Science of the Total Environment 906 (2024) 167154

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Unlocking energy potential: Decarbonizing water reclamation plants with salinity gradient energy recovery

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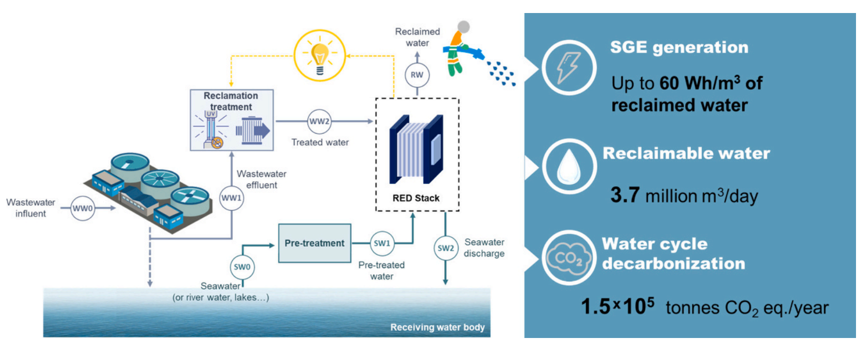
HIGHLIGHTS

- SGE-RED as opportunity to promote sustainable water reclamation.
- Decarbonization of reclamation processes in EU UWWTPs.
- Identification of promising EU UWWTPs to integrate SGE in water reclamation.
- Estimation of 3.7 million m^3/day of water savings.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Laura Bulgariu

Keywords:
Salinity gradient energy
Reverse electrodialysis technology
Water reclamation
Coastal UWWTPs
Water cycle decarbonization

ABSTRACT

Climate change, together with the ecological droughts suffered by a large part of the European Union's territory, calls for joint environmental solutions. In this regard, water reclamation is a promising way to alleviate the pressure on existing water resources. However, reuse strategies are penalized by the extra energy consumed in urban wastewater treatment plants (UWWTPs), facilities mainly powered by fossil fuels. The opportunity to integrate renewable sources of energy into the energy-intensive UWWTPs holds great promise towards decarbonization of the sector. In this context, the energy harvested from a Salinity Gradient (SGE) has attracted great interest in the last decade. This work aims at the analysis of opportunity of implementing integrated processes for water reclamation and SGE recovery in the coastal EU UWWTPs. According to the selection criteria, a total of 281 potential sites located across eighteen coastal countries of the EU have been inventoried attending to the current state of the art. The water reclamation potential has been estimated at 3.7 million m^3/day. As a consequence, the environmental burdens of the reclamation process could result in the reduction of $1.5{\cdot}10^5$ t CO_2/year. The Mediterranean region, highly affected by hydrological drought, has proved to be a hot spot for water reclamation, with the highest number of plants inventoried in the study and a predicted potential for SGE harvesting of 60 Wh/m^3 of reclaimed water. These results highlight a niche of opportunities to encourage water reclamation, avoid water bodies' degradability due to effluent discharge and the further decarbonization of reclamation processes.

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https://doi.org/10.1016/j.scitotenv.2023.167154
Received 25 May 2023; Received in revised form 11 September 2023; Accepted 15 September 2023
Available online 25 September 2023

1. Introduction

The current water scarcity situation exerts increasing pressure on the European Union (EU) freshwater resources, thus increasing water stress and leading to an imbalance in the utilisation of conventional water sources (UNESCO, 2018). Responsible use and sustainable management of water resources is necessary to cope with the ever-growing ecological drought (Sadiqi et al., 2022), largely caused by population growth, economic development and changing consumption patterns (United Nations, 2021; Asmal et al., 2022). Exploiting new sources of water is essential to solve the scarcity of freshwater resources. Desalination of seawater or brackish water, and reclamation and reuse of treated wastewater stand out among non-conventional alternatives (Karimidastenaei et al., 2022). In the EU, urban wastewater treatment plants (UWWTPs) have an associated energy consumption ranging from 0.3 to 2.1 kW/m^3 of treated wastewater (Capodaglio and Olsson, 2020). Furthermore, UWWTPs effluents are generated, thus, treated waters reclamation and reuse could help solving seasonal and climate associated intermittencies.

The Water Framework Directive 2000/60/EC (WFD, 2000) favours the implementation of reclamation and reuse processes of municipal WWTPs' effluents. In this regard, the EU Regulation 2020/741 of the European Parliament and of the council of May 2020 sets minimum quality requirements for the reuse of reclaimed water for agricultural irrigation, industrial use and environmental and recreational purposes. Nevertheless, in the EU only 2.4 % of treated wastewater effluent is reclaimed (European Commission, 2020). Strategies to cope with hydrological drought that include water reuse allow generating a water multiplier effect, by increasing the available water resources circulating in the urban supply system but without generating further pressure on natural resources (Kumar et al., 2016). Reclamation of treated wastewater is directly constrained by the additional energy consumption involved in obtaining high-quality water that meets the standards for water reuse, which currently ranges between 0.002 and 0.26 kWh/m^3.

Even more, in 2020, almost 42 % of the net electricity produced in the EU energy grid, from which wastewater treatment facilities are supplied, came from fossil fuels (Eurostat, 2020). One of the targets set at the UN Climate Change Conference in 2021 includes decarbonization of energy production through a transition to the so-called clean energies in order to limit the global temperature increase to 1.5 °C (COP26, 2021). Specifically, the integration of clean energies in the reclamation of UWWTPs effluents promotes the simultaneous achievement of the Sustainable Development Goals 6 and 7, related to the access to clean water and adequate sanitation networks, and the production of affordable clean energy, respectively (United Nations, 2022). Furthermore, the carbon footprint of UWWTPs has been demonstrated to be significantly improved due to the decarbonisation of electricity (Parravicini et al., 2022).

In this context, the concept of salinity gradient energy (SGE), first developed and proposed by Pattle in 1954 (Pattle, 1954), constitutes a renewable source of energy of growing interest since it offers the possibility of generating energy by bringing into contact two water streams with different salt concentration avoiding atmospheric emissions (Mei and Tang, 2018). Estimates of up to 18 GW of salinity-gradient energy that could be harnessed globally when wastewater effluents are discharged into the sea have been reported (Logan and Elimelech, 2012). Among the considered technologies for SGE harvesting, reverse electrodialysis (RED) has been demonstrated as a very good and promising membrane-based electrochemical alternative for the exploitation of SGE and conversion to electricity (Jia et al., 2014; Yip et al., 2016).

Moreover, several studies have demonstrated the feasibility of generating SGE from treated wastewater at long-time periods. Luque Di Salvo et al. (2018), operated for a period of 15 days a RED unit fed with a model solution of 0.5 M NaCl (similar to seawater) and real reclaimed water (0.004–0.010 M NaCl solutions). Vanoppen et al. (2019), investigated different wastewater pre-treatment techniques to maximize the efficiency of RED systems. Gómez-Coma et al., 2020, successfully operated continuously for 480 h a RED stack fed by real pre-treated wastewater (0.008 M NaCl) and seawater (0.5 M NaCl). Under these conditions, a gross power density of 1.43 W/m^2 (55 Wh/m^3) was generated at a constant temperature of 24 °C. This energy production rate would provide a UWWTP with the energy required for a reclamation treatment.

Thus, it has been so far demonstrated in the literature that with appropriate pre-treatment, wastewater can be used in RED membrane units for SGE harvesting. Furthermore, the pre-treatment strategies of RED technology can be simultaneously used to enable effluent reclamation. The synergistic effect between reclaimed water and SGE energy harvested can boost remediation strategies as well as promote wastewater reuse. Nevertheless, besides the compulsory salinity gradient, adequate plant size, water temperature, and geophysical conditions of the coastal WWTP area are required to assure the potential benefits in terms of efficiency in energy harvesting.

In the EU, there are over 20,098 UWWTPs that generate 29.2 billion m^3 of treated water annually (Food and Agriculture Organization of the United Nations, 2021), which could be a valuable resource. This work evaluates the opportunity of using integrated systems for the remediation of treated water and energy recovery from salinity gradients in UWWTPs in the EU. A predictive mathematical model (Ortiz-Imedio et al., 2019) is used to forecast extractable energy under specific conditions. Additionally, a methodology is established to select suitable locations for sustainable SGE generation. The study also examines the environmental benefits of improving water management, measured through Key Performance Indicators (KPIs) such as reclaimable water and water cycle decarbonization.

2. Methods

This section defines the methodology followed to analyse the viability of integration of the SGE-RED technology in the reclamation of wastewater effluents in WWTPs in the 27-member countries of the European Union.

Recently, the flow diagram of the integrated process of water reclamation and recovery of salinity gradient energy has been reported and is represented in Fig. 1 (Gómez-Coma et al., 2020). The effluent from the WWTP (WW1) is subjected to a water reclamation process with the aim of complying with the limit values established in the Regulation (EU) 2020/741 (2020) for reuse of treated wastewater that consists of a solids removal process either by filtration or physico-chemical treatment followed by a disinfection treatment; this will result in the stream (WW2); these values meet the water quality required to feed the reverse electrodialysis module minimising fouling issues in the ion exchange membranes. In parallel, the stream with a high saline concentration (SW0) is pre-treated to remove the particulate matter present in this water stream of natural origin giving (SW1).

The energy generated when the low-concentration (LC) stream, treated wastewater (WW2), and the pre-treated high-concentration (HC) stream (SW1) are brought into contact in the reverse electrodialysis membrane module is used to self-power the reclamation treatment performed in the treatment facility.

2.1. Mathematical model for RED efficiency prediction

To predict the behaviour of the RED in SGE harnessing in the different scenarios identified, a mathematical model developed by the research group has been used. This mathematical model is described in detail in the scientific publication of Ortiz-Imedio et al. (2019) and allows to determine parameters such as the gross power generated in the RED stack (W) (Eq. (1)) among others.

$$P_{gross} = E_{stack} \cdot I \quad (1)$$

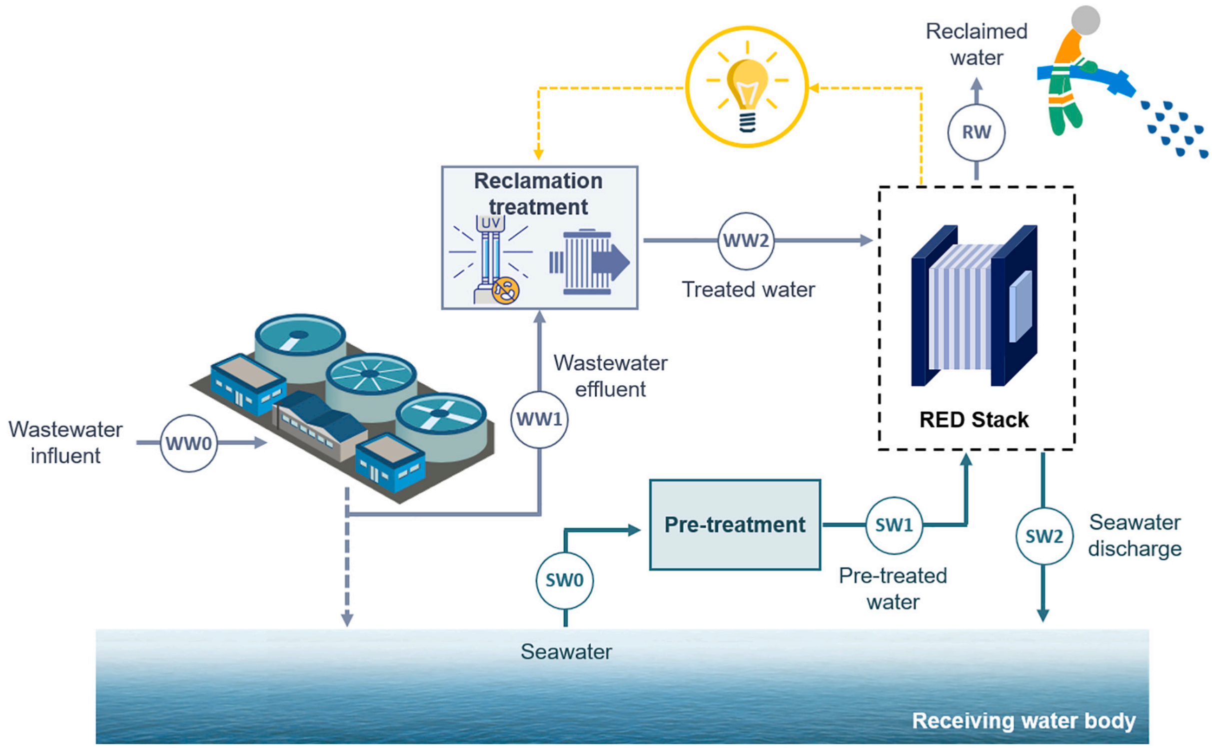

Fig. 1. Water reclamation process powered by salinity gradient energy overall flow diagram.
Adapted from Gómez-Coma et al. (2020).

where E_{stack} is the stack potential (V) and I is the electrical current (A). The power density is given by the ratio between P_{gross} and the effective area of a cell pair of membranes (in this case, the area is equivalent to 0.175 m^2).

The extractable energy is defined for a set LC flow rate (Q_{LC}, m^3/h) as specific energy (*SEC*, expressed in Wh/m^3) and is given according to Eq. (2):

$$SEC = \frac{P_{gross}}{Q_{LC}} \tag{2}$$

The representation in Fig. 2 shows the input parameters to the simulation process and the obtained result. The following site-specific inputs were used in the asset management software, Aspen Plus ® from Aspentech ®: (1) the inlet temperatures of the streams (both LC and HC have been considered equal), (2) streams salinity and (3) the LC volumetric flow rate. The parameters that have been set for the stack in all scenarios correspond to a commercial module manufactured by Fumatech GmbH®.

2.2. Criteria definition

A multi-criteria selection method has been established to carry out the selection of specific real scenarios that could hold potential for the installation of SGE-RED water and energy recovery systems.

Selection guidelines have been set according to key technology aspects which include i) availability of the high-salinity water stream, ii) SGE harnessing feasibility, and iii) reverse electrodialysis performance and economic viability considering the current state of SGE-RED development. The selection procedure consisted of a total of four criteria applied in hierarchical order, from the most to the least restrictive criterion.

2.2.1. Accessibility to saline water bodies

The scenario explored in this study for WW1 reclamation process supported by renewable energy self-production combines treated wastewater (low-concentrated solution) with a high salinity solution for the exploitation of the salinity-gradient energy.

Therefore, due to the use of saline water streams for energy harvesting, European countries with access to salty water bodies have been targeted as a first screening filter for the study of the future replicability of the SGE-RED technology in EU UWWTPs.

2.2.2. Size of the treatment plant

This criterion is determined by the profitability of the membrane process for energy production. According to the principles of economy of scale, UWWTPs with higher wastewater treatment flows stand out, as they have lower energy consumption per load measured in population equivalents (Ganora et al., 2019). Large UWWTPs are more attractive to be studied because, in addition to being more energy efficient, they generally apply more restrictive treatments to the effluent (tertiary treatment). In this sense, although this study can be extended to all UWWTPs in the EU, wastewater treatment plants with a physical capacity of <20,000 p.e. have been ruled out as a first approach.

2.2.3. Wastewater treatment

One of the issues of membrane processes working with natural (i.e. seawater) and waste water streams (i.e. wastewater) is the likely formation of fouling phenomenon in the ion exchange membranes and spacers of the RED module. Fouling causes an increase in the pressure drop in the water channels and a reduction in the gross power density output (Moreno et al., 2017; Vermaas et al., 2013), leading to higher pumping energy requirements.

In order to avoid fouling occurrence and eliminate the negative impact of this phenomenon on the performance of RED technology, WWTPs which include at least secondary treatment and which comply with EU wastewater discharge regulations (Council Directive, 1991) have been selected in the framework of the study.

2.2.4. Geographical location

The gross power density generated and the power required for

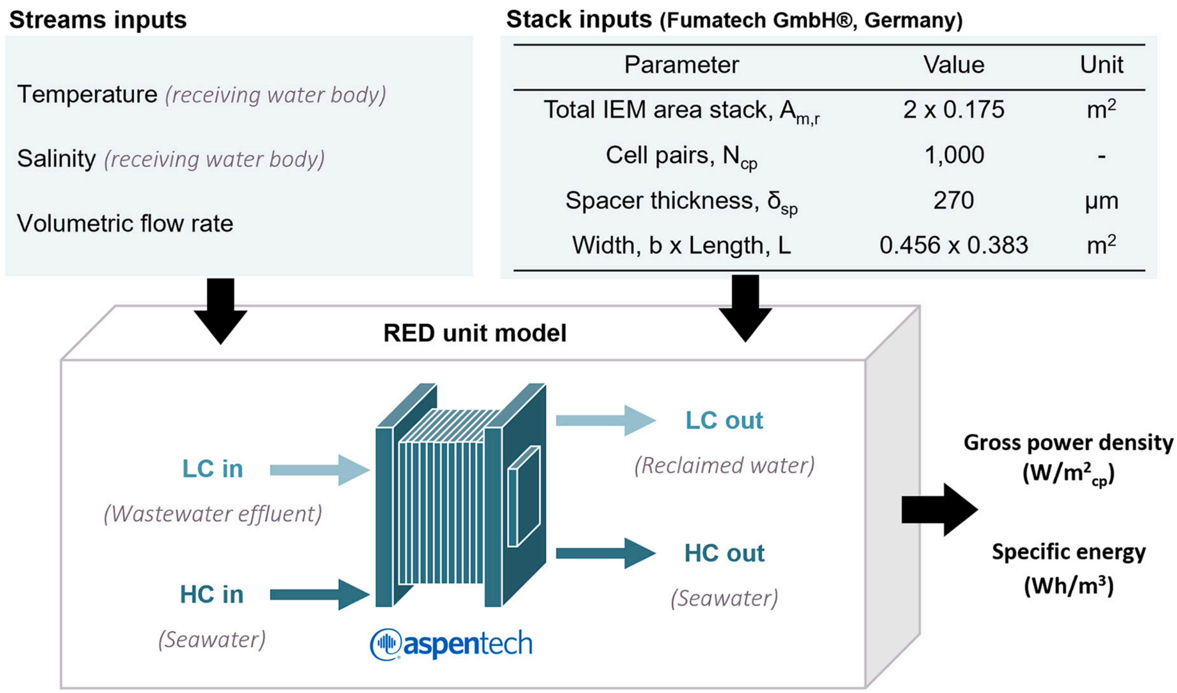

Fig. 2. Simulation diagram adapted to the parameters analysed in the study.

pumping feed solutions to the RED stack are key parameters in the performance of RED technology (Nam et al., 2021). In order to enhance and maximize the energy production, the geographical location characteristics of the WWTP have been considered as fourth selection criterion, with the aim of finding a balance between the generated salinity-gradient power and the energy consumed in pumping.

In this regard, an upper limit value has been set for the altitude above sea level and the distance of the WWTP from the high salinity water body. Based on the results obtained in previous modelling studies for SGE-RED systems up-scaling (Tristán et al., 2020), a maximum altitude of ten meters over sea level and a maximum distance of one kilometre between seawater catchment and wastewater treatment plant has been set, thus facilitating a positive energy gain.

2.3. Tools and databases

The scenario screening performed in this work has been principally based on the “Urban Waste Water Treatment Directive site: dissemination platform” for Europe, an open-source database provided by the European Commission (European Commission, 2017). This database platform is focused on facilitating data management under the urban wastewater treatment Council Directive (1991).

The UWWTD website lists all existing municipal wastewater treatment plants in the European Union with a treatment capacity equal to or >2000 population equivalents (p.e.), bringing the total number of water management facilities connected to the EU’s sanitation systems to 20,098. For each plant included in this database, information is provided on physical treatment capacity, summary of employed treatments, general flow diagram, treatment performance, annual flows of treated wastewater and in some cases a brief characterisation of the effluent to be discharged.

Complementary information has been obtained from country-specific databases on wastewater treatment when available. France and Greece are countries that own a national website for wastewater treatment monitoring; they have been used to obtain more specific and detailed information to conduct this study. The Ministère de la Transition Écologique et Solidaire (2019) of France and the Special Secretariat for Water (2018) of Greece through the “Portail d’information sur l’assainissement communal” and the “Wastewater Treatment Plants Monitoring Database”, respectively, provide more quantity of recent and updated data. In addition, in the case of the Spanish coastal UWWTPs, information has also been obtained through direct contact with the technical managers of the treatment facilities.

Regarding the geographical characteristics of the plants, the distance between water sources and altitude have been measured in all cases using Google Earth ®, an open access geographic vision software (https://earth.google.com/web/).

Table 1
Considered EU receiving water bodies characteristics and simulated SGE-RED potential.

Receiving water bodies	Average salinity (g/L)	Mean annual temperature (°C)	Gross power density (W/m^2_{cp})	Specific energy (Wh/m^3)
Mediterranean Sea	37.8[a]	19.2[a]	1.52	60
Atlantic Ocean	35.5[a]	14.3[a]	1.25	49
North Sea	34.6[a]	10.5[a]	1.09	43
Black Sea	18.6[a]	15.3[a]	0.70	28
Baltic Sea	7.2[a]	9.0[a]	0.18	7
Freshwater lake	<1[b]	–	–	–
River	<0.5[c]	–	–	–

[a] (Copernicus Marine Service, 2021).
[b] (Dugan et al., 2017).
[c] (US Environmental Protection Agency, 2006).

3. Results and discussion

This section discusses the main outcomes derived from the study of the potential sites to install SGE-RED in EU UWWTPs. The possible combinations of the WW2 stream with the different discharge receiving water bodies will be discussed hereafter.

3.1. Selected UWWTPs identification and distribution by country

The various receiving water bodies (HC in) associated with the selected EU UWWTPs in this study have been outlined in Table 1. As evident for the data, the Mediterranean Sea shows the best conditions for SGE harnessing, presenting an average annual salinity in 2021 of 37.8 g/L. On the other hand, the Atlantic Ocean and the North Sea have lower average annual salinities than the Mediterranean Sea at 35.5 g/L and 34.6 g/L, respectively. The Baltic Sea, on the other hand, is the salty body of water with the lowest salinity compared to the Mediterranean Sea, Atlantic Ocean, North Sea and Black Sea, 7.2 g/L annual average. The Black Sea, for its part, has an average annual salinity of 18.6 g/L, which is intermediate in comparison to the other saline water bodies analysed (Copernicus Marine Service, 2021). Additionally, lakes and rivers have salinities significantly lower which vary in the range of 0.5–1 g/L (Dugan et al., 2017; US Environmental Protection Agency, 2006).

Wastewater effluent (LC in) concentration of Total Dissolved Solids (TDS) varies in the range of 250–850 mg/L (Park and Snyder, 2019) after and effective secondary treatment (Raji and Packialakshmi, 2022). Nevertheless, the salinity of such wastewater streams is highly variable, especially in coastal UWWTPs where seawater intrusion can occur in the wastewater collection or discharge system, resulting in a substantial increase in the salt concentration in the wastewater effluent (Wu et al., 2013).

The mean annual temperature data for those water bodies whose saline concentration makes the recovery of energy from the salinity gradient feasible are shown in Table 1. Temperature increase has a positive influence on the power density generated by reverse electrodialysis for the exploitation of the salinity gradient (Daniilidis et al., 2014; Hossen et al., 2020; Mei and Tang, 2018; Ortiz-Imedio et al., 2019). The Mediterranean Sea with the highest average annual temperature of 19.2 °C, would be the most advantageous location for the

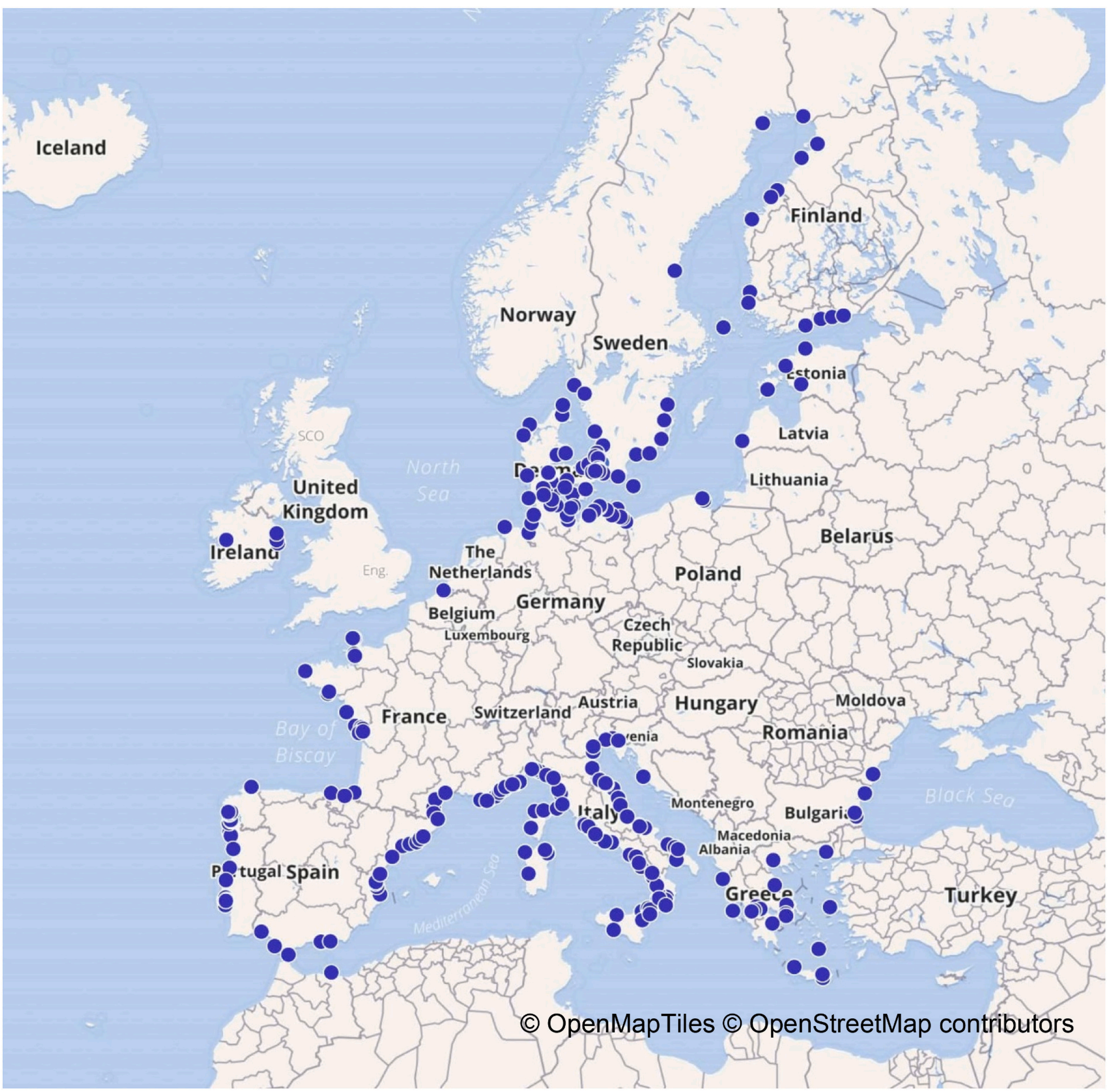

Fig. 3. Location map of all urban wastewater treatment plants selected in the framework of this study.

installation of SGE-RED systems in EU coastal wastewater treatment plants. In contrast, with 9 °C the Baltic Sea has the lowest annual average temperature, thus disfavouring the SGE recovery process due to its negative effect on the output power density. In between these two temperature values lies the rest of SW sources, i.e., the Black Sea, Atlantic Ocean and the North Sea, which have intermediate average annual temperatures of 15.3 °C, 14.3 °C and 10.5 °C, respectively.

The mathematical model described in the methodology section was used to predict the potential power density harnessed in each scenario and the corresponding equivalent specific energy. As confirmed by the results displayed in Table 1, the power generated per membrane cell pair (cp) is disadvantaged by the low salt fraction and the temperature of the concentrated compartment stream. In this sense, the SGE generated for a treated effluent flow entering a RED stack will be significantly higher in WWTPs located on the Mediterranean coast, 60 Wh/m^3, than in those located in the Baltic area, 7 Wh/m^3.

The database provided by the European Commission according to Council Directive (1991) lists a total of 20,098 UWWTPs in the EU connected to the wastewater collecting network. Having determined that seawater provides the most favourable scenario for harnessing SGE, countries with a coastal zone have been considered as the first selection criterion. Consequently, the pool of potential sites is limited to 17,951 UWWTPs. The study of exclusively those plants with a capacity of 20,000 p.e. or more (second criterion applied) results in the most constraining criteria as it significantly reduces the number of potential sites appropriate for the reclamation of WW1 from 17,951 to 4,096 UWWTPs. Nevertheless, when applying the need for inclusion of a secondary treatment, a condition established as the third selection criterion, it is noted that the set of potential UWWTPs remains nearly unchanged and is slightly reduced to 4,046 UWWTPs. Finally, applying the criterion of geographical location gives a total of 281 UWWTPs that meet all the specified criteria.

Fig. 3 depicts the European location map of the coastal UWWTPs that constitute reliable potential emplacements for water reclamation powered by in-situ generated salinity gradient energy. This area includes treatment plants located along the coastal region of the following EU countries: Spain, France, Italy, Slovenia, Croatia, Greece, The Netherlands, Latvia, Estonia, Ireland, Sweden, Denmark, Finland, Germany, Poland, Romania, Bulgaria and Portugal. The EU coastal countries, Belgium, Lithuania, Malta and Cyprus have been also surveyed, but without satisfactory results in meeting the requirements set out in this study. However, the expected progress on the performance of the RED unit due to the development of optimised membranes and improvements in the achievable net power density will increase the number of potential sites in the long-term (Güler and Nijmeijer, 2018). Detailed localization data for each urban wastewater treatment plant, including its proximity to the saline water body, altitude, physical capacity (in p.e.), and volume of wastewater treated (in m^3/day), are compiled in Table S1 of the supplementary information document.

The distribution of the selected UWWTPs classified according to the saline water body is shown in Table 2. It should be underlined that the most favourable scenario, the Mediterranean Sea, is also the one with the highest number of plants selected in the study, 145 UWWTPs. This is followed by the most unfavourable scenario with a total of 73 UWWTPs located on the shoreline of the Baltic Sea. The Black Sea comprises the smallest number of UWWTPs in the study, with 4 UWWTPs. The remaining treatment plants are distributed between the coasts of the Atlantic Ocean and the North Sea, with 45 of the UWWTPs located on the former and 14 UWWTPs on the latter.

Table 2
Distribution of selected UWWTPs classified according to the saline water body.

Saline water body	Number of UWWTPs
Mediterranean Sea	145
Atlantic Ocean	45
North Sea	14
Black Sea	4
Baltic Sea	73

Once the potential sites that meet the specified technical criteria were identified, the analysis of the distribution of the selected wastewater treatment facilities by country and physical capacity were carried out. The results of this analysis are presented in Fig. 4, highlighting that 31 % of the UWWTPs are large (100,000–499,999 p.e.) or mega large (>500,000 p.e.) wastewater treatment plants.

Italy stands out with 84 wastewater treatment facilities potentially suitable for simultaneous water reclamation and SGE recovery. This high number of suitable sites is closely related to the country's large coastal area, with a total of 7914 km. In terms of the physical treatment capacity of these plants, it can be seen that 19 of them are large or mega large plants, so the energy recovery capacity will be enhanced and the associated energy efficiency is also higher in this type of treatment plants (Gu et al., 2017).

France occupies the second place as the country with the most adequate sites for reclaimed water facilities, with 37 UWWTPs, divided between the Mediterranean coast and the Atlantic coast, where 22 and 15 UWWTPs are located, respectively.

Spain has 35 UWWTPs appropriate for the implementation of SGE-RED systems, according to the established selection criteria, with 19 of them located on the Mediterranean coast of the country, while the remaining 16 UWWTPs are located on the South and North Atlantic coast. This country presents the highest potential for the achievement of energy self-sufficiency having a greater number of large treatment plants and mega large treatment plants than the other countries. Analysing the size distribution of the selected Spanish plants, it is noteworthy that 14 of these plants are large treatment facilities or mega large-plants. The Besòs management facility (Catalonia, Spain) is the second largest plant in terms of physical treatment capacity included in the study, with a designed physical treatment capacity of 2,843,750 p.e.

Despite having smaller plants those most other countries, Denmark ranks fourth with 27 UWWTPs located along its 7500 km of coastline. Denmark is followed by Germany, which has 5 UWWTPs located along the North Sea coast and the rest, up to 22, along the Baltic Sea coast, with the highest number of plants in the least favourable scenario for SGE-driven water reclamation.

Another country noteworthy, both in terms of the number of selected wastewater treatment plants and their size distribution, is Greece. 18 plants included in this study are located in Greece, 7 of which are large facilities or mega large plants. It should be also pointed out that the largest UWWTP selected is located in Psyttalia, Greece with a physical treatment capacity of 5,630,000 p.e.

By contrast, countries such as Slovenia, The Netherlands, Latvia, Romania and Croatia each have only a potential single wastewater treatment plant where SGE-RED systems could be implemented. In the case of Slovenia, this is probably due to the small coastal area of this country (approx. 45 km), and in the case of Croatia, it would be related to the fact that only 50 % of the UWWTPs connected to the sanitation network has secondary wastewater treatment implemented as reported by the European Commission, 2017.

3.2. Environmental benefits of SGE-RED integration in reclamation plants

The expected environmental benefits of the proposed water reclamation strategy, in the 281 UWWTPs resulting from this study, have been estimated by means of two Key Performance Indicators (KPIs) (Fig. 5) defined in accordance with previous studies in the literature covering the circularity in water systems, and the performance of wastewater treatment systems and water reuse strategies (Landa-Cansigno et al., 2020; Nika et al., 2020; Pereira et al., 2012).

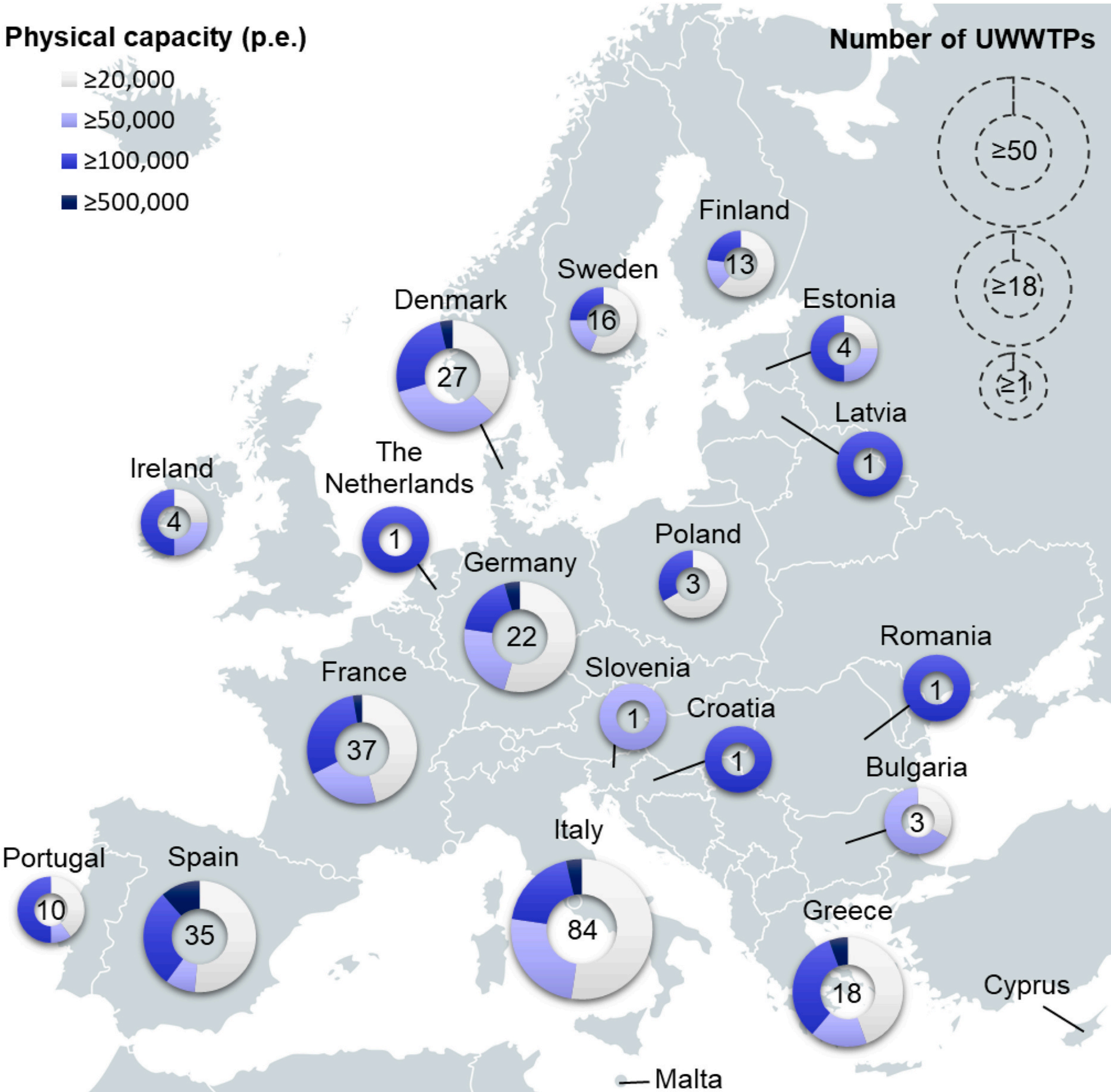

Fig. 4. Distribution map of potential urban wastewater treatment plants for SGE harvesting by country and physical capacity in p.e. The UWWTPs classification made as a function of their physical capacity is as follows: small plants 20,000–49,999 p.e.; medium-size plants 50,000–99,999 p.e.; large plants 100,000–499,999 p.e. and mega plants from 500,000 p.e.

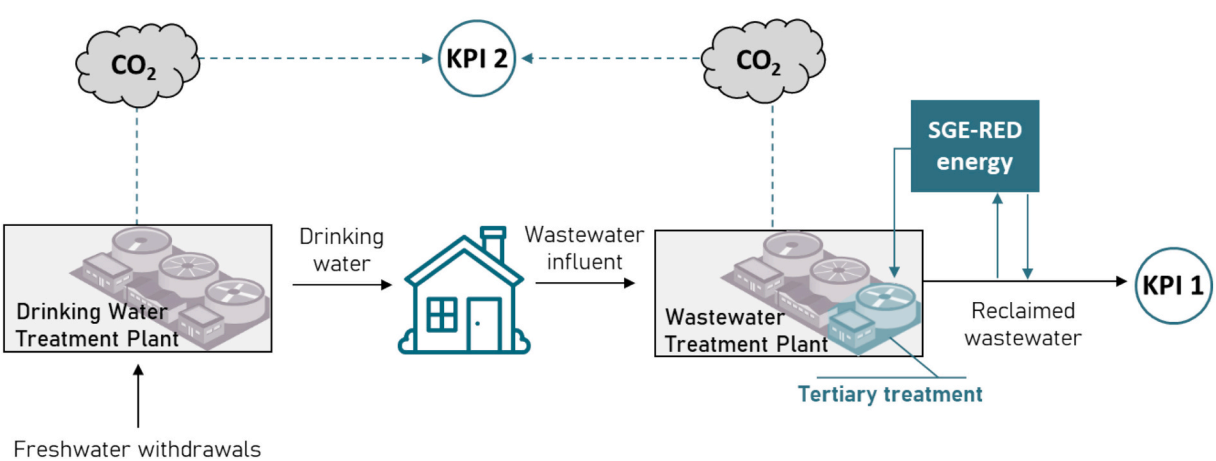

Fig. 5. Representative definition of KPIs.

3.2.1. KPI 1

Reclaimable water (m^3/day) assesses the volume of wastewater effluent (WW1) that could be reclaimed and reused in each country for current needs in recreational, agricultural irrigation or industrial purposes, total or partially powered by SGE-RED energy. Consequently, volume of drinking water saved.

3.2.2. KPI 2

Water cycle decarbonization (ton CO_2 eq./year), this environmental indicator quantifies the greenhouse gas emissions that could be mitigated as a result of (a) the alleviation on freshwater abstraction and drinking water treatment and (b) the decarbonization of the tertiary treatment of the WWTP.

3.2.3. Reclaimable water

Fig. 6 displays the potential wastewater reclamation capacity, considering 174 out of 281 of the UWWTPs included in the study. According to this Figure, 3.7 million m^3/day is the volume of WW1 that could be recovered in the EU shoreline UWWTPs selected in this study by feeding the reclamation process with the energy extracted from the salinity gradient.

There is a lack of information related to the real volume of treated water in Italian UWWTPs; thus, only 25 out of the 84 plants have usable wastewater reclamation capacity data. Therefore, it is likely that the real reclamation capacity could be considerably much greater. In a similar situation in Sweden, only 4 out of the 16-treatment plants studied have available data.

In contrast, Denmark, Greece, France, Italy, and Spain have an abundance of available wastewater reclamation capacity data. In this context, Spain and Greece exhibit a raised potential for non-conventional freshwater sources like treated wastewater effluents, with recoverable wastewater flows of 1.2 and 0.88 million m^3/day, respectively. Additionally, in France, Denmark and Italy the volume of RW could reach 0.42, 0.44 and 0.3 million m^3/day, respectively.

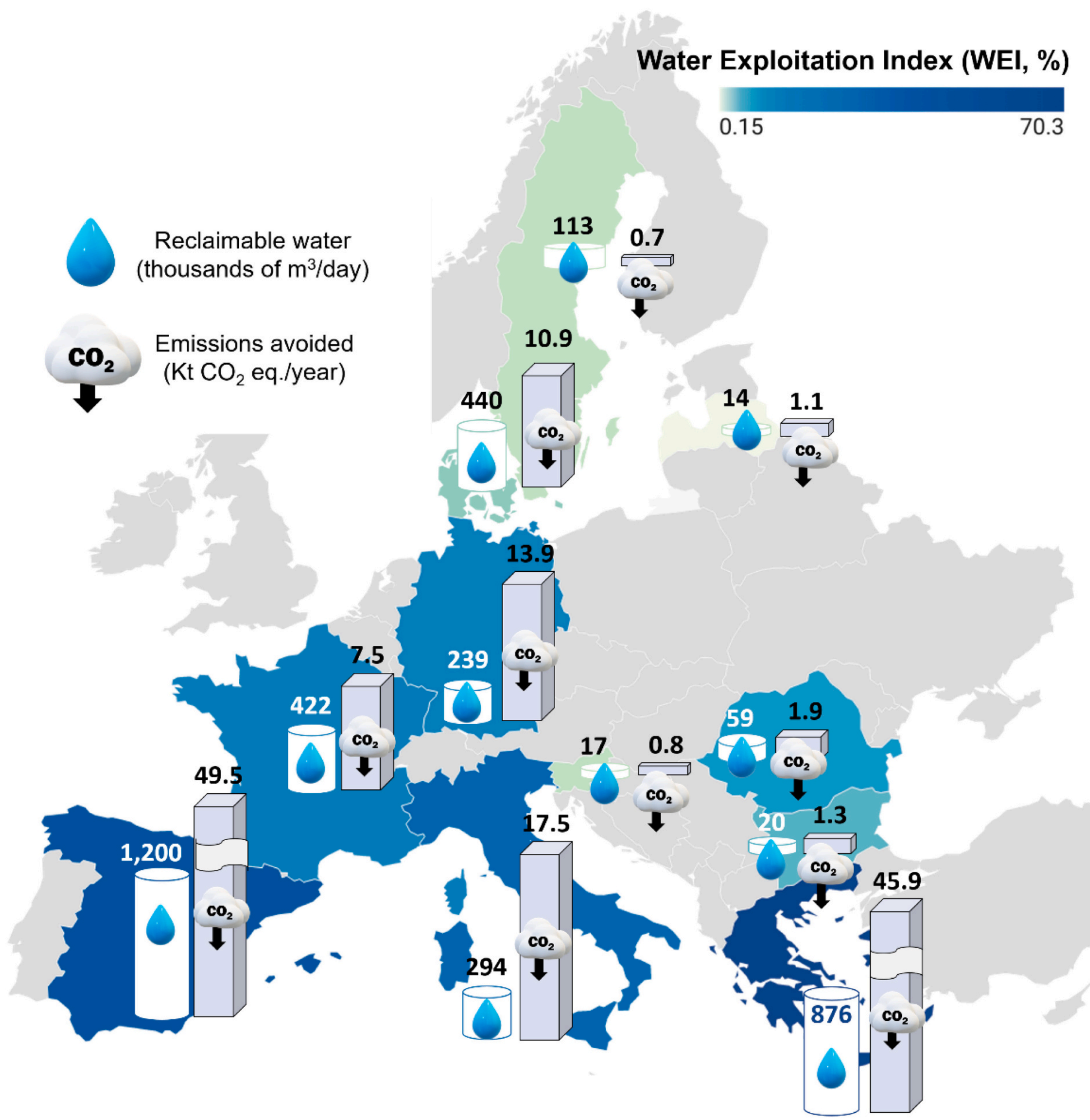

Fig. 6. Estimated wastewater reclamation capacity expressed in thousands of m^3/days (round bars) and avoided carbon dioxide emissions (square bars) in terms of kt CO_2 eq./year, and water exploitation index (WEI) in each country (Eurostat, 2017).

3.2.4. Decarbonization of the water cycle

The implementation of SGE-RED renewable energy production systems to drive wastewater reclamation leads to a quantifiable environmental benefit in terms of avoided carbon dioxide emissions due to: (1) the reduction in freshwater abstractions and its subsequent conditioning process as consequence of wastewater reclamation and (2) the replacement of fossil fuel energy use in tertiary treatment by SGE renewable energy free of air pollutant emissions.

Fig. 6 provides the estimated projections of avoided carbon dioxide emissions. The carbon intensity data of the electricity grid mix of each EU country included in the study have been sourced from Electricity Map, 2022. Considering the recovery of SGE through RED, the energy estimated to be obtained in each WWTP site has been calculated on the basis of the specific energy (Wh/m^3) simulated for the corresponding receiving waterbody, according to data of Table 1. As a result of the SGE harvested in the 281 WWTPs selected, the emissions avoided would amount to 16,515 t of CO_2 eq./year.

On the other hand, the average energy consumption associated with the abstraction of new freshwater and subsequent conditioning that has been considered is 0.4 kWh/m^3 of freshwater produced (International Energy Agency, 2016). Therefore, the CO_2 emissions avoided due to energy savings could reach a total of 134,686 t of CO_2 equivalent per year along the EU wastewater treatment sector. The reduction of freshwater withdrawals is the major contribution to the reduction of CO_2 emissions.

This decrease in carbon dioxide emissions improves the environmental sustainability of the studied UWWTPs, thus contributing to the sustainability of the water cycle. The implementation of integrated water reclamation processes with SGE recovery using membrane-based reverse electrodialysis technology in the selected EU urban wastewater treatment plants, could prevent the atmospheric emission of 151,201 t of carbon dioxide equivalent per year.

Furthermore, Fig. 6 highlights the Water Exploitation Index (WEI) for each country. This index, as defined by the European Environmental Agency, represents the average annual total freshwater demand divided by the long-term average freshwater resources (European Environmental Agency, 2019) within a country. Thus, the WEI offers insights into the pressure exerted on water resources by total water demand and identifies nations with high demand relative to their resources, making them susceptible to water stress issues. In this context, Cyprus, Malta, Greece, Portugal, Italy, and Spain encountered pronounced water scarcity conditions within the EU-27. This underscores, as Fig. 6 shows, that the countries most promising for wastewater reclamation through the SGE strategy align with those facing the highest WEI-related challenges.

3.3. Current status, challenges and opportunities for water reclamation powered by SGE-RED

SGE-RED together with water reclamation encourages the implementation of tertiary treatments in those UWWTPs with no reclamation steps at a zero-energy cost, or promotes the decarbonization of the existing reclamation processes.

Table 3 compiles the energy intensity of different tertiary disinfection and suspended solids removal treatments. In the current state of development of the RED technology for the exploitation of the salinity difference in the wastewater-seawater scenario, 0.055 kWh/m^3 of regenerated effluent have been generated (Ortiz-Martínez et al., 2020). This amount of clean energy produced in-situ would already be able to fully cover the energy requirements of UV irradiation, chlorination, chemicals, disc or sand filtration; or partially cover ozonation, microfiltration, ultrafiltration or coagulation-flocculation treatment electricity needs. Furthermore, disinfection treatments that modify the pH such as chlorination, disinfection with peracetic acid or performic acid can be also applied, since the commercial ion exchange membranes used in the reverse electrodialysis module for SGE harvesting are highly stable in pH acidic and basic environment (Fuel Cell Store, 2022).

In this sense, it is necessary to assess the level of implementation of reclamation treatments in the selected plants. Considering the selection of 281 UWWTPs based on the described criteria in the methodology section, it is noteworthy that a total of 158 cataloged UWWTPs currently lack on-site tertiary treatment based on the data reported in the official sources. However, in such plants, SGE-RED water and energy recovery systems could offer a solution for the recovery of 2.64 million m^3/day of wastewater without additional energy costs and using renewable energy free of pollutant emissions.

Specifically, a tertiary treatment that involves disinfection, eliminating living microorganisms from wastewater effluent, becomes appealing for two primary reasons. Firstly, disinfection aligns with legal criteria for maintaining microbiological quality in the reclaimed water intended for reuse. Secondly, it contributes to the prevention of fouling issues with ion exchange membranes in RED stacks (Vermaas et al., 2013).

Fig. 7 highlights the 123 UWWTPs (44 %) of the study installations that carry out a disinfection treatment to the wastewater effluent. The specific treatment details for each plant, categorized by the presence of secondary treatment, N and P removal, ultraviolet (UV) treatment, ozonization, salt filtration, chlorination, microfiltration, and other primary treatments, are outlined in Table S2 of the Supplementary Information document. Analysing the results obtained, Greece brings together the second higher percentage of selected wastewater treatment plants with disinfection tertiary treatment. This fact means that in Greek UWWTPs the process of recovery of treated wastewater is favoured, taking into account that the effluent from the treatment plant is expected to be of the highest quality. And moreover, the investment costs of WW1 pre-treatment before the RED process is reduced and, consequently, SGE-RED systems implementation is boosted.

Although with a lower percentage, Spain, Portugal and Italy also have a great portion of urban wastewater treatment plants in which some disinfection treatment is applied to their effluent, holding also a noticeably potential for SGE-RED systems for water reclamation and energy recovery. In the case of Bulgaria, 3 out of the 281 UWWTPs under study, UV disinfection is included in all plants.

Coincidentally, countries with higher percentage of UWWTPs that have implemented tertiary disinfection treatment have their own legislation concerning the reuse of treated wastewater. These countries are namely Greece (CMD, 2011), Italy (DM, 2006), Portugal (Marecos

Table 3
Energy consumption of tertiary treatments in an urban wastewater treatment plant.

Tertiary treatment	Energy intensity (kWh/m^3)	Average % of energy intensity covered by SGE	Reference
UV irradiation	0.015–0.066	100	(Plappally and Lienhard V, 2012)
Chlorination	$2\cdot10^{-5}$–$2\cdot10^{-3}$	100	(Arkhangelsky et al., 2017)
Ozonation	0.03–0.26	38	(Rodríguez et al., 2012)
Chemicals	0.009–0.011	100	(Longo et al., 2016)
Disc filters	0.003	100	(Belloir et al., 2015)
Sand filtration	0.01–0.1	100	(Arkhangelsky et al., 2017)
Microfiltration	0.06–0.14	55	(Plappally and Lienhard V, 2012)
Ultrafiltration	0.11–0.15	42	(Kehrein et al., 2021)
Coagulation-flocculation	0.2	28	(Arkhangelsky et al., 2017)

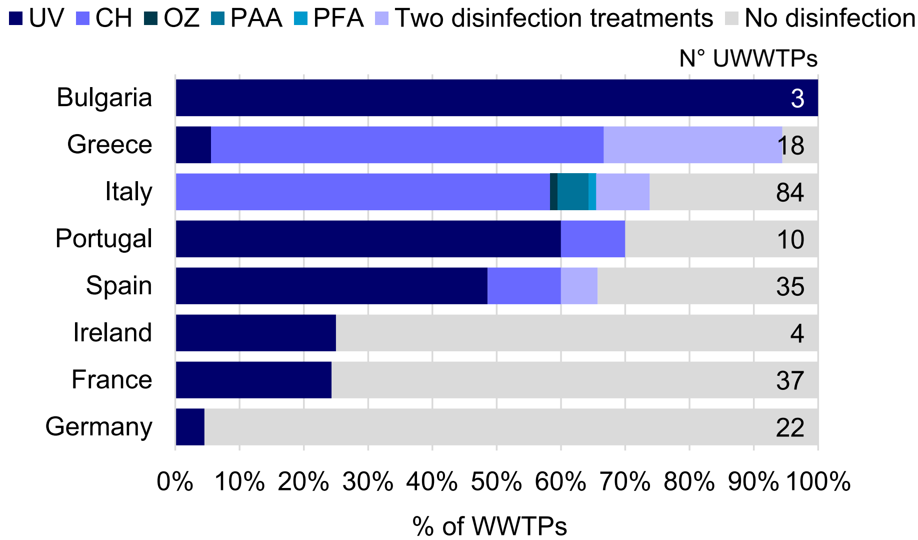

Fig. 7. Percentage distribution of selected UWWTPs according to the disinfection treatments applied to the effluent and number of treatment facilities in each country. The disinfection treatments considered are ultraviolet (UV), chlorination (CH), ozonation (OZ), peracetic acid (PAA) and performic acid (PFA).

and Albuquerque, 2010), Spain (RD (Royal Decree), 2007) and France (Decree 02/08/2010, 2010).

Considering only the 123 UWWTPs with disinfection treatment, the implementation of tertiary processes for the removal of suspended solids has been examined. There are 92 UWWTPs that limit their tertiary process to disinfection, which would present an opportunity to include solids removal and reclaim 0.5 million m^3/day of water at zero-energy cost.

Thirty-one UWWTPs (25 %) with a disinfection stage also include some treatment for the removal of suspended solids. The suspended solids removal processes applied in these UWWTPs can be divided into physical treatments (20 % of the 31 UWWTPs) such as microfiltration, ultrafiltration and sand filtration, and physico-chemical treatments (2 %) such as coagulation-flocculation. The remaining 3 % corresponds to installations combining filtration and physico-chemical treatment.

The existence of treatment facilities that carry out two tertiary treatments such as disinfection treatment and suspended solids removal treatment facilitates the process of recovery of SGE and, thus, the decarbonization of water reclamation plants.

In terms of water volume, of the total potential of reclaimable water that has been estimated as 3.7 million m^3/day, currently only 0.55 million m^3/day (flow corresponding to the 31 UWWTPs) receive adequate treatment for its recovery. These data confirm that there is a gap for the installation of tertiary treatment that could be powered by renewable energy such as SGE.

Possible future improvements of the RED technology to extract more SGE include reducing the electrical resistance of the membranes and fabricating membranes that provide high performance under real conditions without undesired fouling issues.

4. Conclusions

This research presents the potential of a strategy for the reduction of freshwater withdrawals through the integration of sustainable, clean and non-polluting energy sources in effluent recovery stages of coastal WWTPs.

It provides an overview of the current potential for implementing wastewater reclamation processes supported by in-situ generation of salinity gradient energy harnessed through reverse electrodialysis in the EU UWWTPs. In addition, the environmental benefits of the “water multiplier effect” have been assessed through the definition and evaluation of two specific Key Performance Indicators: (1) reclaimable water and (2) water cycle decarbonization.

In total, 281 EU UWWTPs have been identified and inventoried that could constitute reliable future sites for sustainable reclamation processes powered by SGE energy harvesting under the current state of the art of the technology. The Mediterranean Sea has been highlighted as a hotspot for the replicability of the SGE-RED technology for energy support to water reclamation, with 145 UWWTPs selected.

The improvement in the sustainability of the urban water cycle across the EU has been quantified in terms of effluent recovery capacity, determined at 3.7 million m^3/day, and the resulting carbon footprint avoided due to water remediation powered by an emerging renewable source of energy, concluded to be $1.5 \cdot 10^5$ t of CO_2 eq./year kept away from the forecasted energy supply system.

In conclusion, there is currently untapped potential for water reclamation in coastal UWWTPs of the EU. Exploiting this potential would boost the circularity of water systems and, as demonstrated, lessen the dependence on fossil fuels associated with wastewater reclamation processes. It has been assessed that only 15 % of the effluent volume from the 281 inventoried UWWTPs could be reclaimed under the current status. Moreover, according to the technology maturity, it has been found that the energy consumption of typical tertiary treatments such as UV disinfection, chlorination, disinfection by chemical addition, disc or sand filtration processes could be covered via salinity-gradient energy. Finally, the advancement in the technology readiness level is expected to facilitate and increase transferability prospects in EU coastal UWWTPs.

CRediT authorship contribution statement

T. Sampedro: Methodology, Investigation, Writing – original draft, Visualization. **L. Gómez-Coma:** Conceptualization, Investigation, Writing – original draft, Visualization. **I. Ortiz:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **R. Ibañez:** Conceptualization, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research work is supported by the European LIFE Programme (LIFE19 ENV/ES/000143), and the projects RTI2018-093310-B-I00, PID2020-115409RB-I00, PDC2021-120786-I00 and PLEC2021-007718 funded by the Spanish Ministry of Science and Innovation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.167154.

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