  
 278 rate) of the plant were varied by adjusting the frequency of a feed pump, with the aim to get the  
 279 performance curve of the PAT. The tested flow rates were in the range  $Q = (5-9) L/s$ , while the  
 280 pressure heads were in the range  $H = (4.8-33.9) m$ . Head drops  $\Delta H$  were recorded using two  
 281 pressure sensors located, respectively, upstream and downstream of the PAT. The mechanical  
 282 behavior of the PAT was investigated by means of a test bench that allowed the regulation of the  
 283 impeller rotation  $N$  by imposing a braking force  $M$  to the PAT shaft.

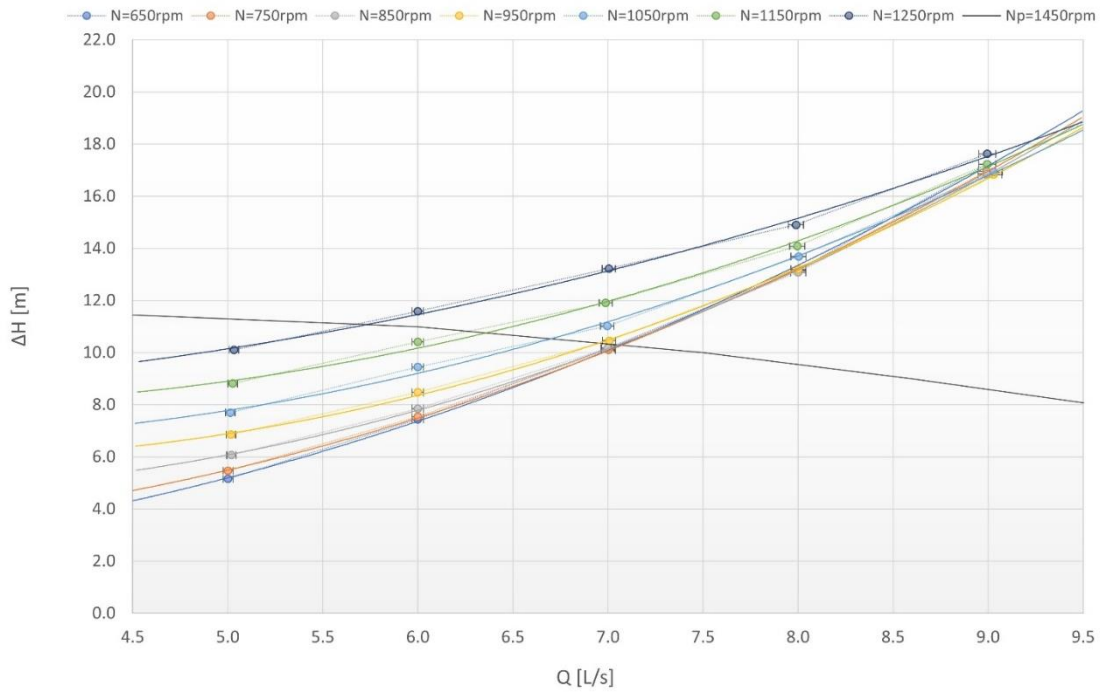


284  
 285 **Figure 1.** Schematic of the supply system, with the insets showing some of the system details.  
 286

### 287 2.1.2 Evaluation of mechanical power

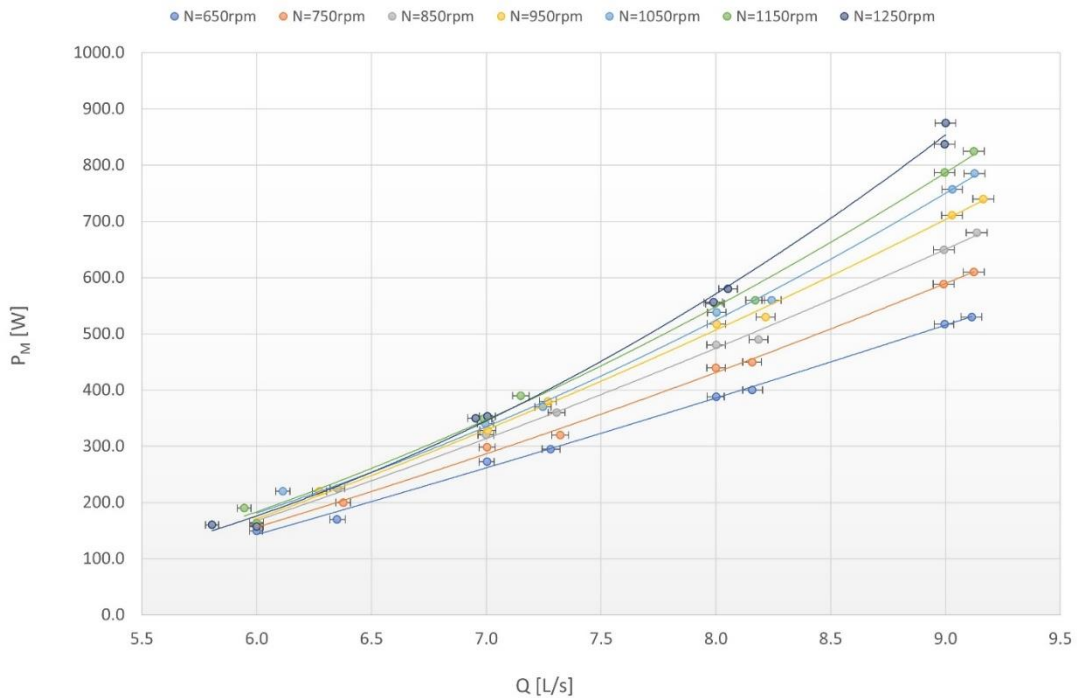
288 Tests with specific flow rates  $Q$  and rotation speeds  $N$ , respectively ranging between  $(5-9)L/s$   
 289 and  $(650-1250)rpm$ , led to the performance characteristic curves, each one related to a specific  
 290  $N$  value (Figure 2). The evaluation of both induced hydraulic power  $P_H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

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



297  
 298 **Figure 2.** Characteristic curves of the PAT, each referring to a specific speed  $N$  (colored lines). The curve referring to the pump  
 299 working in classical mode at  $N = 1450 \text{ rpm}$  is also shown (black line).  
 300

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



305  
 306 **Figure 3.** Mechanical power vs. flow rate through the PAT, each referring to a specific speed  $N$ .  
 307

308 2.1.3 Black undiluted wastewater and municipal wastewater

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,  
 311 according to literature assessment [41], the recipes reported in Table 1 were used to simulate the  
 312 mentioned matrices.

313

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

COMPONENTS	AMOUNTS [G]		REFERENCE
<b>FECES</b>			
<b>HUMIDITY CONTENT (%TS)</b>	80% (S80)	65% (S65)	Penn et al. [41]
	SB80 (g)	SB65 (g)	
<b>YIEST EXTRACT</b>	72.29	126.51	
<b>BIER YIEST</b>	0	0	
<b>MICROCRYSTALLINE CELLULOSE</b>	24.1	42.17	
<b>PSILLIUM</b>	42.17	73.8	
<b>MISO PASTE</b>	42.17	73.8	
<b>VEGETAL OIL</b>	48.19	84.34	
<b>NACL</b>	4.82	8.43	
<b>KCL</b>	4.82	8.43	
<b>CACL<sub>2</sub>·H<sub>2</sub>O</b>	2.41	4.81	
<b>WATER</b>	758.7	577.72	
<b>1 KG FINAL FECES</b>	1000	1000	
<b>URINES</b>			
<b>NACL</b>	3.6		Udert & Wächter [42]
<b>KCl</b>	3.4		
<b>KHCO<sub>3</sub></b>	1.1		
<b>Na<sub>2</sub>SO<sub>4</sub></b>	2.3		
<b>NaH<sub>2</sub>PO<sub>4</sub>·2H<sub>2</sub>O</b>	2.7		
<b>NH<sub>4</sub>NO<sub>3</sub></b>	19.2		

314

315 Feces and urines were used in the batch tests as external carbon source and substrate to keep the  
 316 inoculum to substrate (I:S) ratio constant at value of 2 (VSS basis) [43]. The substrate was added to  
 317 obtain an Organic Loading Rate (OLR) equal to 1 kgCOD/m<sup>3</sup>/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  
 327 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  
 329 to be considered for energy production in decentralized scenarios. Finally, rates obtained with black  
 330 water (F+FI and F+U) were compared with biogas production derived by the anaerobic digestion of  
 331 municipal wastewater at pilot scale.

332 Municipal wastewater is treated in the Pilot Hall of the Università Politecnica delle Marche through  
 333 a UASB reactor, heated at 30°C. The influent from Falconara WWTP is the preliminary treated by  
 334 means of screening, degritting and oils removal before being sent to the pilot-scale UASB. Influent  
 335 is fed with a peristaltic pump (Watson-Marlow, UK) to guarantee an influent flow rate of about 3  
 336 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.  
 345 Pilot scale experimental test was performed to evaluate the biogas and methane productions yield  
 346 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.

357 The BMP tests were conducted according to van Loosdrecht et al. [43] and in a thermostatic bath at  
 358 temperature-controlled conditions at 30°C with an overall HRT of 15 days. Specific biogas  
 359 production was daily registered (in mL) and biogas samples were collected to determine methane  
 360 content in the biogas by means of gas chromatography “Bruel and Kjaer Multi-gas Monitor Type  
 361 1302” based on photoacoustic spectroscopy. Biogas and biomethane production rates were  
 362 calculated and expressed as mL of biogas or biomethane per kg of COD removed or fed.

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

367 Furthermore, specific biogas ( $Y_{biogas}$ ) and biomethane ( $Y_{CH_4}$ ) yields were calculated with the following  
 368 equations 1 and 2:

$$369 \quad Y_{biogas} \left[ \frac{m^3 biogas}{kg COD_{fed}} \right] = \frac{Biogas(t)}{kg COD_{fed}}, \quad (1)$$

$$370 \quad Y_{CH_4} \left[ \frac{m^3 CH_4}{kg COD_{fed}} \right] = \frac{Biogas(t)}{kg COD_{fed}} \cdot \frac{\%CH_4(t)}{100}, \quad (2)$$

371 where:

- 372 •  $Biogas(t)$  is the biogas produced at the duration test  $t$  ( $m^3$ );
- 373 •  $KgCOD_{fed}$  is the amount of the COD which was inserted in the batch volume at the  
 374 beginning of the test ( $kg/m^3$ );
- 375 •  $\%CH_4(t)$  is the percentage of methane in the biogas produced at the duration test  $t$  (%).

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.

387 The selected population cases, consistent with the configurations investigated in [39], are  
388 considered in the following sections for both drinking-water framework/PAT system (Section 2.2.1)  
389 and wastewater framework/biogas (Section 2.2.2), as well as for the definition of the LCC (Section  
390 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.  
395 In the present cases, the reference flow rate is the daily mean water demand required by users  $\mu_q$ ,  
396 estimated through the classical formulation

$$397 \mu_q = \alpha \cdot n \cdot d \quad (3)$$

398 where:

- 399 •  $n$  is the number of served inhabitants, i.e. either 3,000, 4,000 or 5,000;
- 400 •  $d$  is the per-capita water demand, assumed as 160 *lpd* (maximum water required in little  
401 communities [46]);
- 402 •  $\alpha$  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.

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

$$407 Q(t) = \mu_q \cdot C_d(t) \quad (4)$$

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].

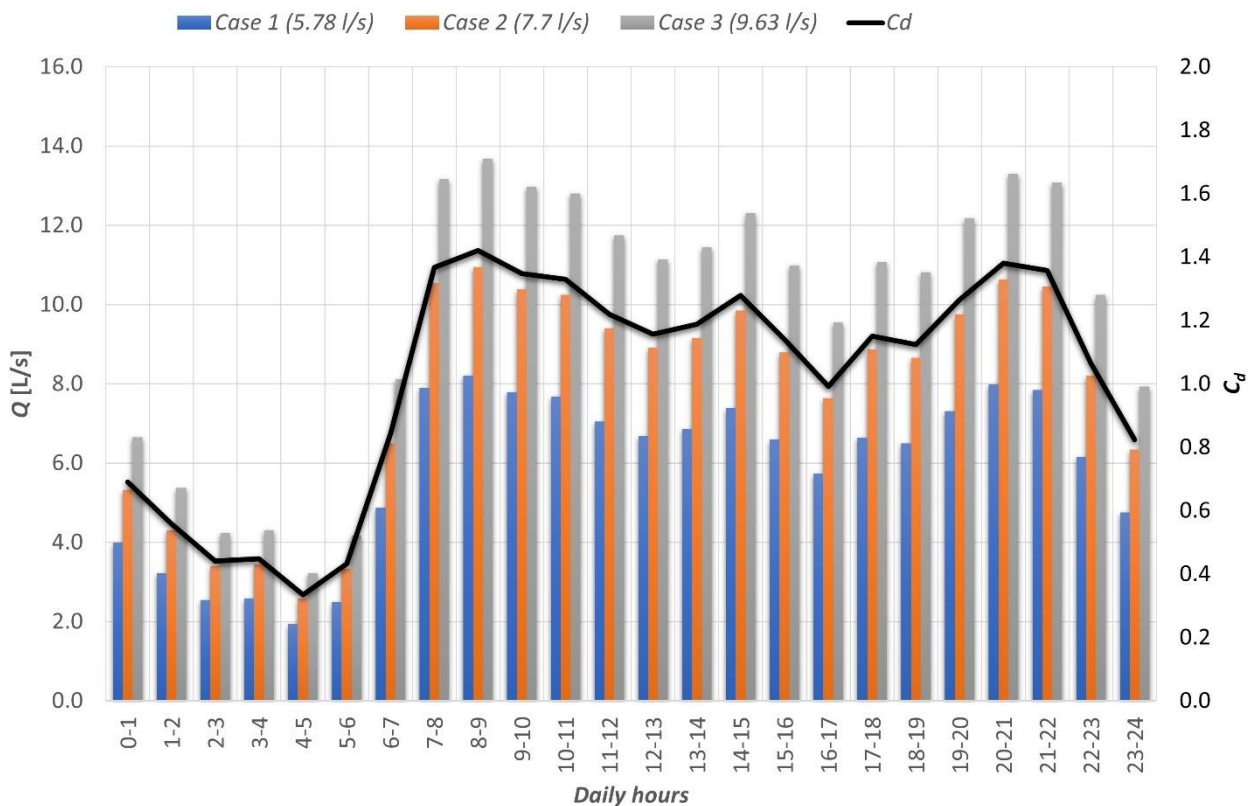
414 The trend of  $C_d$  illustrated in Figure 4 is thus typical of relatively small urban areas. Specifically, while  
415 areas with larger population (over 10,000 people) are identified by  $C_d$  distributions characterized  
416 by a smoothed trend and only one peak [47–49], smaller areas are identified by two or more peaks  
417 [19], that correspond to hours of larger demand. In the present case, a clear increase of water  
418 demand occurs between 5:00 and 8:00 am. Further, the demand is large between 8:00 (first peak)  
419 and 21:00 (second peak), with a minimum around 16:00-17:00.

420 Values of the hourly-averaged flow rate  $Q(t)$  during the day are calculated using eq. (4). Figure 4  
421 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].

430 A first solution, suitable for a real-world application, is the use of a hydraulic regulation (HR) realized  
 431 by combining PAT with PRVs, that allow to reduce the upstream pressure and make the PAT work  
 432 in almost optimal way [16,26]. In fact, with the HR approach, two regulating valves are combined to  
 433 the PAT system: one upstream, in series with the pump, dissipates some of the excess pressure,  
 434 when power generation is important during the day. On the other hand, the second valve is  
 435 integrated into a bypass in parallel with the PAT, providing greater dissipation when the pump is not  
 436 working, i.e. during the nighttime. Such combination allows the PAT to work properly, in terms of  
 437 both head drop and flow rate.



438  
 439 **Figure 4.** Hourly coefficient  $C_d$  (solid line, right y axis) and hourly-averaged water demand for the three proposed scenarios  
 440 (columns, left y axis): case 1 (3,000 inhabitants; blue), case 2 (4,000 inhabitants; orange), case 3 (5,000 inhabitants; gray).

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  
 453 downstream valves, with the aim to make the PATs work in parallel in case of much higher flow  
 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  
 458 contexts, as described by several works [16,26,39,52]. Details on the costs relevant to both  
 459 regulations are provided in Appendix A.

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

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

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

#### 469 2.2.2 Definition of wastewater scenarios

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

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

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

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

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

485 where  $Q_{ww}$  is the influent wastewater ( $m^3/d$ ).

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

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

494 *Table 3. Tested scenarios for the wastewater source.*

Scenario	<i>n</i>	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	-

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

$$499 \quad E_{ww} = \left[ Q_{ww} \cdot COD_{rem} \cdot \left( \frac{0.35 \text{ m}^3 \text{ CH}_4}{\text{kg COD}_{rem}} \right) \cdot \left( \frac{35,864 \text{ kJ}}{\text{m}^3 \text{ CH}_4} \right) - Q_{ww} \cdot \Delta T \cdot C_p \cdot \left( \frac{10^3 \text{ kg}}{\text{m}^3 \text{ H}_2\text{O}} \right) \cdot \left( \frac{1}{Eff_{heat}} \right) \right] \cdot \frac{3600 \text{ kJ}}{\text{kWh}} \quad (8)$$

500 where:

- 501 •  $COD_{rem}$ : COD removed (kg/m<sup>3</sup>)
- 502 •  $\Delta T$ : temperature increase for influent wastewater (°C)
- 503 •  $C_p=4.2$  kJ/°C·kg: specific heat of water
- 504 •  $Eff_{heat}$ : 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.

### 507 2.3 Life Cycle Costing based on estimated DWBTs' energy production

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

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

$$518 \quad GC = CI + \sum_{t=1}^{CP} (CM_t R_t^{disc} R_t^L - CE_t R_t^{disc} R_t^E) \quad (9)$$

519 where:

- 520 • CI is the cost of initial investment;
- 521 •  $CM_t$  is the cost for annual O&M (assumed constant);

- 522 •  $CE_t$  is the annual gain of energy (assumed constant);
- 523 •  $R_t^{\text{disc}}$  is the discount factor;
- 524 •  $R_t^L$  and  $R_t^E$  are the price development rates (respectively for human operation and for
- 525 energy).

526  
 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].  
 534 For each Monte-Carlo iteration, a draw from the macro-economic variables’ distributions is realized,  
 535 thus propagating the stochastic nature of the calculation into the statistical distribution of the  
 536 output Global Cost. Consequently, the economic evaluation of the proposed DWBT solutions is itself  
 537 stochastic and represented by a probability density function, thus expressing both its expected  
 538 mean value and its inherent uncertainty.

540 *Table 4. Summary statistics (Mean and SD= Standard Deviation of distribution, in %) and characterization of the alternative*  
 541 *macroeconomic scenarios for the LCC evaluation: the “regular growth” scenario is the baseline case, ↑ means higher than the*  
 542 *baseline, ↓ means lower than the baseline.*

Variable:	Inflation rate		Interest rate		GDP	
	Mean	SD	Mean	SD	Mean	SD
<b>Macro-economic scenario:</b>						
<b>Regular growth (RG) -Baseline</b>	2.25	0.97	2.77	0.78	2.54	1.64
	=		=		=	
<b>Intense growth (IG)</b>	2.55	0.63	3.45	0.73	3.31	1.19
	↑		↑		↑	
<b>Stagflation (SF)</b>	8.41	3.35	4.81	0.32	0.34	3.21
	↑		↑		↓	
<b>Deflation (DF)</b>	0.46	1.11	1.50	0.63	1.34	1.62
	↓		↓		↓	

543  
 544 The stochastic LCC is performed considering four alternative macro-economic scenarios,  
 545 characterized by different distributions of the macro-economic variables entering eq. (9), in order  
 546 to evaluate the outcomes’ robustness in possible different economic conditions. These scenarios  
 547 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  
 554 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  
 556 that tested during the experimental laboratory phase (i.e.  $\approx 1$  kW). The price of valves has been  
 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  $CM_t$  for the whole CP at 15% of the CI [22,55,58,59]. Table 5 summarizes CI and  $CM_t$  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  
 562 more economically convenient at the time of investment, especially in case of small-sized  
 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.  
 568

569 *Table 5 Summary of the purchase and installation costs of the technological variants considered in the PAT systems evaluation.*  
 570 *Total CI and  $CM_t$  for the LCC assessments are also reported.*

Scenario	$n$	$\mu_q$ [l/s]	CI [€]	$CM_t$ [€]
<b>1a</b>	3,000	5.78	19,539.00	146.54
<b>1b</b>	3,000	5.78	6,318.00	47.39
<b>2a</b>	4,000	7.7	19,539.00	146.54
<b>2b</b>	4,000	7.7	6,318.00	47.39
<b>3a</b>	5,000	9.63	19,539.00	146.54
<b>3b</b>	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  
 576 into the sewage network for decentralized and centralized case, respectively. Furthermore, a total  
 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 *Concerning  $CM_t$ , costs were calculated based on the annual cost per reactor (according to eq.(6))*  
 582 *and the numbers or units needed. Specifically, annual costs were calculated with the same flow*  
 583 *rates considered for CI and the annual operative cost expressed in  $\text{€}/m^3/d$ .*

584  
 585 Table 6 summarizes the CI and  $CM_t$  for the technological variants of the WWTP systems.  
 586 The annual energy gains are calculated multiplying the annual energy production for the energy  
 587 selling price related to the specific energy carrier in Italy: at 0.186 €/kWh for electricity (in the case  
 588 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).  
 592

593

594

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

Scenario	$n$	Description	Total investment Cost (purchase + installation) [€/m <sup>3</sup> /d]	Annual O&M Cost [€/m <sup>3</sup> ]
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	3,000	Small Centralized 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

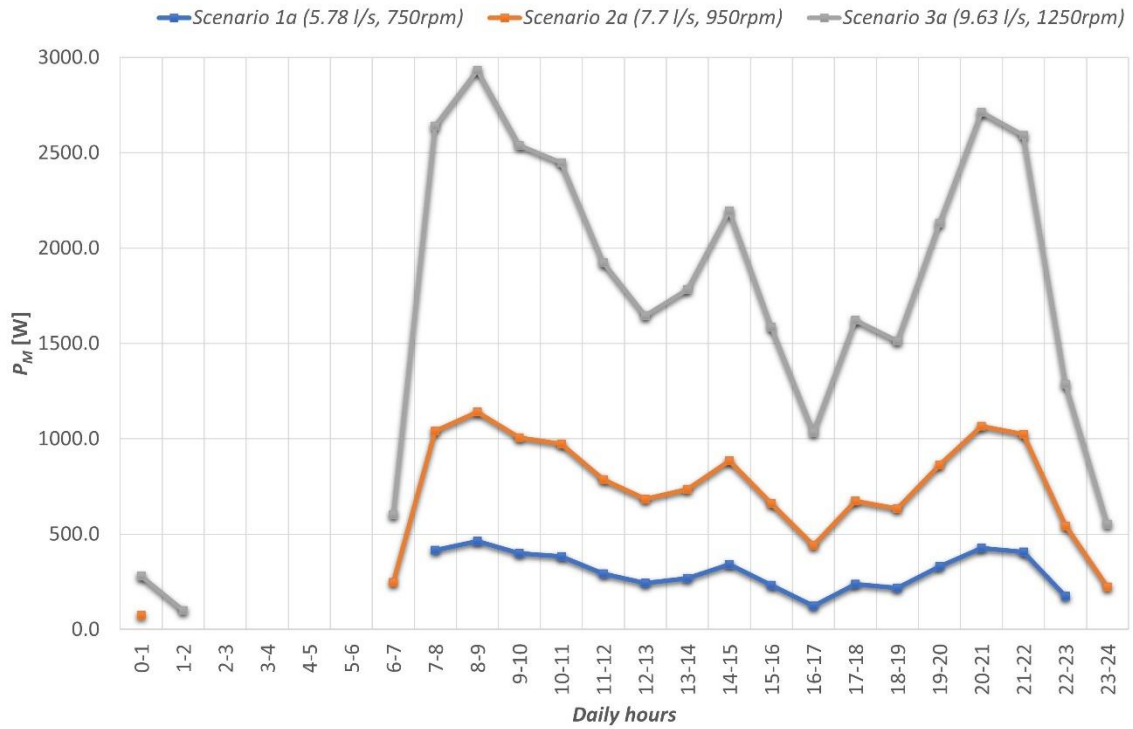
595

### 596 3 Results

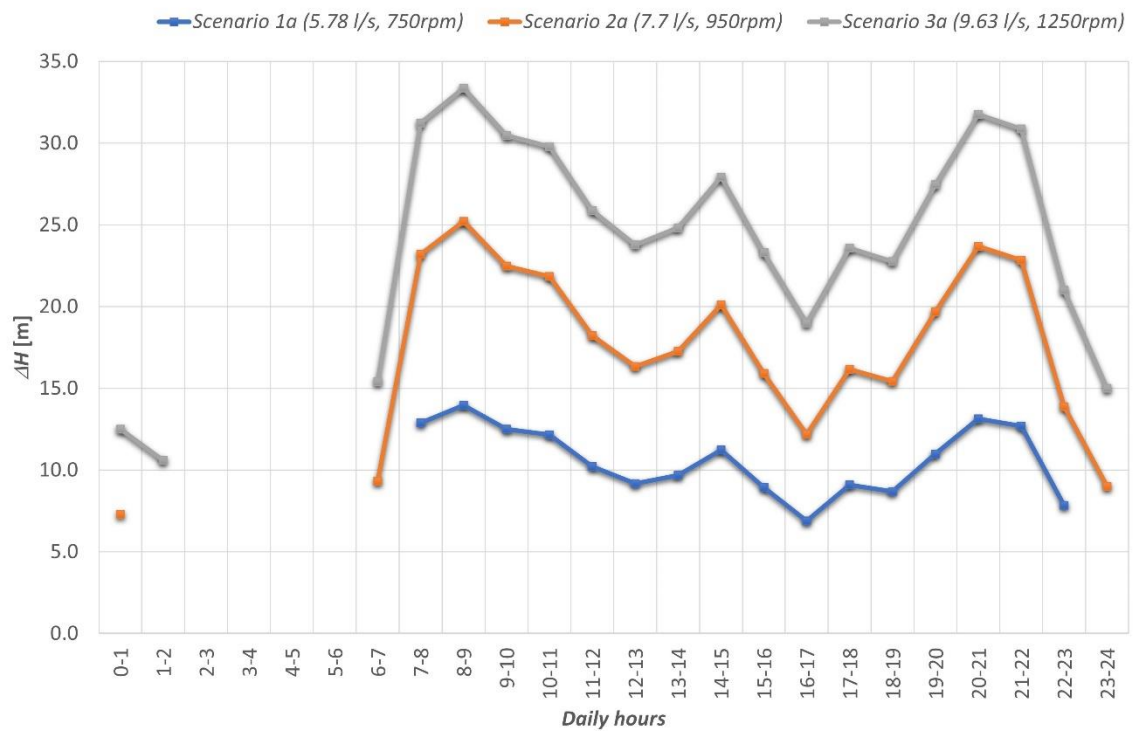
#### 597 3.1 Energy and Global costs from drinking water

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]).

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



611  
612  
613  
614  
**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).



615  
616  
617  
618  
**Figure 6.** Daily distribution of head drop for the three HR scenarios (see also Table 2): scenario 1a (blue line), scenario 2a (orange line), scenario 3a (gray line).

619 In terms of functioning (i.e. for  $Q > 5$  L/s, as stated above), the system would work during most of  
620 the day, i.e. for 16 hours (time range 7:00-23:00) in scenario 1a, and for 19 hours and 20 hours in  
621 scenarios 2a and 3a, respectively. In general, all scenarios show similar trends in terms of both  $P_M$

622 and  $\Delta H$ , replicating the Q distribution (Figure 4) and identified by the following crucial conditions: i)  
 623 increase starting at 6:00, ii) first peak between 8:00 and 9:00, iii) local minimum at 4:00-5:00, iv)  
 624 second peak at 20:00-21:00.

625 Other interesting features concern the change in the mechanical power when passing from a  
 626 scenario to another (Table 7). Specifically, passing from 3,000 to 4,000 to 5,000 inhabitants, the  
 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 ( $\Delta H_{mean}$ ) and maximum ( $\Delta H_{max}$ ) 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	$n$	$\mu_q$ [L/s]	$P_{M,mean}$ [W]	$P_{M,max}$ [W]	$\Delta H_{mean}$ [m]	$\Delta H_{max}$ [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  
 636 The total amount of mechanical energy produced during the day is equal to 4.96 kWh, 13.70 kWh  
 637 and 34.11 kWh for scenarios 1, 2 and 3, respectively. The yearly production is also calculated and  
 638 then used for the estimate of the electrical energy through an efficiency of the generator which is  
 639 different for HR and SSP approaches. For the classical HR regulation, it is assumed  $\eta_{g,HR} = 0.8$ , while  
 640 for the SSP regulation, in agreement with the difference in plant capability between such regulation  
 641 modes [16,64,65], it is assumed  $\eta_{g,SSP} = 0.46$ . Finally, the yearly produced electrical energy is  
 642 evaluated integrating in time the mechanical power:

$$E_{dw} = \eta_g \cdot 365 \cdot \sum_{h=1}^{24} P_M \quad (10)$$

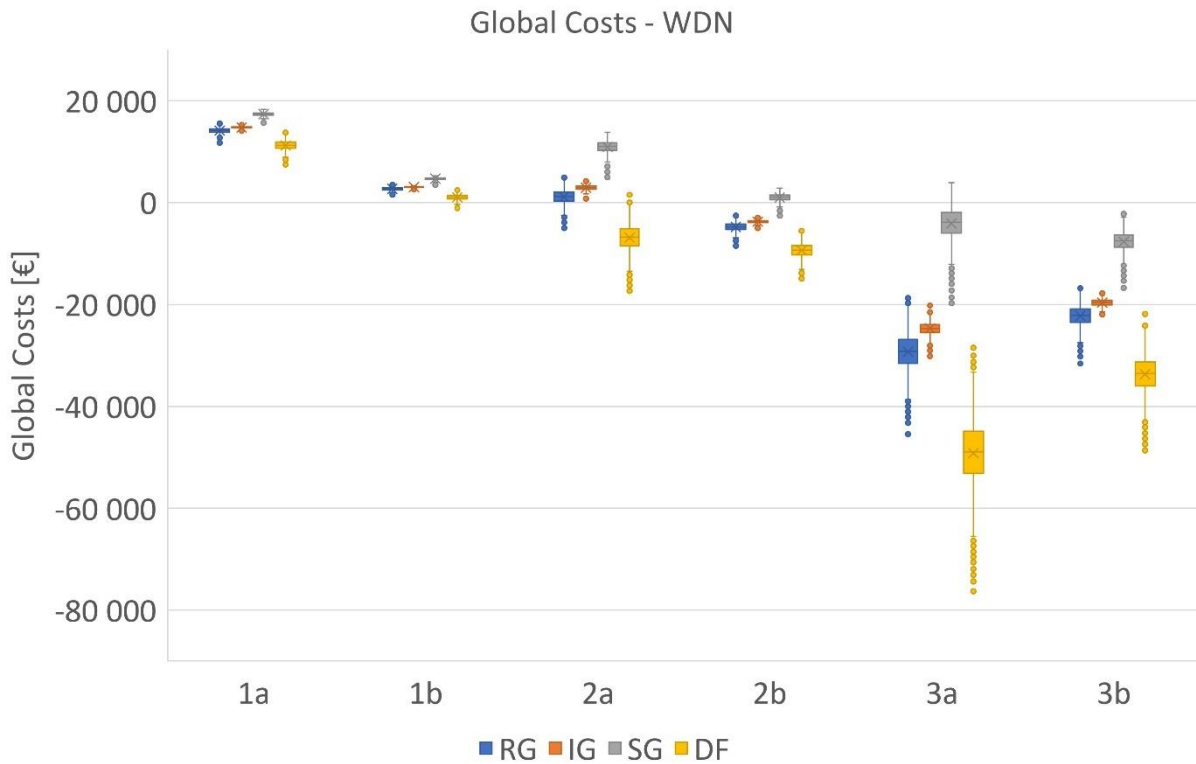
643  
 644 The final outputs are illustrated in Table 8, showing large variability among the considered scenarios,  
 645 with the scenario 3a providing the largest energy production (9,961.38 kWh), while the scenario 1b  
 646 provides the smallest value (832.41 kWh).

647 *Table 8. Mechanical and electrical energy from all scenarios.*

Technological approach	HR			SSP		
	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
$\eta_g$	0.8			0.46		
$E_{dw}$ [kWh/year]	1,447.68	4,000.46	9,961.38	832.41	2,300.26	5,727.80

648  
 649 The above results suggest that some of the proposed scenarios provide a significantly low energy  
 650 saving and the PAT operation falls close to the lower limit of applicability [66]. However, to properly  
 651 analyze the feasibility of each scenario, the results of the LCC evaluation are reported, also bearing  
 652 in mind that the present work only proposes a methodology to be applied to a decentralized  
 653 context, hence the PAT here used can be substituted with another one that best suites the  
 654 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-axis), considering the four alternative macroeconomics conditions (represented by different colors).  
 656 It should be reminded that Global Costs are represented by distributions given the stochastic nature  
 657 of the macro-economic variables entering the LCC assessments.  
 658 Global Costs have positive values where in 20 years the energy produced is not sufficient to  
 659 compensate for the initial investment, negative values in case of an economic gain. In general, the  
 660 highest GCs for all PAT scenarios are obtained in the Stagflation scenario, while the lowest ones in  
 661 the Deflation scenario.  
 662



663

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

666 In all macroeconomic conditions, scenarios 1a and 1b result not affordable. For solution 1a, GC  
 667 median value ranges from a minimum of about 11,200 € (in the Deflation scenario) to a maximum  
 668 of about 17,400 € (in the Stagflation scenario), while the range of GC median value for solution 1b  
 669 is included between 1,040 € (in the Deflation scenario) and 4,700 € (in the Stagflation scenario).  
 670 Indeed, these scenarios entail quite high investment costs (19,539 € for 1a as all HR systems and  
 671 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.

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

681 Figure 7 exhibits another interesting information provided by the stochastic LCC assessment, i.e. the  
 682 uncertainty expressed by GC variability. Indeed, the interquartile range grows 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.

687

### 688 3.2 Energy and Global costs from wastewater

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

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

697

*Table 9. Summary of Scenarios Economic Assessment*

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	<b>600</b>	10	<b>800</b>	10	<b>1000</b>
Persons per house	5		5		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 [€]	<b>29207</b>	<b>58965</b>	<b>38943</b>	<b>74225</b>	<b>48678</b>	<b>88731</b>
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]	<b>26459</b>	<b>9386</b>	<b>35278</b>	<b>10870</b>	<b>44098</b>	<b>12180</b>
Total Annual Operative Cost [€/PE]	9	3	9	3	9	2
Land requirement [m2/m3/d]	10	5	10	5	10	5

698 From the assessment it was evident that, although the specific CAPEX [€/m<sup>3</sup>/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 (m<sup>3</sup>/d).  
 701 Moreover, when considering a centralized implementation, specific CAPEX was found to decrease  
 702 with the treatment capacity, passing from 136 €/m<sup>3</sup>/d to 123 €/m<sup>3</sup>/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 m<sup>2</sup>/m<sup>3</sup>wastewater 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 m<sup>3</sup> 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.

713 From the assessment a higher methane production was detected when concentrated wastewater  
 714 (e.g., black water/domestic water) is treated rather than diluted wastewater (e.g., grey+black  
 715 water/urban wastewater), at same reactor temperature. Averagely, for concentrated wastewater  
 716 methane yield was estimated equal to +17% m<sup>3</sup>CH<sub>4</sub>/kgCOD<sub>fed</sub> and +70% m<sup>3</sup>CH<sub>4</sub>/kgCOD<sub>removed</sub>  
 717 respect to municipal wastewater treatment. However, a slight decrease was detected in the biogas  
 718 production. This could be due to a higher CH<sub>4</sub> percentage in the produced biogas when a  
 719 concentrated wastewater is treated.

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

723

*Table 10. Summary of experimental tests results*

Expected full-scale performance									
Scenario	OLR	T	HRT	Biogas Yield	CH <sub>4</sub> Yield	%CH <sub>4</sub> /biogas	COD <sub>fed</sub>	Biogas	CH <sub>4</sub>
-	kgCOD/m <sup>3</sup> /d	°C	h	m <sup>3</sup> biogas/kgCOD <sub>fed</sub>	m <sup>3</sup> CH <sub>4</sub> /kgCOD <sub>fed</sub>	%	kgCOD/d	m <sup>3</sup> /d	m <sup>3</sup> /d
<b>1FF</b>	1	30	360	1.13	0.44	39	968	1093	426
<b>1FU</b>	1	30	360	0.94	0.44	47	968	909	427
<b>2FF</b>	1	30	360	1.13	0.44	39	1290	1458	569
<b>2FU</b>	1	30	360	0.94	0.44	47	1290	1213	570
<b>3FF</b>	1	30	360	1.13	0.44	39	1613	1822	711
<b>3FU</b>	1	30	360	0.94	0.44	47	1613	1516	712
<b>1C</b>	1	30	6	0.09	0.03	34	108	10	3
<b>2C</b>	1	30	6	0.09	0.03	34	144	13	4
<b>3C</b>	1	30	6	0.09	0.03	34	180	16	5

724

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 m<sup>3</sup>biogas/kgCOD<sub>fed</sub> with an  
 727 average CH<sub>4</sub> content of 39% (i.e. 0.44 m<sup>3</sup>CH<sub>4</sub>/kgCOD<sub>fed</sub>). 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 m<sup>3</sup>/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 m<sup>3</sup>/d of biogas and 426 and 569 m<sup>3</sup>/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 m<sup>3</sup>/d for 5,000 inhabitants, while lower yields down to 909 m<sup>3</sup>biogas/d and 427 m<sup>3</sup>CH<sub>4</sub>/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 m<sup>3</sup>/kgCOD<sub>fed</sub>, respectively. These values led to considerable low expected yields of biogas and  
740 methane in the range of (10-16) and (3-5) m<sup>3</sup>/d respectively, calculated for the full-scale scenario  
741 (e.g., scenario 1C, 2C and 3C).

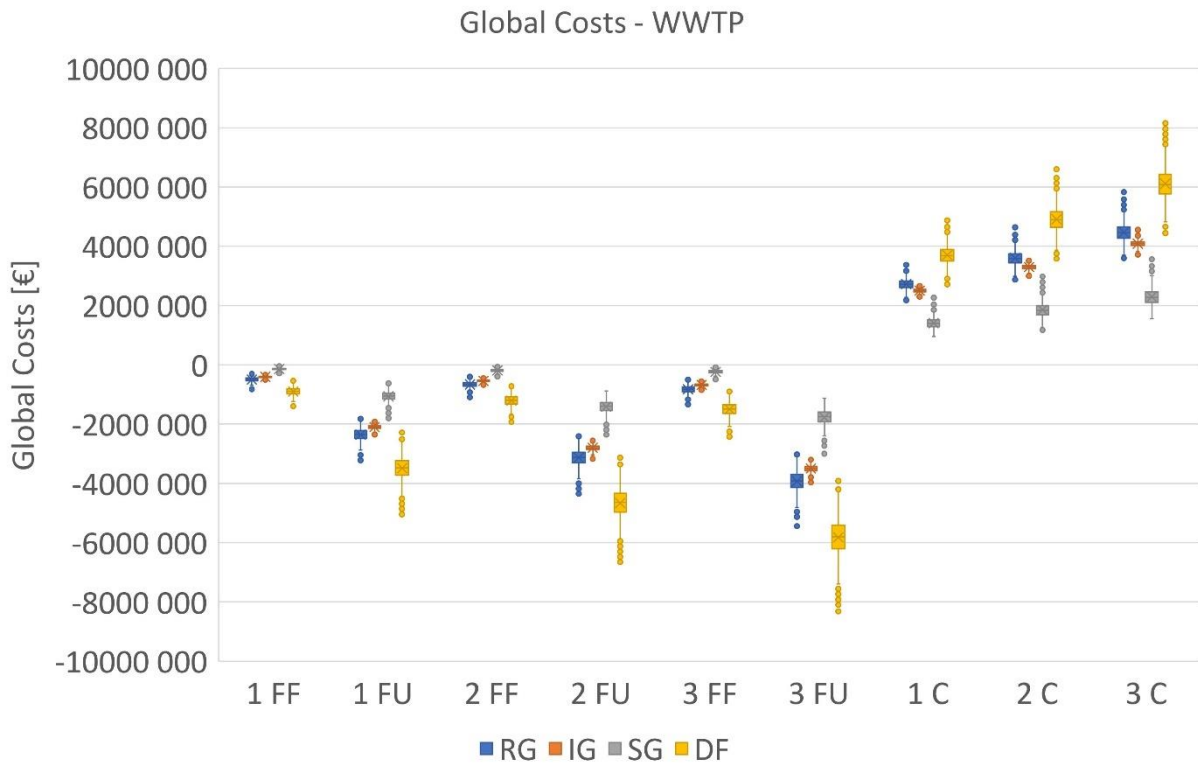
742 Thus, considering the expected yields estimated for all the scenarios, energy assessment was  
743 delivered, and the net energy production was calculated according to eq. (7). Results are  
744 summarized in Table 11, considering: a temperature inside the reactor equal to 30°C; an energy  
745 conversion factor of 3,600 kJ/kWh; an energy content of CH<sub>4</sub> at standard conditions equal to  
746 35,846 kJ/m<sup>3</sup>CH<sub>4</sub>; 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.

751 As a result, on one side all the decentralized scenarios resulted in a positive energy consumption  
752 with a gross energy production higher than the energy consumed. Specifically, thanks to the  
753 biodegradation process, scenario FU resulted the most optimized system in terms of energy  
754 efficiency when compared to scenarios FF. For the analyzed capacities and considering a gas tariff  
755 equal to 0.075 €/kWh, possible revenues for F+U+F systems are in the range of (105,731-  
756 176,219) €/y.

757 On the other side, centralized scenarios could be considered as the less energy-efficient cases, as in  
758 winter season the biogas produced is not sufficient to provide the amount of energy needed to heat  
759 the digester. Thus, although in summer positive results could be achieved, the overall yearly energy  
760 balance highlights further energy required in the range of (1,217,131-2,028,552) kWh/y. This implies  
761 costs for energy demand from 90,841 to 151,402 €/y, respectively. Possible implementation of  
762 further phase of Anaerobic Membrane after the UASB could improve the biogas recovery and the  
763 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.

776 Finally, as already shown for drinking water, the interquartile range of boxplots, representing the  
777 uncertainty associated with the calculated stochastic Global Costs, grows as the value of GC  
778 increases, and especially in Stagflation and Deflation Scenarios, confirming that the macroeconomic  
779 variables affecting the energy prices are the main source of uncertainty.



780  
781  
782

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

Table 11. Summary of UASB performance in terms of energy recovery

Parameters	Unit	Decentralized system(F+F)						Decentralized system (F+U+F)						Small Centralized WWTP (F+U+F)					
		1FF		2FF		3FF		1FU		2FU		3FU		1C		2C		3C	
CH4 prod.*	m <sup>3</sup> CH <sub>4</sub> /kgCOD	0.44		0.44		0.44		0.44		0.44		0.44		0.03		0.03		0.03	
CH4 yield	m <sup>3</sup> CH <sub>4</sub> /d	426		569		711		427		570		712		3		4		5	
Flow rate	m <sup>3</sup> /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
Working time	h/d	10	10	10	10	10	10	10	10	10	10	10	10	24	24	24	24	24	24
Energy Production	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
	kWh/d	<b>1769</b>	<b>11769</b>	<b>2359</b>	<b>2359</b>	<b>2948</b>	<b>2948</b>	<b>4256</b>	<b>4256</b>	<b>5675</b>	<b>5675</b>	<b>7094</b>	<b>7094</b>	<b>33</b>	<b>33</b>	<b>43</b>	<b>43</b>	<b>54</b>	<b>54</b>
	kW/m <sup>3</sup>	27	27	27	27	27	27	66	66	66	66	66	66	0.08	0.08	0.08	0.08	0.08	0.08
Energy Request	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
	kWh/d	<b>592</b>	<b>174</b>	<b>790</b>	<b>232</b>	<b>987</b>	<b>290</b>	<b>592</b>	<b>174</b>	<b>790</b>	<b>232</b>	<b>987</b>	<b>290</b>	<b>6720</b>	<b>0</b>	<b>8960</b>	<b>0</b>	<b>11200</b>	<b>0</b>
	kWh/m <sup>3</sup>	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
Net Energy	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
	kWh/m <sup>3</sup>	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
	kWh/season	2.1 E+05	2.9 E+05	2.9 E+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		6.73 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

#### 785 **4 Discussion on the combined system**

786 In the perspective of a domestic water cycle, an energy production analysis is possible by combining  
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  $Q \approx (30-80) \text{ L/s}$  VS  $(5-10) \text{ L/s}$ , and obtained a produced daily energy that is also one order of  
805 magnitude larger than that obtained in the present work, i.e.  $E \approx (90-280) \text{ kWh/day}$  VS  $(4-$   
806  $27) \text{ kWh/day}$ .

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 ( $\text{m}^3\text{biogas}/\text{m}^3 \text{ reactor}/\text{d}$ ) 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  
815 greater biogas production in the F+F scenario, the methane content is higher in the F+U+F probably  
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].  
824 Although the order of magnitude of the two energy sources is quite different, the present  
825 configuration suggests that the integrated presented solutions may be applied to a small-sized  
826 municipality or urban area, with particular attention to the most appropriate and convenient  
827 solutions for the involved stakeholders (e.g., utility, municipality).

828 Hence, if a relevant economic effort might be exerted and a significant budget is available, the  
829 realization of a decentralized wastewater treatment could be designed and realized, bearing in mind  
830 that this is a suitable choice for population ranging between 3,000 and 5,000 inhabitants. In such a  
831 condition, a PAT system could also be installed, as it deals with small investment if compared to the

832 investment for the decentralized WWTP, but the small energy harvesting from WDN would affect  
833 only slightly the overall economic gain.

834 On the other hand, the installation of the only PAT system guarantees an economic gain when the  
835 population is around 5,000 inhabitants. Such solution might be applied whether a wastewater  
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**

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

- 846 - Experimental tests on DWBTs and the related data analysis have provided insights on the  
847 potential energy production under several scenarios, which have been built on the variation  
848 of both population (ranging between 3,000 and 5,000) and technological approach  
849 (hydraulic or single-series-parallel approach, for the PAT system; urine diverting toilet or dry  
850 toilet, for the wastewater treatment).
- 851 - The analyzed scenarios have led to a yearly electrical energy, provided by the PAT system, in  
852 the range  $\sim(0.9-10)$  MWh, while the daily production of biogas (between  $\sim 900$  and  
853  $\sim 1800$  m<sup>3</sup>) and methane (between  $\sim 400$  and  $\sim 700$  m<sup>3</sup>) have provided a yearly energy  
854 production in the range  $\sim(500-2,000)$  MWh.
- 855 - The LCC assessment has highlighted that, under several potential macroeconomic scenarios,  
856 the Global Costs after 20 years may reach important gains for both PAT and UASB systems,  
857 especially in case of a large population, i.e. up to  $\sim 50$  k€ and  $\sim 6$  M€, respectively.
- 858 - Although the valorization of domestic wastewater source may lead to an amount of energy  
859 significantly larger than the electrical energy produced exploiting a PAT, the different  
860 economic gain/loss provided by the two investigated technologies translates into a different  
861 economic investment, which could make the difference for little municipalities or rural  
862 communities located in developing or developed countries.

863 Finally, the work demonstrates that a novel approach is possible, based on energy exploitation from  
864 the whole domestic water cycle. The novelty comes from the integration of the investigated  
865 technologies in small-sized decentralized urban contexts, such integration being rarely considered  
866 in the literature, and from the analyzed macroeconomic scenarios, which provide a guideline for the  
867 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.

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889 **Data Availability**

890 A dataset related to this article can be found at: [https://univpm-](https://univpm-my.sharepoint.com/:x:/g/personal/p005420_staff_univpm_it/ERMwQsmBtbVKgJh-7mulhWgBBPQMm6q0csJ6SHth-8llcA?e=t50B1J)  
891 [my.sharepoint.com/:x:/g/personal/p005420\\_staff\\_univpm\\_it/ERMwQsmBtbVKgJh-](https://univpm-my.sharepoint.com/:x:/g/personal/p005420_staff_univpm_it/ERMwQsmBtbVKgJh-7mulhWgBBPQMm6q0csJ6SHth-8llcA?e=t50B1J)  
892 [7mulhWgBBPQMm6q0csJ6SHth-8llcA?e=t50B1J](https://univpm-my.sharepoint.com/:x:/g/personal/p005420_staff_univpm_it/ERMwQsmBtbVKgJh-7mulhWgBBPQMm6q0csJ6SHth-8llcA?e=t50B1J)

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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.*

<b>N</b>	<b>Components</b>	<b>EGE (€)</b>	<b>CW (€)</b>	<b>TC (€)</b>	<b>MC (€/year)</b>
1	PAT	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.*

<b>N</b>	<b>Components</b>	<b>EGE (€)</b>	<b>CW (€)</b>	<b>TC (€)</b>	<b>MC (€/year)</b>
2	PAT	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

1175

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
<b>Wastewater (WW) type</b>		Domestic WW	Domestic WW	Domestic WW	Domestic WW	Excrements, Kitchen waste	Concentrated black water	Municipal WW	Municipal WW	Municipal WW	
<b>Flow rate</b>	mld	-	0.00005	0.009	-	-	-	50	-	-	
<b>Inhabitants</b>	n°	-	-	50***	160000***	550 up to 1200	-	-	-	9733	
<b>COD<sub>tot</sub> rem</b>	%	70 - 80	51 - 83	80	-	-	61 - 74	80 - 85	55 - 70	59	
<b>BOD rem</b>	%	75 - 83	-	-	-	-	-	80 - 88	60 - 75	72	
<b>TSS rem</b>	%	70 - 80	57 - 88	-	-	-	-	80 - 85	65 - 80	67	
<b>Biogas Production</b>	m <sup>3</sup> /kg COD rem d	0.05 – 0.25	0.17	-	-	-	0.13-0.16	0.08-0.11	-	-	
	m <sup>3</sup> /kg COD fed d	0.07 – 0.3	0.11	-	-	-	0.1	0.1 – 0.13	-	-	
<b>Footprint</b>	kgCO <sub>2</sub> /kg COD rem	0.5 - 1	-	-	-	-	-	-	-	-	
<b>Area Required</b>	m <sup>2</sup> /mld	1450	-	-	-	-	-	1800	-	-	
<b>OLR for sewage treatment</b>	kgCOD/m <sup>3</sup> d	1 - 2.0	0.23 0.96	-	-	-	-	1.15-1.25	-	-	
<b>Economic Life</b>	y	30	-	-	-	-	-	30	-	-	
<b>Annual Power Cost</b>	€/y	-	-	-	-	-	-	15588	-	-	
<b>Total Investment Costs</b>	€/inhab.	10.7 - 18	-	11.8	15.28	36.7	-	-	10.7 - 18	29.2	18.3
<b>Total annual O&amp;M Costs</b>	€/inhab. y	0.9 – 1.34	-	-	1.35	73	-	-	0.9 – 1.35	-	1.1

1180 <sup>a</sup>Data for this column are referred to UASB + Final Polishing Unit

Table B. 2. Summary of parameters and performance

Ref.	WW Type	Vol	Qin	CODin	CODrem	OLR	T	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/kgCOD D rem	m3/kgCOD fed	m3/kgCOD rem
Gao et al. [89]	Black water*	0.0047	0.003	1050	73	0.76	35	34	-	0.0003	-	-	0.09	0.34
	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]	Concentrated 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	-	-
<b>AVERAGE</b>	-	-	-	-	75	0.6	-	-	-	-	0.10	0.18	0.15	0.59
<b>ST.DEV</b>	-	-	-	-	9.3	0.3	-	-	-	-	0.01	0.05	0.06	0.48
Stazi and Tomei [93]	Sewage wastewater	64000	-	267	50-75	-	25.2	4-6	-	-	-	-	-	0.19
	Sewage wastewater	4	-	1000	94	3	27.9	8	-	-	-	0.49	-	-
	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
<b>AVERAGE</b>	-	-	-	-	67	2.3	-	-	-	-	0.15	0.31	0.12	0.18
<b>ST.DEV</b>	-	-	-	-	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