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Nexus analysis and life cycle assessment of regional water supply systems: A case study from Italy

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11 **Abstract**

12 Ensuring reliable access to water sources is an emerging issue being currently addressed by
13 governments and international communities. However, local conditions play a primary role in
14 determining requirements for urban water supply systems and cascade implications due to
15 simultaneous interlinkages with complementary resources such as energy. As such, addressing
16 sustainability in water management comes through quantitative evaluation modelling and
17 assessment.

18 To this aim, nexus analysis and life cycle assessment methodologies are applied to the drinking
19 water supply system in the Romagna region (Italy). Our research provides detailed characterization
20 of the involved material and energy flows, which is used as a basis for determining water-for-
21 energy and energy-for-water results, and to conduct environmental assessment for complementary
22 impact categories by withdrawal, treatment, and distribution processes.

23 The results show that the energy needed to produce drinking water ranges from 0.27 MJ to 2.53 MJ
24 per cubic meter of water delivered. Water deriving from the artificial basin and treated following a
25 conventional technology turned out to be both the less energy intensive and the less impacting
26 process. Overall, the study provides an exhaustive comparison of the environmental impacts of
27 different water production alternatives, which may ultimately support decision-makers and local
28 communities to the planning of strategies for optimized and long-term reliable access to water
29 resources.

30

31 **KEYWORDS:** *Water-energy nexus, water sustainability, life cycle assessment, water treatment,*
32 *cumulative energy demand*

33

Nomenclature		GHG	Green House Gas
CED	Cumulative Energy Demand	GW	Groundwater
CER	Canale Emiliano Romagnolo	HCT	Human Carcinogenic Toxicity
FC	Forli-Cesena	HnCT	Human non-Carcinogenic Toxicity
LCA	Life cycle assessment	Mm ³	Million Cubic Meters
LCI	Life cycle inventory	p.c.	Per Capita
LCIA	Life cycle impact assessment	RD	Ridracoli Dam
RA	Ravenna	SW	Surface Water
RADWSS	Romagna Acque Drinking Water Supply System	SWCO	Surface Water Conventional Treatment
RN	Rimini	SWUF	Surface Water Ultrafiltration Treatment

34

35 ***1. Introduction***

36 The balance between water supply and demand is an essential issue, marked over time by
37 political and environmental conflicts, as well as the impacts of natural disasters and the daily
38 demand for several uses. The water issue is also mainstreamed by the United Nations that, in the
39 “2030 Agenda for Sustainable Development”, inserted “Clean water and sanitation” between the
40 17 sustainable development goals (United Nations, 2015).

41 Despite being in principle a renewable resource, water is often consumed faster than it
42 accumulates in natural reservoirs or withdrawn from water bodies and re-entered into the
43 ecosystem with a lower quality. These problems have resulted in the need of considering water
44 as a limited resource to define sustainable consumption models (Valhondo and Carrera, 2019),
45 reduce the risks of water scarcity (UNICEF, 2021) and the potential global tensions, and
46 conflicts that might derive from them (Farinosi et al., 2018).

47 In addition, interconnections between complementary environmental emergencies (e.g., climate
48 change and sea level rising) might exacerbate the water insecurity and relative conflicts in a
49 vicious loop (World economic forum, 2019). For instance, extreme weather events such as

50 droughts or floods are affecting an increasing number of world regions, which are in many cases
51 already sensitive to food provisioning issues and social instability (Liu et al., 2015). Due to the
52 increasing water demand, 40% of the global population suffered from water shortages in 2018
53 (Larsen and Drews, 2019), but demographic trends and projections expect that up to 60% of the
54 global population might suffer from water scarcity by the year 2025, so that some regions –
55 generally, the most densely populated ones – might have to rely on non-conventional water
56 sources to alleviate this problem (Lam et al., 2017; Lane et al., 2015; Pistocchi et al., 2020;
57 Qadir et al., 2007). As a consequence, dramatic changes in urban water supply system are
58 globally under consideration and implementation (Mo et al., 2014).

59 However, investigating and developing novel methods and techniques for addressing
60 sustainability in water management requires that not only interconnections between
61 environmental impacts but also those between resources are carefully considered and assessed.
62 In particular, the nexus analysis aims to reveal the simultaneous linkages between different
63 natural resources and raw materials of essential importance to modern society, finally
64 addressing the question of how to identify and prioritize key resources considering alternatives
65 and conflicting interests (Chen et al., 2021; Font Vivanco et al., 2018; Lee et al., 2021). These
66 insights open the doors to more comprehensive resource management practices leading to
67 increased synergies and co-benefits. Of relevance here, since no water supply infrastructure or
68 system, no matter how rudimentary it can be, can be operated without energy (Rio Carrillo and
69 Frei, 2009; VanBriesen et al., 2014), the “water-energy nexus” is addressed in order to better
70 define and catch the energy and water reciprocal functions and the related trade-offs in terms of
71 cost and availability (Gabbar and Abdelsalam, 2020).

72 As a strategical methodology for assessing the environmental performance of products, services
73 and systems, life cycle assessment (LCA) has been previously applied to studies on drinking
74 water supply systems reflecting an enhanced awareness of water-energy interdependence and
75 the related implications for water management and energy systems (Ciacci and Passarini, 2020;

76 Feo et al., 2015; Lakho et al., 2022a; Lane et al., 2015; Mo et al., 2014; Prézéus et al., 2021).
77 However, interlinkages between water and energy are extremely spatial and temporary dynamic,
78 such that local conditions play a primary role in determining energy sources and requirements
79 for water supply systems (Mo et al., 2014). This aspect amplifies for regions characterized by
80 very intensive agricultural activity, a strong presence of the food industry as well as relatively
81 high-density population and tourism activity, of which Emilia-Romagna region, in northern
82 Italy, is a representative example.

83 The Romagna-Acque drinking water supply system (RADWSS) is enabling the water
84 distribution in Romagna, which corresponds to the sub-regional territory where three provinces,
85 namely Ravenna (RA), Forli-Cesena (FC) and Rimini (RN), are located. Historically, thanks to
86 the presence of an artificial water reservoir that is also finalized to hydropower generation, the
87 territory has never faced critical water shortages. Anyway, the lowest reservoir water levels are
88 normally detected during the summertime, i.e. when the increased drinking water demand for
89 tourism needs meets the minima in precipitation and water flows alteration (Toller et al., 2020;
90 Van Vliet et al., 2016). This aspect has risen serious concerns about the ability to meet future
91 water demand in the region, in which LCA is applied to examine the RADWSS from a water-
92 energy nexus perspective and explore environmentally sustainable technologies to be strengthen
93 or implemented in the region.

94 Although this topic has been widely assessed in the related literature (Bârjoveanu et al., 2019;
95 Barrios et al., 2008; Bhakar and Singh, 2018; Bonton et al., 2012; Del Borghi et al., 2013;
96 Dettore, 2009; Garcia-Suarez et al., 2019; Garfí et al., 2016; Karnaningroem and Anggraeni,
97 2021; Lakho et al., 2022a; Mohapatra et al., 2002; Ortiz Rodriguez et al., 2016; Prézéus et al.,
98 2021; Saad et al., 2019; Vince et al., 2008), there is partial agreement on which technological
99 solutions for water withdrawal and treatment should be preferred. Ultimately, this uncertainty
100 boils down to specific local conditions of the systems under investigation that often prevent a
101 fair comparison between alternative scenarios. For this reason, the need for site-specific studies

102 has been recommended (Loiseau et al., 2018; Ripa et al., 2017) and constituted a primary
103 motivation for this study. This is particularly relevant for the Romagna region for which, to the
104 best of our knowledge, no prior, extensive environmental impact assessments have been carried
105 out. Further novelty of this study is the focus proposed on the nexus between two essential
106 resources such as water and energy, the interlinkages of which are known (Font Vivanco et al.,
107 2018; Gabbar and Abdelsalam, 2020; Mo et al., 2014) but their quantification remains in many
108 cases unclear, notwithstanding the current interest in energy and water supply security and
109 footprinting.

110

111

112 ***2. Materials and methods***

113 According to the ISO standards 14040-14044, LCA is a strategic technique to identify and quantify
114 the potential environmental impacts associated with a product or a system throughout its life cycle.
115 The common LCA framework consists of the following conceptual phases, namely goal and scope
116 definition, life cycle inventory (LCI), and life cycle impact assessment (LCIA), which applies
117 environmental mechanisms and characterization models to relate the LCI results to selected
118 category indicators for a quantitative evaluation of environmental impacts. A fourth phase, i.e.,
119 interpretation, is transversal to the previous ones to guarantee consistency between the aims of a
120 study and its execution and finally structured to draw recommendation. In the following paragraphs,
121 the four phases are described with reference to the system under investigation.

122 ***2.1 Goal and scope definition***

123 The aim of this work is to develop a regional LCA model for the RADWSS to improve the overall
124 understanding of the functioning of the water supply systems and of reciprocal interlinkages with
125 the energy dimension.

126 In the first part, water and energy flows are identified and quantified to discuss the relationships
 127 between the two resources. Then, the LCA methodology is applied to evaluate and compare
 128 different process alternatives aimed to withdraw, treat, and deliver drinking water in the system,
 129 with the purpose to identify the weaknesses of the RADWSS, support the investigation of new
 130 solutions and reducing the energy intensity of water production and the release of greenhouse gas
 131 (GHG) emissions while maintaining high quality water supply standards under future pressures
 132 resulting from climate change.

133 2.1.1 System description

134 The system under scrutiny covers the entire RADWSS established in the Romagna territory,
 135 counting more than 1 million inhabitants and as many as tourists, facing an overall demand for
 136 more than 100 million cubic meters (Mm³) of water per year, supplied by means of a water grid
 137 extended over more than 600 km (Figure 1).



138
 139 *Figure 1: Romagna Acque system's map (Romagna Acque - Società delle fonti S.p.A., 2021)*

140 More in detail, the RADWSS system comprehends a water dam in Ridracoli, the Conca dam
141 (located in the RN province), about 140 wells employed for water withdrawal from local
142 groundwater sources, and water pumps distributed along 3 main surface water bodies. On average,
143 about 55% of the total annual water supply in the RADWSS is sourced from Ridracoli dam (RD),
144 while groundwater (GW) reservoirs and surface water (SW) sources contribute for the rest
145 (Romagna Acque - Società delle fonti S.p.A., 2021).

146 Although the market share contribution of GW and SW is similar, their geographical distribution is
147 such that most GW sources are located in the FC and RN provinces, while SW characterizes the RA
148 province and the dedicated water channel (named Canale Emiliano Romagnolo, CER), in which a
149 fraction of the Po River is detoured. In case of water shortages, RA province may also rely on two
150 supplemental SW sources, constituted by the Lamone and Reno rivers, and two GW sources located
151 inside its territory. The RN province, instead, relies on the Conca dam as a supplemental water
152 source during water shortages, but such derivation has to undergo intensive treatment for complying
153 with the water quality standards (Romagna Acque - Società delle fonti S.p.A., 2021). Anyway, the
154 volume of water withdrawn from Lamone, Reno, underground RA sources and the Conca dam is
155 negligible in ordinary conditions and not considered further in this case study.

156 On the energy side, the RADWSS's electricity demand is met either from the Italian grid mix plus
157 photovoltaics and hydroelectric production plants installed within the system. The location of the
158 photovoltaics and hydroelectric stations is depicted in Figure 1.

159 *2.1.2 Withdrawal, treatment and distribution processes*

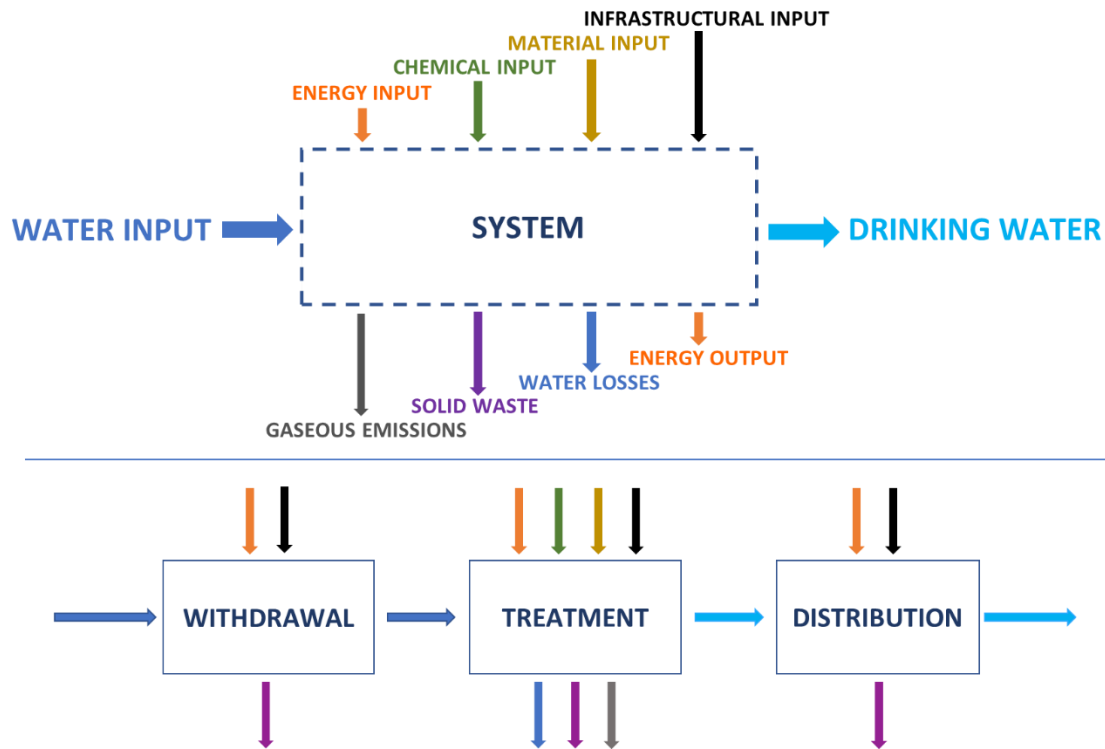
160 Withdrawal is considered the step in which water is extracted from a natural source and conveyed to
161 a water treatment plant. Depending on the water source, treatment plants may differ in terms of
162 installed capacity, methods and techniques implemented for water processing. Water treatments are
163 aimed at improving the water quality by means of the removal, or the lowering of concentrations, of
164 contaminants and other undesirable pollutants contained in the water inflow to meet national

165 requirements for potable water and other uses (e.g., agricultural or industrial purposes). In the
166 system under scrutiny, 15 different small (0.2 m³/s) to medium (to 3.6 m³/s) size potabilization
167 plants are fully operating: 14 of them are equipped with conventional technologies, while one plant
168 has been recently upgraded with an ultrafiltration process (SWUF).
169 Commonly, in the conventional processes, the water inflow is treated with chlorine dioxide or
170 potassium permanganate to oxidize organic substances, decrease turbidity, and reduce iron and
171 manganese concentrations. Then, water is subjected to chemical conditioning and perchloration
172 with chlorine dioxide or sodium hypochlorite. Subsequently, clariflocculation and filtration stages
173 occur, in which aluminum sulfate is added as a coagulating agent to promote particle collision and
174 precipitation (Romagna Acque - Società delle fonti S.p.A., 2021; Sillanpää and Matilainen, 2015).
175 The resulting sludge is then filtrated, removed, and sent to final disposal.
176 In contrast, SWUF consists of a pressure-driven membrane separation process, where
177 polyvinylidene chloride membranes with pore sizes of about 20 nm are employed to achieve high
178 removal efficiency of bacteria, viruses, and other polluting substances (Romagna Acque - Società
179 delle fonti S.p.A., 2021). The main advantages of this technology are that ultrafiltration reaches
180 very high removal efficiency rates even in conditions of very polluted water inflows (Dupont, 2008;
181 Jacquet et al., 2021; Prézélus et al., 2021).
182 Eventually, the distribution process is the final stage that conveys treated water outflows (e.g.,
183 potable water) to a third company which deals with its delivery to final users such as municipalities,
184 residential and commercial buildings, and industrial plants.

185 *2.1.3 System boundaries*

186 A summary representation of the RADWSS is proposed in Figure 2, with the main process stages,
187 resource and waste flows depicted. Water is withdrawn from a specific source, conveyed to the
188 dedicated treatment plant, and then delivered to the consumers through the distribution process.
189 Because the supply to the consumers is under the administration of a third company, the distribution

190 process has been excluded from the analysis. In this view, the system boundaries of our study cover
 191 the geographical area served by the RADWSS. To this aim, energy, chemical, material, and
 192 infrastructural inputs have been identified and quantified. Water and energy losses as well as
 193 gaseous and solid waste outflows reduce the overall efficiency of the system (AL-Washali et al.,
 194 2020).



195
 196 *Figure 2: a) Summary representation of inputs and outputs in the system (modified from Zhou et al., 2014); b)*
 197 *sequential representation of the three main steps of the generic drinking water supply system under investigation.*

198 Energy inputs include both electricity requirements for water withdrawal, treatment, and
 199 distribution processes, plus the heat employed for disinfection, with this step being performed only
 200 in surface water conventional treatment plants (SWCO). Chemical inputs include substances and
 201 compounds necessary to treat water (e.g., aluminum sulfate, chlorine dioxide, potassium
 202 permanganate). Material inputs refer to products such as, for instance, filters that are employed both
 203 in the removal of coarse fractions and pathogens from the conventional and ultrafiltration processes.
 204 Infrastructural inputs concern all the operations and construction material employed to build and

205 maintain fundamental elements of the system such as withdrawal stations, treatment plants, and
206 distribution network.

207

208 *2.1.4 Functional unit definition*

209 In consistency with similar studies in the literature (Byrne et al., 2017; Garfí et al., 2016; Prézé-
210 lus et al., 2021; Raghuvanshi et al., 2017), the whole system evaluation and the comparison between
211 different water production alternatives is performed setting 1 m³ of delivered drinking water as the
212 functional unit.

213

214 *2.2 Life cycle inventory*

215 *2.2.1 Data collection*

216 The study included a preliminary identification and quantification of the main inflows and outflows
217 of the system, disaggregated at the province level (i.e., FC, RA, and RN).

218 Data related to water, energy, and chemical flows were provided directly by Romagna Acque for
219 the most recent year available (i.e., 2020). These inventories included the total volume of water
220 delivered to each province from a specific source derivation (i.e., RD, GW or SW sources), the
221 volume of water sent to SWCO and SWUF treatment plants, the amount of energy generated from
222 photovoltaics and hydroelectric production stations, the electricity requirements for water
223 withdrawal and distribution, by water source and treatment process applied (i.e., SWCO, SWUF).

224 An exhaustive inventory of the type and amounts of chemicals employed in the water treatment
225 plants for the three main water sources was also determined (for more detail, see Tables S1a-e in the
226 Supplementary Material). Similarly, engineering information provided by Romagna Acque has
227 enabled a site-specific LCA modelling of the Ridracoli and Conca dams (Tables S2a-c).

228 Information about waste generated by water treatment plant (Tables S3a-e) was collected and
229 classified according to the European waste catalogue codes (2000/532/EC). As for the LCA

230 modelling, each waste type has been associated consistently to an existing process in the Ecoinvent
231 3.7 database (Wernet et al., 2016). Further details are reported in the Supplementary material.

232

233 2.2.2 *Model assumptions*

234 Although the LCI mainly relied on primary data sources, several assumptions were needed to deal
235 with a lack of information as following discussed.

236 Water losses amounts to 0.40% and 1.50% (Romagna Acque - Società delle fonti S.p.A., 2021) of
237 water inflows at the water treatment and distribution stages, respectively.

238 Electricity produced at hydroelectric stations and photovoltaic stations is either self-consumed or
239 sold to the national grid. The total electricity produced by renewable energy sources of the system
240 amounted to 3.7E+07 MJ in 2020, but only the 8.7% of it has been self-consumed by the RADWSS.
241 This fraction, however, does not fulfill the energy needs of the system, with the remaining fraction
242 being supplied from the Italian grid. The resulting electrical energy estimates were then subtracted
243 to the total energy required by each process to compute the energy input purchased from the Italian
244 electricity grid. Instead, the amount of electricity self-produced but sold to the national grid (i.e.,
245 3.4E+07 MJ in 2020) was entered as an avoided product in the LCA model for the RAWDSS. I.e.,
246 according to the ISO standards, the generation of electrical energy from renewable sources was
247 credited for the avoided production of the same amount of energy from the national grid mix, which
248 included fossil sources for about 52.2% of the total in 2020 (IEA, 2022).

249 Chlorine dioxide is produced in-situ and was modelled according to the stoichiometry of the
250 reaction (Equation 1) and annual amounts utilized by the company, employing sodium chlorite at
251 25% w/w or 7.5% w/w, and hydrochloric acid at 32% w/w or 9% w/w.



253 *Equation 1: chlorine dioxide generation reaction*

254 Lastly, the Ecoinvent 3.7 database was the preferred source for missing data related to materials and
255 infrastructure: in particular, for inventories related to the construction of the Ridracoli and Conca
256 dams, pump stations, and water supply pipelines (Tables S2a-c) according to direct information
257 from the company.

258

259 *2.3 Life cycle impact assessment*

260 The LCIA phase includes quantitative determination of the potential environmental impacts
261 resulting from the system under scrutiny (ISO 14040). To this aim, environmental mechanisms and
262 characterization models are applied to relate the LCI results to the selected impact category
263 indicators. The ReCiPe 2016 method (Huijbregts et al., 2017) and the cumulative energy demand
264 (CED) method were here considered. ReCiPe 2016 is one of the most comprehensive LCA methods
265 for environmental impact evaluations, as it provides results both at midpoint and endpoint levels.
266 The CED method was applied to quantify the total energy demand as the sum of direct and indirect
267 energy inputs, with the latter ones being accounted as primary energy required during the whole life
268 cycle of a product, including extraction, manufacturing, and waste disposal (Huijbregts et al., 2006).
269 In our model, indirect energy inputs are associated with raw materials and auxiliary products such
270 as chemicals and filters.

271 The two LCIA methods are employed to compare four alternative scenarios for drinking water
272 production, namely: RD (dam water + conventional treatment), SWCO (surface water +
273 conventional treatment), SWUF (surface water + ultrafiltration treatment), GWCO (groundwater +
274 conventional treatment).

275

276 *2.4 Sensitivity and uncertainty analysis*

277 A contribution analysis is performed to determine which are the most impacting processes of the
278 system. Then, sensitivity analysis is performed to test the robustness of the model created, enabling

279 identification and quantification of the influence of certain parameters onto the environmental
 280 impact of the entire system (Goedkoop, 2016).

281 Uncertainty evaluation was performed for the midpoint impact categories results. In general, as
 282 discussed above, the LCA model for RAWDSS was entered with primary data, directly measured in
 283 the system under consideration. As such, these data can be considered very reliable and fulfilling
 284 the highest scores for data quality criteria commonly applied in LCA such as, for instance,
 285 geographical, temporal, and technological representativeness. For a quantitative determination of
 286 uncertainties associated to each LCI parameter, we referred to the data quality pedigree matrix
 287 (Weidema and Wesnæs, 1996). Table S5 in the Supplementary Material lists the indicator scores
 288 assigned to each parameter and the related geometric standard deviation used in uncertainty
 289 analysis. Then, a Monte Carlo simulation with 10,000 runs was carried out to determine how the
 290 intrinsic variability of the parameters and the quality of the data used in the modelling may affect
 291 the outcomes.

292 *2.5 Softwares and databases*

293 SimaPro 9.2 software, implemented with Ecoinvent 3.7 database, was used for LCA modelling of
 294 RAWDSS and e!Sankey 4.0 software was employed for the creation of Figure 3.

295 **3. Results and discussions**

296 *3.1 The water-energy nexus*

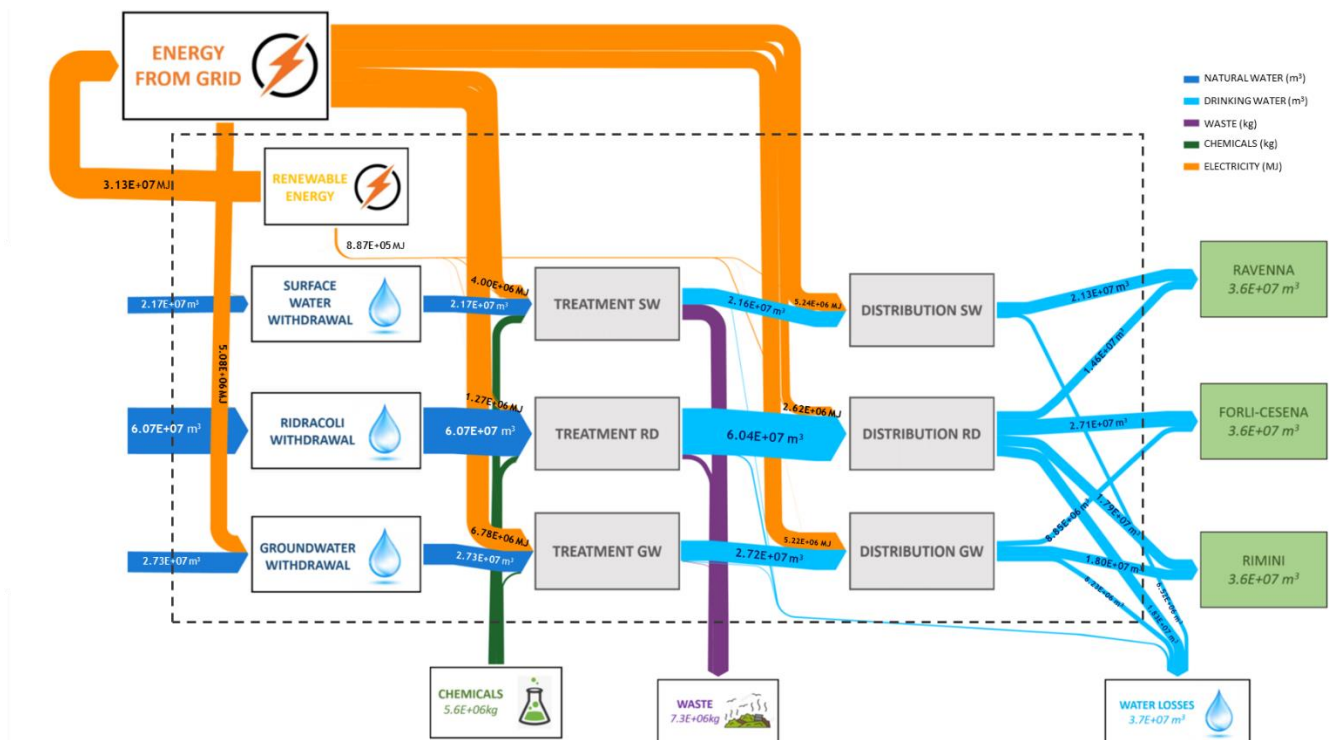
297 Water and energy flows of RADWSS are reported in Table 1, while a Sankey diagram representing
 298 the most relevant water (m³/year) and electricity (MJ/year) flows is displayed in Figure 3.

299 Table 1: Water and energy flows and fractions of distribution (%)

Drinking water (m³/year)	Total	FC	RA	RN
Ridracoli (RD)	5.95E+07	2.71E+07	1.46E+07	1.79E+07
		46%	24%	30%
Groundwater (GW)	2.68E+07	8.85E+06	-	1.80E+07
		33%	-	67%
Surface water (SW)	2.13E+07	-	2.13E+07	-

		-	100%	-
Electric energy (MJ/year)	Total	RD	GW	SW
National grid	1.09E+08	1.45E+07	6.16E+07	3.34E+07
		13%	56%	31%
Hydroelectric auto-consumed	6.42E+05	3.74E+05	3.21E+05	1.36E+04
		48%	50%	2%
Photovoltaic auto-consumed	2.53E+06	1.14E+06	3.06E+03	1.39E+06
		45%	0%	55%

300



301

302 Figure 3: Sankey diagram of the main water (m³), energy (MJ), chemicals (kg) and waste (kg) flows of the RAWSS for
 303 the year 2020

304 3.2 Description of the RADWSS

305 RD is the main water source in the region, covering about 55% of the volume supplied in the
 306 RADWSS (i.e., 108 Mm³ in 2020). The RD volume of about 60 Mm³ is distributed to the provinces
 307 with the following shares: FC, 46%; RN, 30; RA, 24%. GW and SW sources contribute for the rest
 308 as dictated by the distribution of local water bodies, with GW sources supplying RN (18 Mm³/year)
 309 and FC (9 Mm³/year), and SW sources serving the RA province (21 Mm³/year) mainly through
 310 water withdrawal from the CER.

311 At the province scale, the water needs for each one of the three examined provinces is about 36
312 Mm³/year, reflecting a per capita (p.c.) drinking water demand of about 91 m³/inhabitant in the FC
313 province, 92 m³/inhabitant in RA and 106 m³/inhabitant in RN. The total direct and indirect water
314 consumption is calculated by knowing the volume of water losses and water virtually embodied in
315 processes and materials involved in the RADWSS. The amount of water involved in RADWSS
316 consists of water delivered (1.1E+08 m³/year), water consumed or lost in treatments (4.3E+05
317 m³/year), water lost because of inefficiencies along the distribution network (1.6E+06 m³/year),
318 water virtually embodied in chemicals and materials (1.12E+05 m³/year), in infrastructure
319 (2.23E+06 m³/year), and water involved in waste management processes (6.29E+03 m³/year).
320 Consequently, it results that per each cubic meter of water delivered about 1 m³ of water is lost or
321 consumed during withdrawal, treatment, and distribution stages. Assuming to shift from energy
322 scenario 1 to energy scenario 2, i.e., electricity derives exclusively from renewable sources, the
323 water consumption would reduce to 0.08 m³/year.

324 The water treatment stage is also characterized by additional chemical agent flows for pollutants
325 removal that, in 2020, amounted to about 5.6 kt. This stage, also because of such inflow, involves
326 the generation of 7.3 kt of sludge, that is sent to final disposal (Romagna Acque - Società delle fonti
327 S.p.A., 2021).

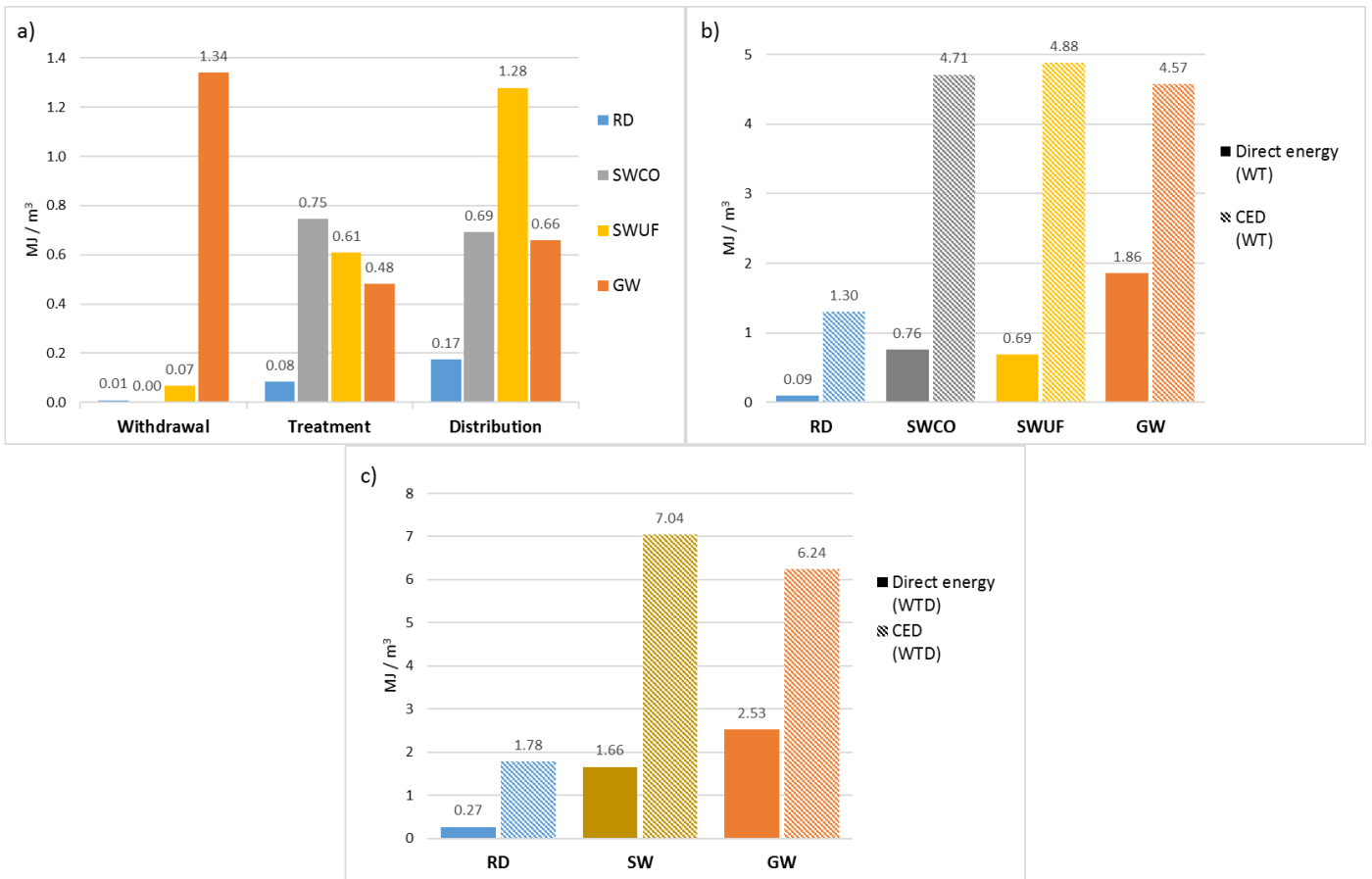
328 *3.3 Energy-for-Water and Water-for-Energy in the system*

329 *3.3.1 Energy for water, by process and by source*

330 The total electricity demand for water resulted in 3.1E+08 MJ in 2020. Of this amount, only 4%
331 was self-produced from renewable energy sources installed in the system and consumed, with 96%
332 of electrical energy inputs (i.e., 1.09E+08 MJ/year) being purchased from the national grid.
333 Concerning energy intensity, in 2020, 3.2E+06 MJ (8.6% of the electricity produced by renewable
334 energy stations) was employed for the system processes, while the remaining 3.4E+07 MJ (91.4%)

335 were sold to the national grid at the free market or through contracts with energy services (Romagna
336 Acque - Società delle fonti S.p.A., 2021).

337 By process stage, about 49% of total electricity needs were required for water distribution followed
338 by treatment (33%) and withdrawal (18%) stages, respectively. Figure 4a depicts the energy
339 intensity per 1 m³ of water outflow (i.e., in MJ/m³) by process (i.e., withdrawal, treatment,
340 distribution) and by water source (i.e., RD, GW, and SW). For water withdrawal, GW sources show
341 the highest energy intensity (1.34MJ), followed by SWUF (6.67E-2MJ), RD (9.07E-03MJ) and
342 SWCO 1.04E-3MJ, which presented much lower values. Concerning the treatment stage, RD
343 showed the best energy performances while, comparing the two SW sources, a difference of 0.14
344 MJ/m³ resulted in favor of SWUF compared to SWCO, notwithstanding the amount of higher
345 energy required to pump water through the ultrafiltration process. For the distribution stage, instead,
346 SWUF performed worst, followed by SWCO, GW and RD.



347

348

349

350

Figure 4: a) energy flows associated to processes and sources (MJ/m³ of water delivered; b) energy efficiencies and cumulative energy demand, considering only withdrawal and treatment processes, WT (MJ/m³); c) energy efficiencies and cumulative energy demand, considering withdrawal, treatment, and distribution processes, WTD (MJ/m³)

351

In Figure 4b, we have excluded from the chart the energy inputs to distribution, since these ones are generally affected by local parameters less uniform among the provinces such as the morphology of the territory, the location and extension of urban and rural areas to supply with drinking water. The distribution step is anyway included in Figure 4c, for completeness. Despite the partial view that derives, this choice is intended to enable a fair comparison between the technical aspects of the alternatives. Similarly, the direct energy comparison does not consider the amount and type of material used for water treatment. These variables mainly depend on both the process technology and water quality issues, which are site-specific and strictly connected to water sources.

359

The energy intensity estimated from the model ranks RD as the preferable option, although it is worth noting that the values consider only direct electricity requirements. In fact, supplemental energy needs are associated with the production of chemicals, filters, infrastructural equipment, or

361

362 similar goods employed in the system as well as with materials transportation, waste management
363 and treatment. As shown in Figure 4b, if indirect energy requirements are included and computed
364 by the CED method, the cumulative energy intensity of withdrawal, treatment, and distribution by
365 source, excluding as mentioned the distribution stage, raises from 0.1 to 1.3 MJ/m³ for RD, from
366 0.8 to 4.7 MJ/m³ for SWCO, from 0.7 to 4.9 MJ/m³ for SWUF and from 1.9 to 4.6 MJ/m³ for GW.
367 In case of RD, SWCO and SWUF, the direct energy represents between the 10-15% of total
368 cumulative energy demand, while for GW, the direct energy requirements are responsible for 41.3%
369 of the total value observed, highlighting the influence of the withdrawal process.

370 *3.3.2 Water for Energy*

371 As described above, energy demand is met by electricity inputs from both renewable energy plants
372 (i.e., photovoltaics and hydropower stations) installed in the system and electricity supplied from
373 the national grid. Based on the model created and quantitative information of water footprint by
374 energy source (Wernet et al., 2016), we have estimated the water-for-energy indicator
375 characterizing the RADWSS.

376 Considering the whole system, the total volume turbinated to produce hydropower in 2020 was
377 7.4E+07 m³ (Romagna Acque - Società delle fonti S.p.A., 2021), which corresponds to 2.1 m³ of
378 turbinated water every electrical MJ produced. This value is supplemented by water inputs for
379 infrastructure of photovoltaic plants and for direct and indirect water inputs related to electricity
380 supplied from the national grid, which are estimated at 0.39 m³/MJ (of which around 62% is
381 attributed to the silicon-based material production) and 0.96 m³/MJ, respectively (Wernet et al.,
382 2016). Overall, the resulting water-for-energy amounts to 3.45 m³ per MJ of electrical energy
383 consumed in the system. In absolute quantities, the water-for-energy amounts to 9.15 E+07 m³,
384 which corresponds to about 83% of the total water inflow to RADWSS.

385 *3.3.3 Comparison with previous results and future improvements*

386 Our results are to be interpreted in the context of the water supply system in the Romagna region
387 (RADWSS) as the environmental impacts associated to water supply systems are often highly
388 location-specific and extremely dependent on variables such as different water treatments,
389 geographical characteristics of the system, derivation and quality of the water inflow and the
390 electricity generation mix (Racoviceanu et al., 2007). For these reasons, a fair comparison between
391 different water supply systems is not always straightforward. Anyhow, it is possible to find in the
392 literature many studies in which the aim was to provide energy intensity results.

393 For instance, in Molinos-Senante and Sala-Garrido, 2018, the direct energy requirements of a
394 pressure filtering treatment is estimated to be 0.76 MJ/m^3 , which is 37% higher than the value
395 associated to the ultrafiltration treatment of the RADWSS (0.47 MJ/m^3). The same authors suggest
396 a lower value (0.65 MJ/m^3) when coupling the pressure filtration with a more traditional
397 coagulation process. In Barrios et al., 2008, even if the treatment technology is not specified, it has
398 been estimated a value of 1.07 MJ/m^3 , comprehensive of withdrawal and treatment process, that
399 deviates from the values observed for the RADWSS, since it ranges from 0.03 MJ/m^3 (RD) to 0.51
400 MJ/m^3 (GW). In Mo et al., 2011, it is found that the on-site direct energy use of the GW system is
401 approximately 27% higher than SW supply system but, on the other hand, GW requires 31% less
402 indirect energy with respect to SW. The proposed case study confirmed this trend but with different
403 relative contribution, since comparing SWUF and GW, it emerged that GW requires the 63.0%
404 more direct energy in comparison with SWUF, while SWUF uses 35.3% more indirect energy than
405 GW. To resume, this study and the existing literature in this field agree in demonstrating that GW
406 withdrawal is more energy intensive with respect to SW withdrawal (Bhakar and Singh, 2018; Mo
407 et al., 2011) and that the energy demand of the ultrafiltration treatment is higher with respect to the
408 conventional one (Molinos-Senante and Sala-Garrido, 2018; Zijp and van der Laan, 2015).

409 Although the projections for water availability in the Romagna region do not expect supply issues for
410 the coming years, the results of this work can be used as a quantitative basis for future improvements

411 and timely recognition of potential issues of water scarcity, should these occur. First, the
412 performances of the examined processes can be taken as local reference to be compared with sea
413 water desalination, which is one the most promising routes to alleviate the water scarcity problem
414 (Friedrich et al., 2017; Pistocchi et al., 2020; Qadir et al., 2007) and of particular relevance for the
415 RADWSS considering the access of RN and RA provinces to the Adriatic Sea. The implementation
416 of desalination water treatment plants would grant some advantages, as a low energy consumption
417 during the withdrawal step, in comparison with the GW sources, and (theoretically) unlimited
418 availability of water (Friedrich et al., 2017; Pistocchi et al., 2020). Anyway, despite the fact that this
419 technology is nowadays widely diffused, there are also some challenges that hinder its
420 implementation: the treatment energy demand associated with removing salts and dissolved
421 contaminants is far greater than treatment of freshwater associated with conventional water treatment
422 processes (Tarpani et al., 2021). Furthermore, desalination technologies are also subjected to poor
423 public perception related to the discharge of concentrated brine and chemical residuals (Zhou et al.,
424 2014).

425 Globally, Liu et al. (2016) estimated that the energy demanded for total water supply worldwide
426 increased steadily in the past decades from 5.9 EJ in 1975 to 10.2 EJ in 2010. Yet, technology
427 improvement has led to a significant optimization of the energy consumption associated to water
428 management. Liu et al. (2016) found also that electricity used for water supply accounts for the
429 1.7%-2.7% of the total global primary energy consumption but, on the regional scale, the total
430 electricity consumed by RADWSS resulted to be 0.40% of the total electricity produced in the three
431 provinces FC, RA and RN (TERNA S.p.A., 2021), revealing that, for the RADWSS, despite energy
432 is essential for drinking water production, in comparison with other sectors, it presents a limited
433 responsibility concerning the electricity consumption of the Romagna territory.

434 Overall, the water-energy nexus analysis is essential to evaluate the sustainability of a drinking
435 water supply system, since the environmental impacts are extremely dependent on the amount of
436 energy consumed by process and, in particular, the electricity production mix.

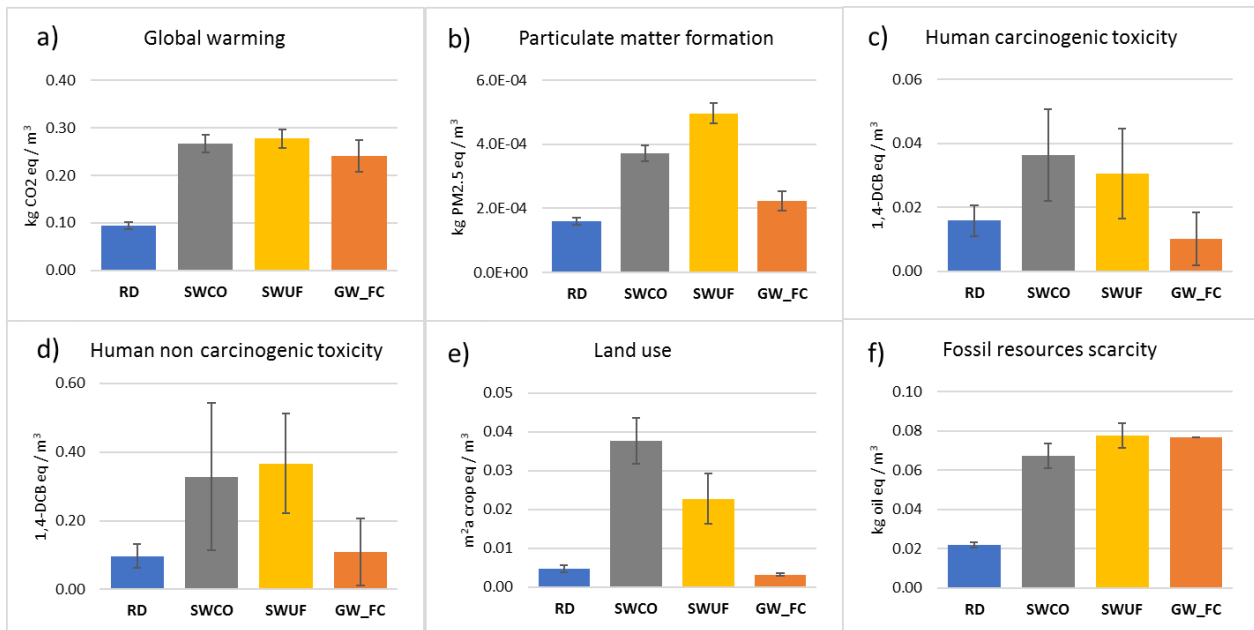
437 *3.4 Life cycle assessment*

438 *3.4.1 ReCiPe 2016: midpoint analysis*

439 While quantitative determination of water-for-energy and energy-for-water indicators provides the
440 scientific reference for understanding the nexus between two essential resources such as water and
441 energy, addressing the environmental sustainability challenge requires the assessment of
442 complementary impact categories and indicators, of which LCA enables proper estimation.

443 In Figure 5, we plotted the results for selected LCA midpoint categories, namely potential
444 contribution to global warming, particular matter formation, human carcinogenic toxicity, human
445 non-carcinogenic toxicity, land use, and fossil resource scarcity. This selection considers the main
446 impact categories contributing to the single score results, aligning to previous findings in the
447 literature (Bulle et al., 2019). In particular, the chosen categories: global warming (39.7%), fine
448 particulate matter formation (33.7%), human carcinogenic toxicity (HCT) (14.7%), human non-
449 carcinogenic toxicity (HnCT) (7.8%), fossil resource scarcity (1.36%); embody the 97.3% of the
450 total information included in the single score.

451 The results, normalized to 1 m³ of water, are distinguished by water supply source and process stage
452 considered. Error bars plotting uncertainty ranges are included.



453

454 *Figure 5 (a, b, c, d, e, f): Environmental impacts related to different water supply sources and treatments (impact*
 455 *categories). RD: Ridracoli water- conventional treatment; SWCO: Surface water- conventional treatment; SWUF:*
 456 *Surface water- ultrafiltration treatment; GW_FC: Groundwater- conventional treatment*

457 As earlier motivated, also in this case the impacts calculated for RD, SWCO, SWUF, and GW are
 458 compared excluding the distribution process. Numerical results with related uncertainty are
 459 available in Table S7.

460 Overall, the impact categories selected show similar orders of preference with the different options
 461 ranking often from SWUF being the worst scenario and RD the best one. For the remaining
 462 scenarios, GW is generally less impacting than SWCO. The uncertainty analysis confirms this rank,
 463 although for HCT and HnCT the uncertainty ranges do not attribute a net preference between the
 464 scenarios, at a confidence level of 95%. From these results, it emerges that processes associated to
 465 SW sources have generally higher impacts than the alternatives, especially in case of particulate
 466 matter formation (SWCO, 3.72E-04; SWUF, 4.97E-4) and land use (SWCO, 3.77E-02; SWUF
 467 2.28E-2), partially reflecting the environmental burdens related to the treatment of input water of
 468 lower quality (Liu et al., 2016; Mo et al., 2014). On the other side, RD water has the best

469 environmental performance. Especially, RD's GHG emissions ($9.45E-02$ kg CO₂ eq/m³) are about
470 three time lower than those occurring from SWUF. More details are available in Table S7.

471 As mentioned in the introduction section, a relative high number of studies in the literature has
472 evaluated the environmental performance of different water supply systems. Despite discrepancies
473 in the authors' methodological choices and the inherent characteristics of geographical contexts
474 which limit the comparison of the results with prior studies, some general considerations that align
475 to our findings can be drawn. More specifically: (i) GW is attributed a lower impact than SW; (ii)
476 conventional processes for water treatment are less energy intensive than ultrafiltration processes;
477 (iii) The studies which have examined the environmental performance of drinking water
478 desalination agree in sentencing that this choice is much higher impacting with respect to the
479 alternatives, mainly because of the notable energy intensity of the processes (Del Borghi et al.,
480 2013; Godskesen et al., 2013) (iv) The variety of the environmental categories considered in the list
481 of the available LCA studies is another factor which limits the comparison between the obtained
482 results. The selection of different impact categories is sometimes forced by the LCIA methodology
483 while, in other cases, derives by arbitrary choices. Anyway, it is found that some categories are
484 almost always considered in all the studies, for instance: Global warming potential (Bârjoveanu et
485 al., 2019; Bhakar and Singh, 2018; Bonton et al., 2012; Garcia-Suarez et al., 2019; Garfí et al.,
486 2016; Lakho et al., 2022b; Ortiz Rodriguez et al., 2016; Saad et al., 2019), Human Toxicity
487 (Bârjoveanu et al., 2019; Bhakar and Singh, 2018; Lakho et al., 2022b), Land use (Bârjoveanu et
488 al., 2019; Bhakar and Singh, 2018; Lakho et al., 2022b) and Particulate matter formation
489 (Bârjoveanu et al., 2019; Bhakar and Singh, 2018). Concerning this, the global warming potential
490 category is considered as good basis for comparison.

491 More specifically, Godskesen et al. (2011) analyzed six different water supply scenarios obtaining
492 that GW presents relative lower impacts with respect to all the alternatives. It is anyway specified
493 that the treatment of water deriving by an artificial reservoir (in our case, RD) was not included in
494 his study. The artificial reservoir has been instead considered by Lane et al. (2015) and, even if the

495 complexity of the examined multi-technological drinking water supply system does not allow to
496 directly get a reference value associated to the dam water treatment, it is found that the contribution
497 of the infrastructure is always less relevant with respect to the operational processes.

498 Zijp and van der Laan (2015) performed an LCA aimed at comparing the ultrafiltration and
499 conventional processes and, also in this case, the results basically agree with the ones obtained in
500 our study, since the author describes a difference between the two alternatives in favor of the
501 conventional practice of approximately the 30% in case of global warming potential, 40% for
502 human toxicity and 25% for CED.

503 Rodriguez et al. (2016) analyzed some different Colombian drinking water treatments scenarios.
504 For two of the examined scenarios, the technology and the nature of the sourced water are
505 comparable with SWCO and the resulting values (ranging from 0.17 and 0.38 kg CO₂ eq/m³) are
506 quite similar to the 0.27 kg CO₂ eq/m³ obtained in our study. Also Saad et al. (2019), evaluating a
507 treatment process in Turkey very similar to SWCO, obtained a carbon intensity of 0.34 kg CO₂
508 eq/m³.

509 Some discrepancy have been instead observed by Bonton et al. (2012), which provided a
510 comparison, using the impact 2002+ (Jolliet et al., 2003) LCIA method, between conventional and
511 nanofiltration treatments, with the latter not faced in our work. Specifically, the conventional
512 treatment showed values between 0.68-0.79 kg CO₂ eq, which are quite higher with respect to ours,
513 even if of the same order of magnitude. He obtained also that nanofiltration seems to be the more
514 convenient technology, but such result is justified by the different energy mixes considered for the
515 two technologies, i.e. the nanofiltration plant relies almost exclusively by hydroelectric energy.

516 A more evident discrepancy has been observed by Prézéus et al. (2021), who analyzed an
517 ultrafiltration treatment which by resulted in a global warming potential of 0.004 kg CO₂ eq, value
518 significantly lower with respect to the 0.269 kg of CO₂ eq obtained for the SWUF scenario. The
519 very low value obtained seems anyway to strengthen our suppositions, since it is due to a high
520 quality input water and to a minor consumption of electricity to perform the process (0.12 MJ/m³

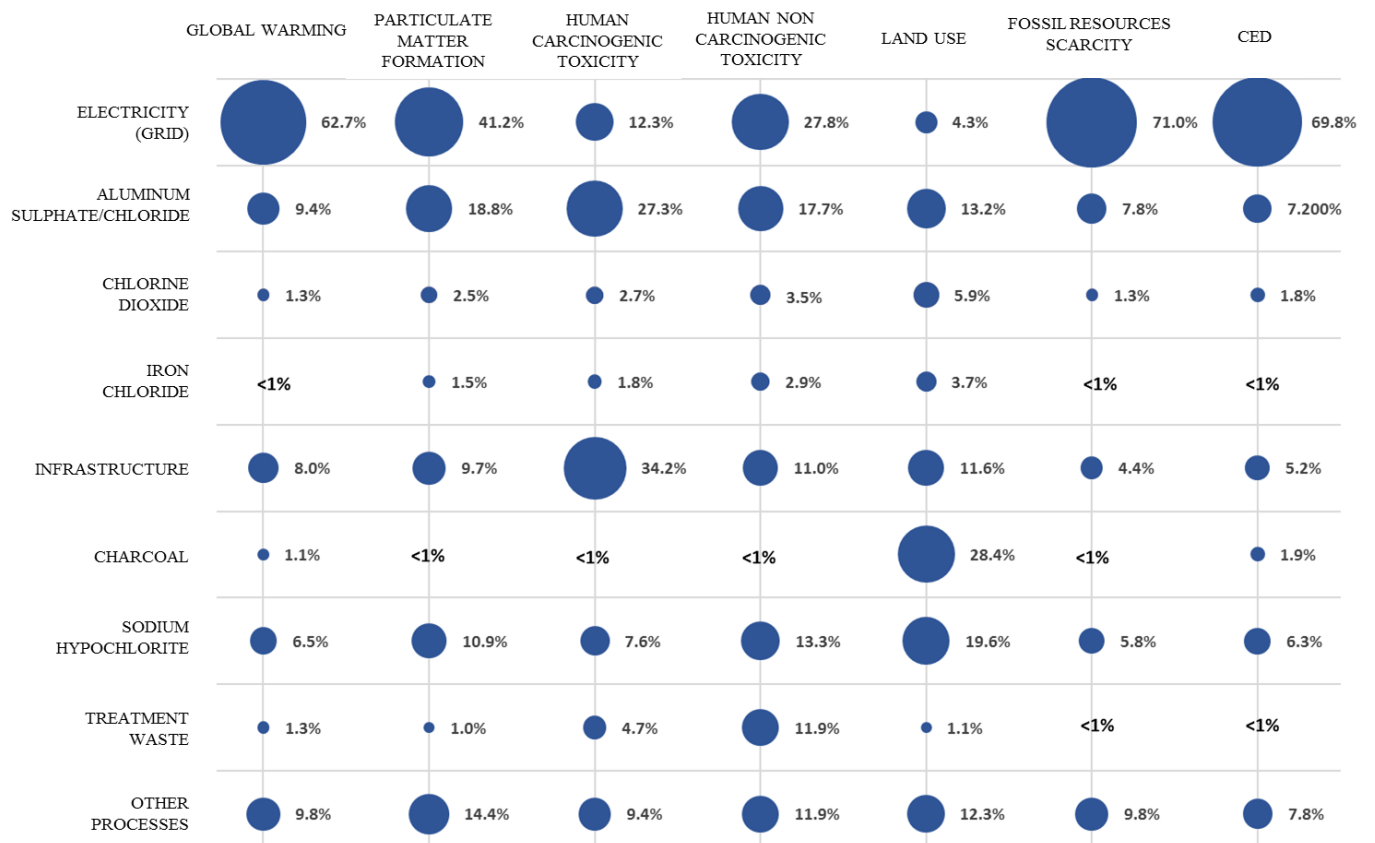
521 instead of 0.61 MJ/m³). In addition, Prézéus et al. (2021) assumed to use electricity deriving by
522 the French mix (71% nuclear, 10% hydropower, 6% natural gas, 4% wind, 2% coal and 7% other),
523 which has significantly a lower carbon intensity with respect to the Italian one. Such dissimilarity
524 highlights the influence of the geographical contest.

525

526 *3.4.2 Contribution analysis*

527 The contribution analysis was carried out to identify the most significant processes in determining
528 the environmental profile of the system, i.e., those variables that should be prioritized to reduce the
529 overall environmental impact associated with water supply in RADWSS. Figure 6 shows the
530 relative contribution of the selected processes to midpoint categories.

531 In general, certain trends in the relative shares of the selected processes are noticeable by impact
532 category (i.e., in columns) and by process (i.e., in row), with some exceptions. Specifically, the
533 different processes rank with a similar order in column, although few distinctions are worth
534 mentioning.



535

536 *Figure 6: contribution analysis of midpoint categories*

537 In line with the majority of the studies on this topic (Friedrich et al., 2017; Lane et al., 2015; Ortiz
538 Rodriguez et al., 2016; Stokes and Horvath, 2006; Vince et al., 2008), electricity dominates the
539 potential contribution to fossil resources scarcity (71.0%), global warming (62.7%), particulate
540 matter formation (41.2%), and -to a less extent- HnCT (27.8%). In the former three impact
541 categories, the remaining processes do not contribute for more than 10% each. Infrastructure is the
542 main contributor to HCT (34.2%), followed by aluminum sulphate/chloride, and electricity.
543 Charcoal prevails for land use (28.4%), followed by sodium hypochlorite, and aluminum
544 sulphate/chloride.

545 Our analysis reveals that, beyond electricity, other relevant contributors are aluminum compounds
546 involved in the water treatment (18.8% in particulate matter formation, 27.3% in HCT and 17.7 in
547 HnCT), sodium hypochlorite (19.6% for land use and 13.3% for HnCT) and the infrastructure,

548 which includes the two dams, pump stations, water treatment facilities and the distribution network.
549 These results align to previous studies in the field (Bonton et al., 2012; Lane et al., 2015). Lower
550 burdens are attributed to the chemicals employed during the potabilization process: iron chloride,
551 charcoal, and chlorine dioxide.

552 The high contribution of the aluminum sulfate powder is due to its production route, including both
553 the process in place and raw materials supply. The drawback of using inorganic floating agents such
554 as aluminum sulfate or iron sulfate is well-known and research is active in the development of
555 alternative solutions aimed at reducing the environmental impact (Taneez and Hurel, 2019). For
556 instance, promising routes include the use of organic polyelectrolytes (Bolto and Gregory, 2007) as
557 substitutes.

558 Supplemental reduction of the overall environmental impact of the system under scrutiny may also
559 derive from improvements in the current waste management through, for instance, reuse of the
560 residue from inorganic drinking water treatment in building material manufacturing (Gomes et al.,
561 2020; Ramirez Zamora et al., 2008) as a preferable recovery and recycling strategy to current
562 disposal by landfilling.

563 Regarding SW, the contribution analysis reveals intrinsic differences between the two
564 configurations analyzed (i.e., UF and CO). For SWUF, the factors that mainly contribute to the
565 observed impacts are sodium hypochlorite (41% in climate change, 45% in particulate matter
566 formation, 62% land use and 41% in CED) and electricity (29% in climate change, 12% in
567 particulate matter formation and 30% in CED). In contrast, for SWCO, the major contributors are
568 aluminum sulfate (12% in climate change, 31% in particulate matter formation, 13% in land use and
569 13% in CED), electricity (33% in climate change, 18% in particulate matter formation and 34% in
570 CED) and charcoal (8% in climate change, 61% in land use, 15% in CED). Complementing
571 fractions to 100% distribute among the remaining material and energy needs and waste
572 management.

573 In addition, the relatively long lifetime of filters employed in the ultrafiltration treatments (between
574 10 and 15 years) (Romagna Acque - Società delle fonti S.p.A., 2021) explains a contribution <1%
575 to the overall impact: for this reason, filters are not included in Figure 6.

576 3.4.3 Sensitivity analysis

577 The contribution analysis highlighted the relevant influence of the electricity consumption on the
578 environmental performance of the system so that sensitivity analysis compared two energy
579 scenarios (Table S6). In particular, being well-known the role of the electricity mix on the
580 environmental impacts of electricity usage (Breeze, 2018; Šerešová et al., 2020), input deriving
581 from renewable sources was set as the exogenous variable and made it vary according to two
582 possible energy scenarios, described as follows:

- 583 - Scenario 1: the electricity requirements are satisfied by the renewable electricity produced
584 and auto-consumed by the system (3.19E+06 MJ/y) plus an amount (3.69E+07 MJ/y)
585 purchased from the national grid. For the modelling of the electricity sourced from the
586 national grid, including import from foreign country suppliers, the mix reported by the
587 International Energy Agency for the latest year available (i.e., 2019) has been considered
588 (IEA, 2022).
- 589 - Scenario 2: RADWSS consumes only renewable energy, assuming the electricity purchased
590 from the grid is 100% renewable. Overall, the renewable electricity mix is set as follows:
591 hydroelectric, 77.1%; wind, 19.5%; solar 3.4%. This mix has been modelled according to
592 the energy plan developed by Romagna Acque.

593 Results are reported in figure S6 of the supplementary material. As expected, a significant
594 reduction of the impacts is observed for scenario 2, reflecting the influence of greening the
595 energy mix Zijp and van der Laan (2015). Compared to Scenario 1 (i.e., the current situation), in
596 Scenario 2, the impacts decrease by 71.6% for global warming and for the 44.4% for particulate
597 matter formation. HCT, HnCT and land use, according to the contribution analysis, are instead

598 less susceptible to electricity generation. Overall, the sensitivity analysis demonstrated that the
599 model is robust to perturbation of modelling parameters, indicating that a transition to
600 renewable energy sources would certainly benefit the overall environmental performance of
601 RADWSS.

602 **3 Conclusions**

603 In the presented study, water sustainability issues affecting the drinking water supply system in the
604 Romagna region have been addressed by means of LCA. This quantitative assessment framework
605 has enabled to evaluate and examine the environmental impacts associated to different water
606 sources and treatment technologies implemented in this system. From the outcomes, some clear
607 patterns can be summarized as follows. (i) The withdrawal process is much less energy intensive for
608 dam water (i.e., RD) and surface water (SW) sources than for groundwater (GW) reservoirs.
609 However, while RD ranked as the less impacting scenario also under a “life-cycle” perspective,
610 surface water scenarios showed the worst environmental performance, with groundwater ranking as
611 the second best. (ii) The RADWSS is highly energy demanding so that its environmental impact
612 decreases significantly when higher shares of renewable energy are utilized in the electricity grid
613 mix, showing a clear way for de-carbonization of water supply systems. (iii) Nexus analysis applied
614 to water-energy interconnections provides more in-depth understanding of the water-for-energy and
615 energy-for-water implications related to the provisioning of drinking water. However, when these
616 considerations are scaled up to contexts higher in scope such as the whole regional energy and
617 water systems, they become less significant suggesting a primary application to analyses focused on
618 the local scale. (iv) More broadly, LCA confirms to be a fundamental framework for system-
619 thinking approaches, which may ultimately support decision-makers and local communities to the
620 planning of strategies for optimized and long-term reliable access to natural resources.

621

622 ***Conflicts of interests***

623 There are no conflicts of interests to declare.

624 ***Acknowledgments***

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627

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