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

F. Arfelli[a]*, L. Ciacci[a]*, I. Vassura[a,b], F. Passarini[a,b]

[a]Department of Industrial Chemistry "Toso Montanari", University of Bologna, viale del Risorgimento 4, 40136 Bologna, Italy.

[b]Interdepartmental Centre of Industrial Research "Renewable Resources, Environment, Sea and Energy", University of Bologna, via Angherà 22, 47922 Rimini, Italy.

*email of the corresponding authors: *francesco.arfelli3@unibo.it (F. A.); luca.ciacci5@unibo.it (L.C.)*

# Abstract

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

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

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



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

| 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 |

# *1. Introduction*

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

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

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

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

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

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

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

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

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

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

## *2. Materials and methods*

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

### *2.1Goal and scope definition*

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

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

### *2.1.1 System description*

The system under scrutiny covers the entire RADWSS established in the Romagna territory, counting more than 1 million inhabitants and as many as tourists, facing an overall demand for more than 100 million cubic meters ($Mm^3$) of water per year, supplied by means of a water grid extended over more than 600 km (Figure 1).

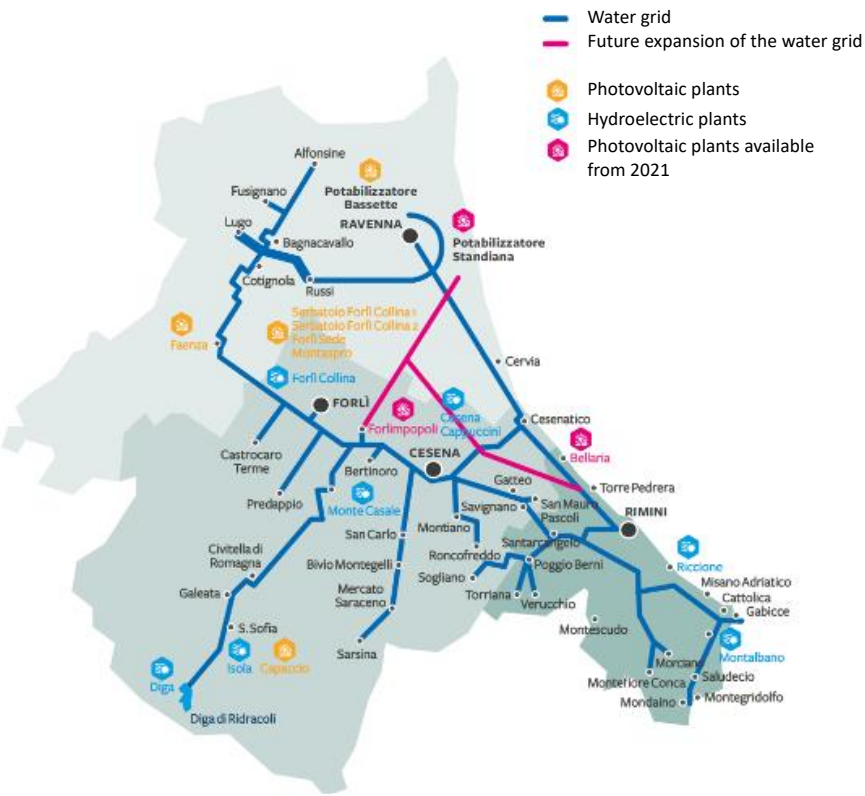


*Figure 1: Romagna Acque system's map* (Romagna Acque - Società delle fonti S.p.A., 2021)

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

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

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

### *2.1.2 Withdrawal, treatment and distribution processes*

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

requirements for potable water and other uses (e.g., agricultural or industrial purposes). In the system under scrutiny, 15 different small (0.2 $m^3/s$) to medium (to 3.6 $m^3/s$) size potabilization plants are fully operating: 14 of them are equipped with conventional technologies, while one plant has been recently upgraded with an ultrafiltration process (SWUF).

Commonly, in the conventional processes, the water inflow is treated with chlorine dioxide or potassium permanganate to oxidize organic substances, decrease turbidity, and reduce iron and manganese concentrations. Then, water is subjected to chemical conditioning and perchloration with chlorine dioxide or sodium hypochlorite. Subsequently, clariflocculation and filtration stages occur, in which aluminum sulfate is added as a coagulating agent to promote particle collision and precipitation (Romagna Acque - Società delle fonti S.p.A., 2021; Sillanpää and Matilainen, 2015). The resulting sludge is then filtrated, removed, and sent to final disposal.

In contrast, SWUF consists of a pressure-driven membrane separation process, where polyvinylidene chloride membranes with pore sizes of about 20 nm are employed to achieve high removal efficiency of bacteria, viruses, and other polluting substances (Romagna Acque - Società delle fonti S.p.A., 2021). The main advantages of this technology are that ultrafiltration reaches very high removal efficiency rates even in conditions of very polluted water inflows (Dupont, 2008; Jacquet et al., 2021; Prézélus et al., 2021).

Eventually, the distribution process is the final stage that conveys treated water outflows (e.g., potable water) to a third company which deals with its delivery to final users such as municipalities, residential and commercial buildings, and industrial plants.

### *2.1.3 System boundaries*

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

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

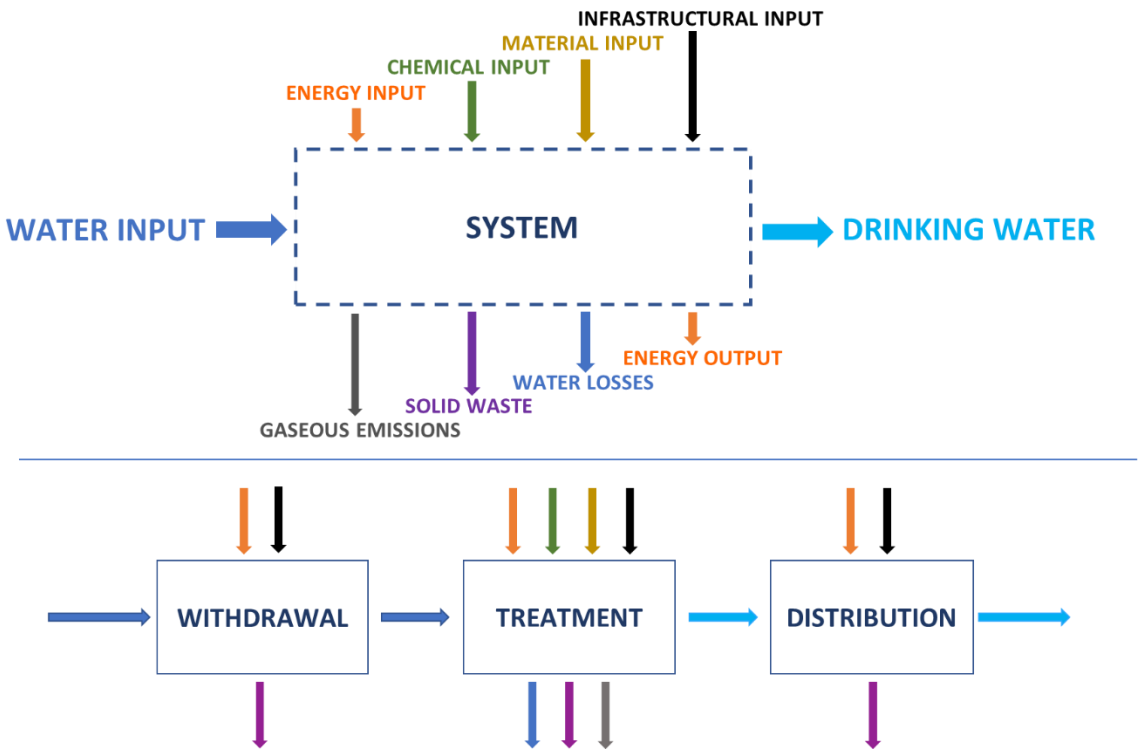


*Figure 2: a) Summary representation of inputs and outputs in the system (modified from Zhou et al., 2014); b) sequential representation of the three main steps of the generic drinking water supply system under investigation.*

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

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

### *2.1.4 Functional unit definition*

In consistency with similar studies in the literature (Byrne et al., 2017; Garfí et al., 2016; Prézélus et al., 2021; Raghuvanshi et al., 2017), the whole system evaluation and the comparison between different water production alternatives is performed setting 1 $m^3$ of delivered drinking water as the functional unit.

## *2.2 Life cycle inventory*

### *2.2.1 Data collection*

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

Data related to water, energy, and chemical flows were provided directly by Romagna Acque for the most recent year available (i.e., 2020). These inventories included the total volume of water delivered to each province from a specific source derivation (i.e., RD, GW or SW sources), the volume of water sent to SWCO and SWUF treatment plants, the amount of energy generated from photovoltaics and hydroelectric production stations, the electricity requirements for water withdrawal and distribution, by water source and treatment process applied (i.e., SWCO, SWUF). An exhaustive inventory of the type and amounts of chemicals employed in the water treatment plants for the three main water sources was also determined (for more detail, see Tables S1a-e in the Supplementary Material). Similarly, engineering information provided by Romagna Acque has enabled a site-specific LCA modelling of the Ridracoli and Conca dams (Tables S2a-c). Information about waste generated by water treatment plant (Tables S3a-e) was collected and classified according to the European waste catalogue codes (2000/532/EC). As for the LCA

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

### *2.2.2 Model assumptions*

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

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

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

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

$$5NaClO_2 + 4HCl \rightarrow 4ClO_2 + 5NaCl + 2H_2O$$

*Equation 1: chlorine dioxide generation reaction*

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

## *2.3 Life cycle impact assessment*

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

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

## *2.4 Sensitivity and uncertainty analysis*

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

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

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

### *2.5 Softwares and databases*

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

## *3. Results and discussions*

### *3.1 The water-energy nexus*

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

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

| **Drinking water ($m^3$/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% |

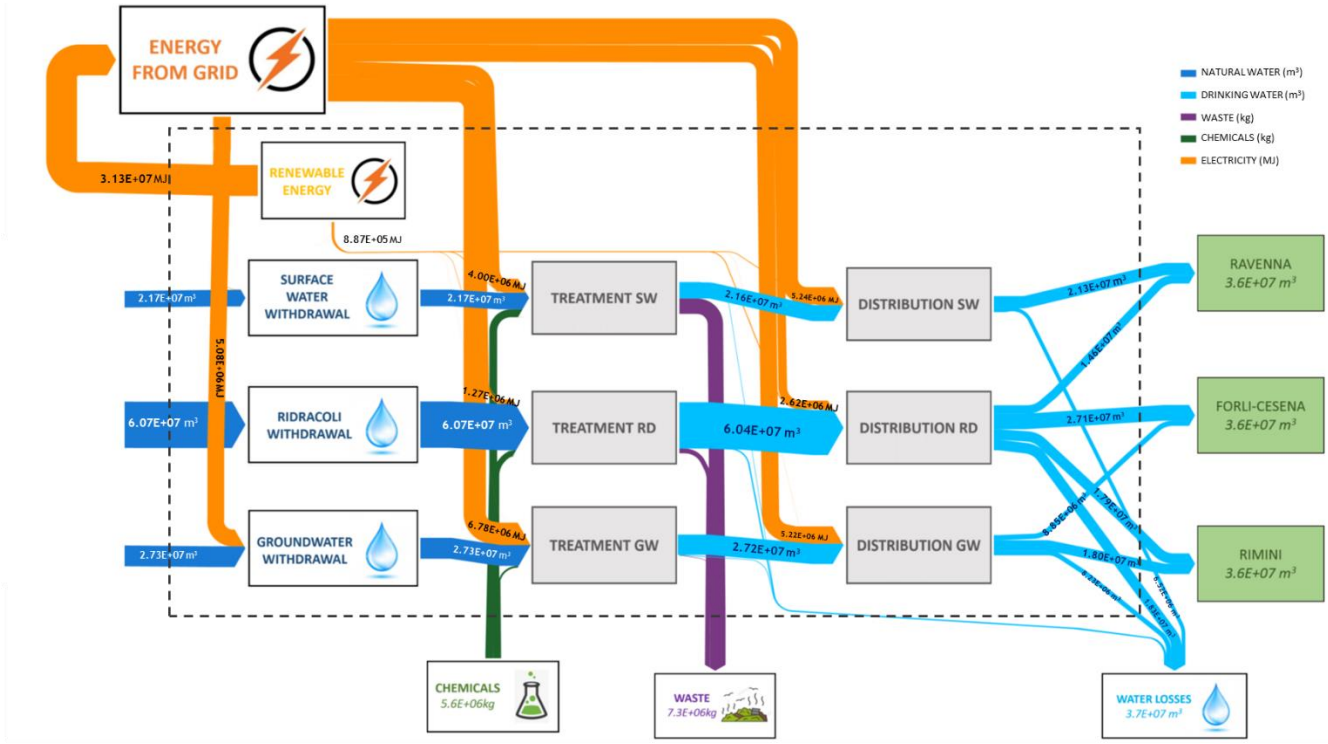


*Figure 3: Sankey diagram of the main water ($m^3$), energy (MJ), chemicals (kg) and waste (kg)l flows of the RAWSS for the year 2020*

## *3.2 Description of the RADWSS*

RD is the main water source in the region, covering about 55% of the volume supplied in the RADWSS (i.e., 108 $Mm^3$ in 2020). The RD volume of about 60 $Mm^3$ is distributed to the provinces with the following shares: FC, 46%; RN, 30; RA, 24%. GW and SW sources contribute for the rest as dictated by the distribution of local water bodies, with GW sources supplying RN (18 $Mm^3$/year) and FC (9 $Mm^3$/year), and SW sources serving the RA province (21 $Mm^3$/year) mainly through water withdrawal from the CER.

At the province scale, the water needs for each one of the three examined provinces is about 36 $Mm^3$/year, reflecting a per capita (p.c.) drinking water demand of about 91 $m^3$/inhabitant in the FC province, 92 $m^3$/inhabitant in RA and 106 $m^3$/inhabitant in RN. The total direct and indirect water consumption is calculated by knowing the volume of water losses and water virtually embodied in processes and materials involved in the RADWSS. The amount of water involved in RADWSS consists of water delivered (1.1E+08 $m^3$/year), water consumed or lost in treatments (4.3E+05 $m^3$/year), water lost because of inefficiencies along the distribution network (1.6E+06 $m^3$/year), water virtually embodied in chemicals and materials (1.12E+05 $m^3$/year), in infrastructure (2.23E+06 $m^3$/year), and water involved in waste management processes (6.29E+03 $m^3$/year). Consequently, it results that per each cubic meter of water delivered about 1 $m^3$ of water is lost or consumed during withdrawal, treatment, and distribution stages. Assuming to shift from energy scenario 1 to energy scenario 2, i.e., electricity derives exclusively from renewable sources, the water consumption would reduce to 0.08 $m^3$/year.

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

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

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

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

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

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

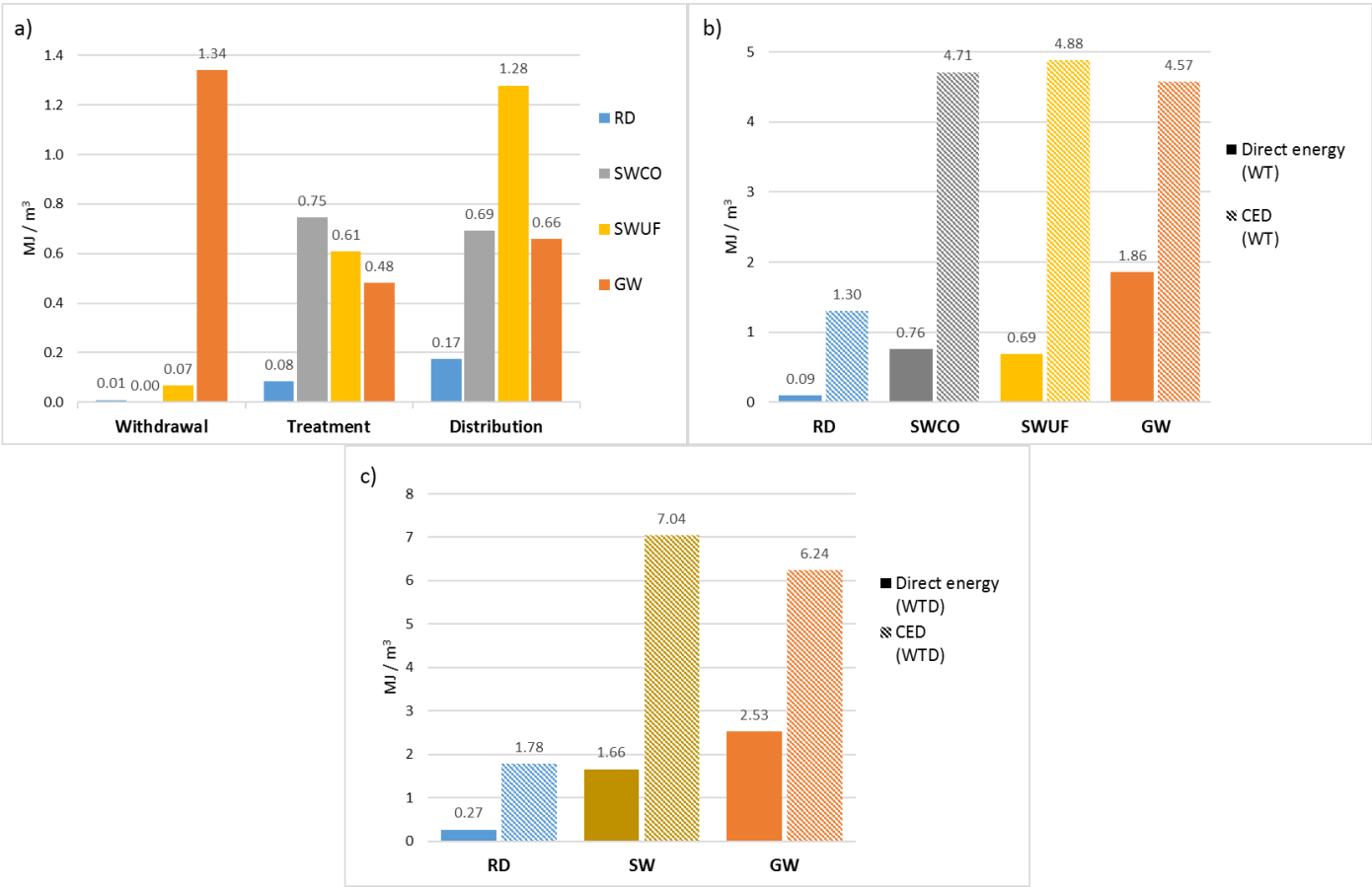


*Figure 4: a) energy flows associated to processes and sources (MJ/m$^3$ of water delivered; b) energy efficiencies and cumulative energy demand, considering only withdrawal and treatment processes, WT (MJ/m$^3$); c) energy efficiencies and cumulative energy demand, considering withdrawal, treatment, and distribution processes, WTD (MJ/m$^3$)*

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.

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

similar goods employed in the system as well as with materials transportation, waste management and treatment. As shown in Figure 4b, if indirect energy requirements are included and computed by the CED method, the cumulative energy intensity of withdrawal, treatment, and distribution by source, excluding as mentioned the distribution stage, raises from 0.1 to 1.3 MJ/$m^3$ for RD, from 0.8 to 4.7 MJ/$m^3$ for SWCO, from 0.7 to 4.9 MJ/$m^3$ for SWUF and from 1.9 to 4.6 MJ/$m^3$ for GW. In case of RD, SWCO and SWUF, the direct energy represents between the 10-15% of total cumulative energy demand, while for GW, the direct energy requirements are responsible for 41.3% of the total value observed, highlighting the influence of the withdrawal process.

### *3.3.2 Water for Energy*

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

Considering the whole system, the total volume turbinated to produce hydropower in 2020 was 7.4E+07 $m^3$ (Romagna Acque - Società delle fonti S.p.A., 2021), which corresponds to 2.1 $m^3$ of turbinated water every electrical MJ produced. This value is supplemented by water inputs for infrastructure of photovoltaic plants and for direct and indirect water inputs related to electricity supplied from the national grid, which are estimated at 0.39 $m^3$/MJ (of which around 62% is attributed to the silicon-based material production) and 0.96 $m^3$/MJ, respectively (Wernet et al., 2016). Overall, the resulting water-for-energy amounts to 3.45 $m^3$ per MJ of electrical energy consumed in the system. In absolute quantities, the water-for-energy amounts to 9.15 E+07 $m^3$, which corresponds to about 83% of the total water inflow to RADWSS.

### *3.3.3 Comparison with previous results and future improvements*

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

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

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

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

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

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

## *3.4 Life cycle assessment*

### *3.4.1 ReCiPe 2016: midpoint analysis*

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

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

The results, normalized to 1 $m^3$ of water, are distinguished by water supply source and process stage considered. Error bars plotting uncertainty ranges are included.

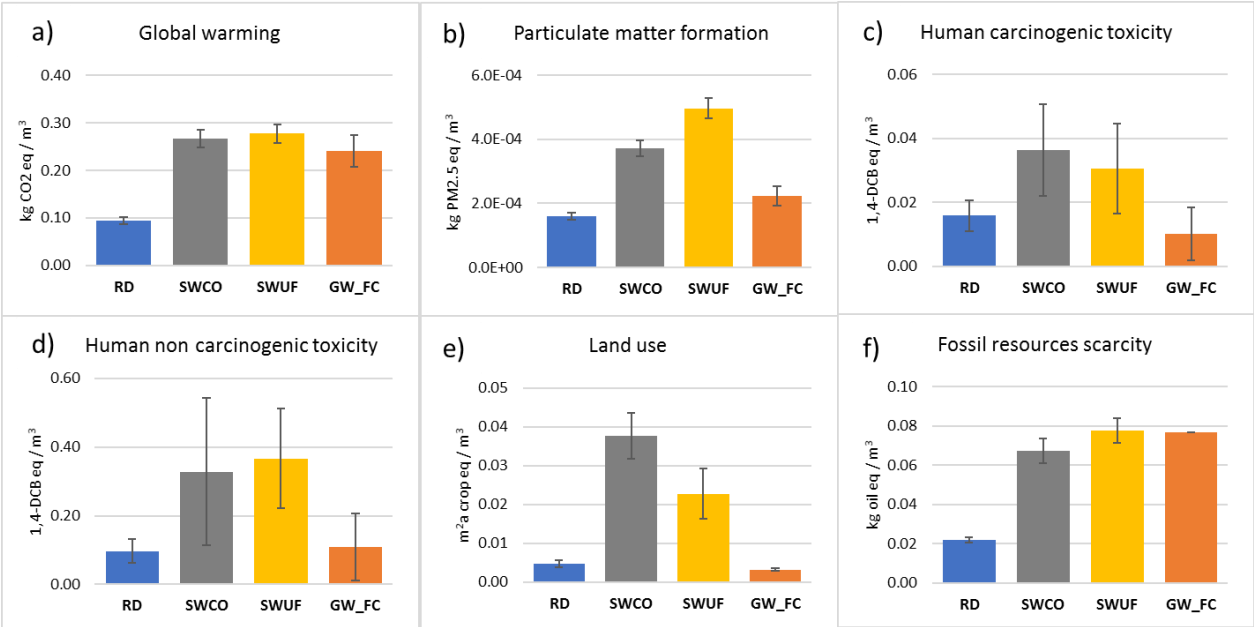


*Figure 5 (a, b, c, d, e, f): Environmental impacts related to different water supply sources and treatments (impact categories). RD: Ridracoli water- conventional treatment; SWCO: Surface water- conventional treatment; SWUF: Surface water- ultrafiltration treatment; GW_FC: Groundwater- conventional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

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

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

environmental performance. Especially, RD's GHG emissions (9.45E-02 kg $CO_2$ eq/$m^3$) are about three time lower than those occurring from SWUF. More details are available in Table S7.

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

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

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

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

Rodriguez et al. (2016) analyzed some different Colombian drinking water treatments scenarios. For two of the examined scenarios, the technology and the nature of the sourced water are comparable with SWCO and the resulting values (ranging from 0.17 and 0.38 kg CO2 eq/$m^3$) are quite similar to the 0.27 kg $CO_2$ eq/$m^3$ obtained in our study. Also Saad et al. (2019), evaluating a treatment process in Turkey very similar to SWCO, obtained a carbon intensity of 0.34 kg $CO_2$ eq/$m^3$.

Some discrepancy have been instead observed by Bonton et al. (2012), which provided a comparison, using the impact 2002+ (Jolliet et al., 2003) LCIA method, between conventional and nanofiltration treatments, with the latter not faced in our work. Specifically, the conventional treatment showed values between 0.68-0.79 kg $CO_2$ eq, which are quite higher with respect to ours, even if of the same order of magnitude. He obtained also that nanofiltration seems to be the more convenient technology, but such result is justified by the different energy mixes considered for the two technologies, i.e. the nanofiltration plant relies almost exclusively by hydroelectric energy.

A more evident discrepancy has been observed by Prézélus et al. (2021), who analyzed an ultrafiltration treatment which by resulted in a global warming potential of 0.004 kg $CO_2$ eq, value significantly lower with respect to the 0.269 kg of $CO_2$ eq obtained for the SWUF scenario. The very low value obtained seems anyway to strengthen our suppositions, since it is due to a high quality input water and to a minor consumption of electricity to perform the process (0.12 MJ/$m^3$

instead of 0.61 MJ/$m^3$). In addiction, Prézélus et al. (2021) assumed to use electricity deriving by the French mix (71% nuclear, 10% hydropower, 6% natural gas, 4% wind, 2% coal and 7% other), which has significantly a lower carbon intensity with respect to the Italian one. Such dissimilarity highlights the influence of the geographical contest.

### *3.4.2 Contribution analysis*

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

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

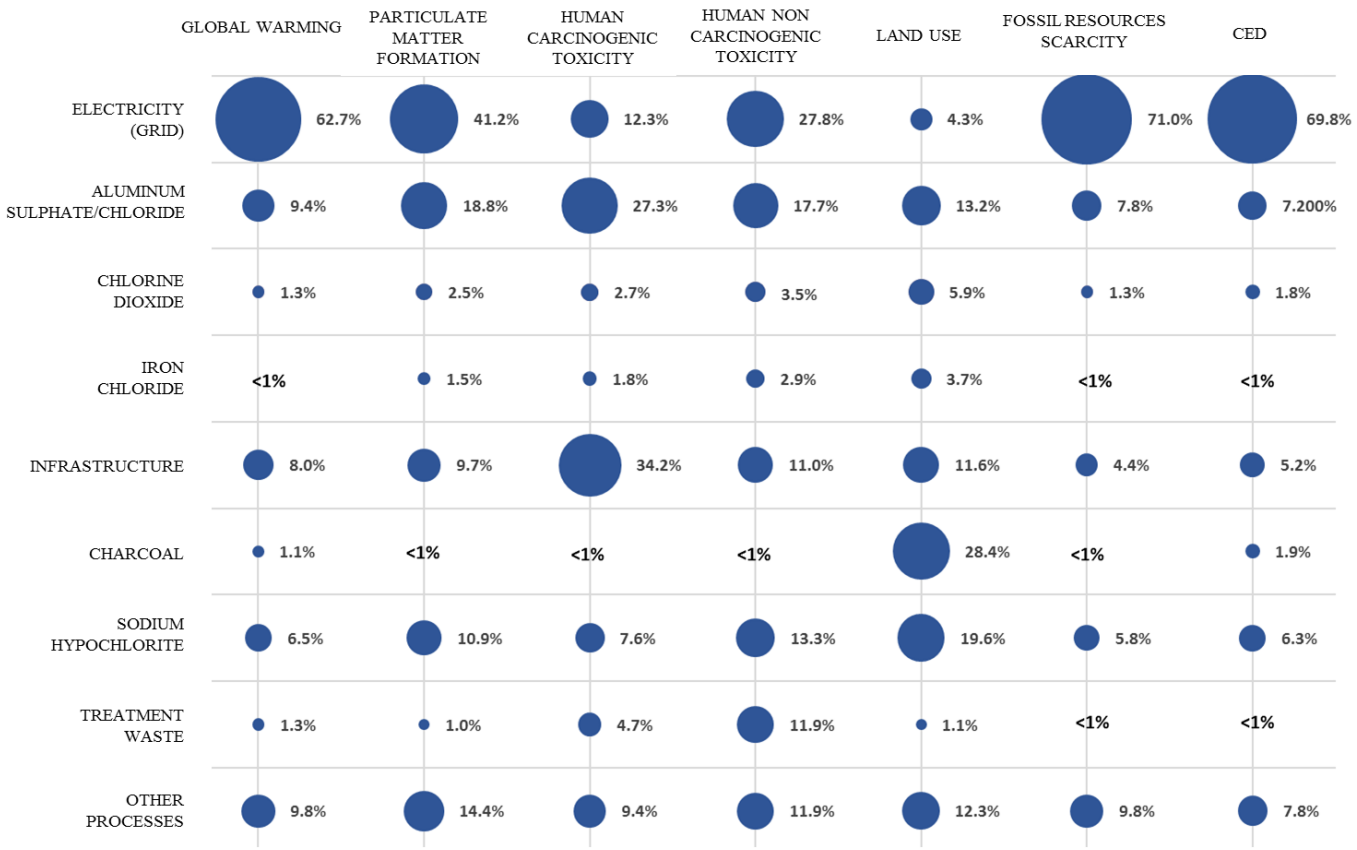


*Figure 6: contribution analysis of midpoint categories*

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

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

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

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

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

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

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

### *3.4.3 Sensitivity analysis*

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

- Scenario 1: the electricity requirements are satisfied by the renewable electricity produced and auto-consumed by the system (3.19E+06 MJ/y) plus an amount (3.69E+07 MJ/y) purchased from the national grid. For the modelling of the electricity sourced from the national grid, including import from foreign country suppliers, the mix reported by the International Energy Agency for the latest year available (i.e., 2019) has been considered (IEA, 2022).

- Scenario 2: RADWSS consumes only renewable energy, assuming the electricity purchased from the grid is 100% renewable. Overall, the renewable electricity mix is set as follows: hydroelectric, 77.1%; wind, 19.5%; solar 3.4%. This mix has been modelled according to the energy plan developed by Romagna Acque.

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

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

## *3 Conclusions*

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

## *Conflicts of interests*

There are no conflicts of interests to declare.

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