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SWRO concentrates for more efficient wastewater reclamation

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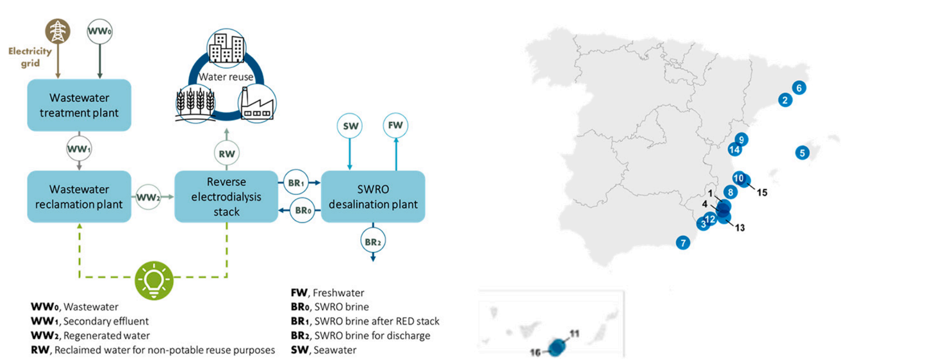
HIGHLIGHTS

- Harnessing the energy embedded in the saline gradient between SWRO and WWTP effluents
- Recovery of energy from SWRO concentrates through electro-membrane RED systems
- Innovation in the water-energy nexus through SWRO brines energy valorization

GRAPHICAL ABSTRACT



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ABSTRACT

Developing technical alternatives to increase the volume of remediated waters is a promising way to alleviate pressure on natural water basins. However, the extra energy consumed in Wastewater Treatment Plants (WWTPs), mainly powered by fossil fuels, hampers this strategy. This work focuses on promoting efficient upgrading alternatives of treated waters by recovering energy within the treatment process. The approach consists on the recovery and integration of Salinity Gradient Energy (SGE) generated from the contact between SWRO brines and reclaimed wastewaters in reverse electrodialysis modules. The analysis of opportunity of implementing integrated processes in Spanish WWTPs near SWRO desalination plants is tackled. 16 SWRO-WWTP pairs have been inventoried, 10 of them located in Jucar and Segura river basins, hot spot areas for water reclamation. A gross power density of 0.46 W/m^2 (71 Wh/m^3 reclaimed water) of SGE has been generated in the contact between SWRO brines and reclaimed wastewater, increased up to 0.23 kWh/m^3 in the most favourable scenario. Estimates of freshwater withdrawals savings up to 434,387 m^3/day within the selected installations are obtained. Decrease in water abstraction and integration of renewable source of energy in the remediation process will contribute to water sources protection and water industry decarbonisation.

1. Introduction

The global shortage of blue water is one of the greatest challenges of today and future society [1]. The unavailability of sufficient water has promoted the use of non-conventional water sources, such as desalination of water streams with a high content of salt (brackish water and

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seawater) and the reuse of wastewater effluents in its various forms. In energy terms, wastewater reclamation represents a more competitive alternative than seawater reverse osmosis (SWRO) desalination, with an average consumption of 1–2.5 and 4–6 kWh/m^3 for both technologies, respectively [2,3].

The future potential of wastewater as a new water source is justified by the volume of wastewater produced annually worldwide estimated at 359.4 billion m^3 [4]. The European Union has an effluent recovery rate for treated urban wastewater of 2.4 % [5]. Currently, the recovery potential is estimated to be significantly higher, especially for Spain, which is already a leader in the reuse of reclaimed water in the EU [6]. In 2018, the Spanish National Institute of Statistics reported the volume of reused water at 11.3 % of the total volume of treated wastewater [7]. Of this reclaimed water, 65.8 % went to agricultural uses, 28.6 % to urban uses of garden irrigation and street cleaning, and the rest is divided between industrial uses (3.8 %) and other uses (1.8 %).

The EU has recently regulated this practice through Regulation 2020/741 [8] on the reuse of wastewater effluents, with the aim of reducing freshwater withdrawals from renewable water sources and the environmental impact of discharging waste flows generated in European Wastewater Treatment Plants (WWTPs). Spain, France, Italy, Greece, Portugal and Cyprus are European countries that aim to mitigate their raised Water Exploitation Index (WEI) and currently have their own national legislation to regulate and promote water reuse for non-potable purposes [9–14].

However, the planned reuse of wastewater is constrained by several factors: the necessary infrastructure of a separate supply network and the extra energy demand of more extensive purification treatments compared to direct discharge of the effluent [15]. In addition, the WWTPs are mainly supplied by the state electricity grid to which they are connected. The energy grid is an energy mix of both renewable and non-renewable energy sources, with fossil fuel origin sources predominating [16]. Mitigating and progressively adapting to climate change and its environmental consequences requires feasible solutions that integrate efforts to reduce carbon and water footprints [17]. In this regard WWTPs, needed to maintain controlled levels of pollutants within the water cycle and highly energy-demanding facilities, strongly called for a vision that includes the transition to an electricity supply obtained from renewable nature resources.

Among the opportunities for decarbonisation, wastewater treatment facilities occupy fairly large areas of land that can be used for the installation of solar thermal systems such as photovoltaic panels. In addition, sludge incineration is not only a heat and electricity generation process, but also reduces the waste that ends up in landfill [18]. In addition, wastewater could itself be a potential source of energy in the form of chemical, thermal and kinetic energy [19]. The main supply of additional energy in WWTPs comes from the biogas produced in the sludge digestion process [20]. Other energy recovery processes in these treatment plants are hydropower, chemical energy from organic substances in the wastewater or the microbial fuel cell [18]. Blue Energy or Salinity Gradient Energy (SGE) is an emerging renewable and sustainable source of energy capable of harnessing the chemical potential gradient generated in the contact between wastewater and a higher salinity water stream; membrane-based electrochemical reverse electrodialysis (RED) technology, appears as a promising technology option to achieve this goal. It has been estimated that worldwide between 1.4 and 2.6 TW could be harnessed by SGE [21]. SGE represents an inexhaustible and non-intermittent source of energy, unlike solar or wind power subjected to weather variability [22,23]. The main components that make up a RED cell are the ion exchange membranes (IEMs) (cationic and anionic), the spacers, the electrodes and the electrolyte solution. The characteristics of the IEMs, such as electrical resistance and permselectivity, directly condition the performance and efficiency of the overall SGE extraction process [24]. The development of membranes with higher selectivity to monovalent Na^+ and Cl^- ions, and lower electrical resistance at an affordable cost is one of the main bottlenecks for the full development of the technology at industrial scale and market opening [25,26].

The combination of water streams gives rise to different chemical potential gradients. The use of secondary effluents and seawater feeding RED modules has become one of the scenarios that has received most attention in the research field through several publications [27–31]. However, the utilisation of concentrated waste flows from seawater desalination plants is the saline gradient opportunity with the best prospects. Through the mathematical model developed by Ortiz-Imedio et al. [32] and Ortiz-Martínez et al. [33] a maximum gross power density of 1.6 W/m^2 of pair-cell membrane was determined using 0.5 M seawater and 0.02 M secondary effluent, while for 1 M seawater RO brine and 0.02 M secondary effluent this potential increased to 2.5 W/m^2. Tedesco et al. [34] managed to experimentally obtain 6 W/m^2 for a 0.1 M dilute stream (similar to river water) and a 5 M concentrate (corresponding to concentrated brine) for operating conditions of 40.4 °C.

Going a step further, Tristán et al. [35] evaluated the theoretically extractable specific energy in real scenarios. For the case study of the Barcelona (Llobregat) desalination plant, a ratio of 0.14 kWh/m^3 was obtained from the rejects of the first (1.23 M) and second (0.045 M) RO steps at a temperature of 19 °C. Recently, Yasukawa et al. [36] carried out SGE energy extraction in a bench-scale RED stack with 200 pairs of membranes and a total area of 40 m^2. For this, they used natural RO brine streams from seawater (22.4–25.4 °C) and municipal effluent (24.3–26.6 °C) and generated 0.071 kWh/m^3. The SGE produced would be destined to post-treatment technologies that enable water reclamation by removing micro-pollutants and pathogens present in the secondary effluent. Additional treatments such as disinfection with ultraviolet lamps + sand filtration can lead to a consumption of 0.015–0.066 kWh/m^3 [37] and 0.01–0.1 kWh/m^3 [38] respectively, although the consumptions are very site-specific.

Currently, the volume of brines generated worldwide is estimated at 141.5 million m^3/day [39]. The source stream (seawater) is thoroughly pre-treated prior to RO to remove particulate matter, colloids, organic foulants, reduce turbidity and total suspended solids, making brines of particular interest to avoid fouling issues in the RED stack [40,41]. Additionally, the management of brine and its discharge into the aquatic environment is one of the major environmental problems of desalination plants. Besides, brines currently represent a promising source for both material and energy valorization by means of different technologies under development [42].

In this way, a synergy can be established between the two non-conventional water resources that will coexist in the future, based on desalination brines waste flows energy valorization to promote carbon-neutrality of the reclamation and reuse of treated wastewater. The objective of this study is to identify potential future real scenarios for jointly driving the planned reuse of treated wastewater, and the reduction of the carbon footprint of WWTPs by in-situ generation of SGE-RED using desalination brines as high-concentrated solution. In this context, Spain has been selected as a case study due to its intensified lack of water resources in tourist areas or with agricultural systems, especially the Mediterranean region, and the high degree of implementation of seawater desalination systems [43].

2. Methodology

This section describes the methodology followed for (1) the identification of suitable water cycle process facilities and, (2) the assessment of the synergy potential of water and energy using computational tools based on a mathematical model describing the behavior of SGE-RED systems.

Fig. 1 is a representation of the concept addressed in this work. The concept is based on the regeneration of secondary effluents (WW1) from WWTP in water reclamation plants, which will be supplied by the SGE generated using regenerated water (WW2) as low-concentrated solution

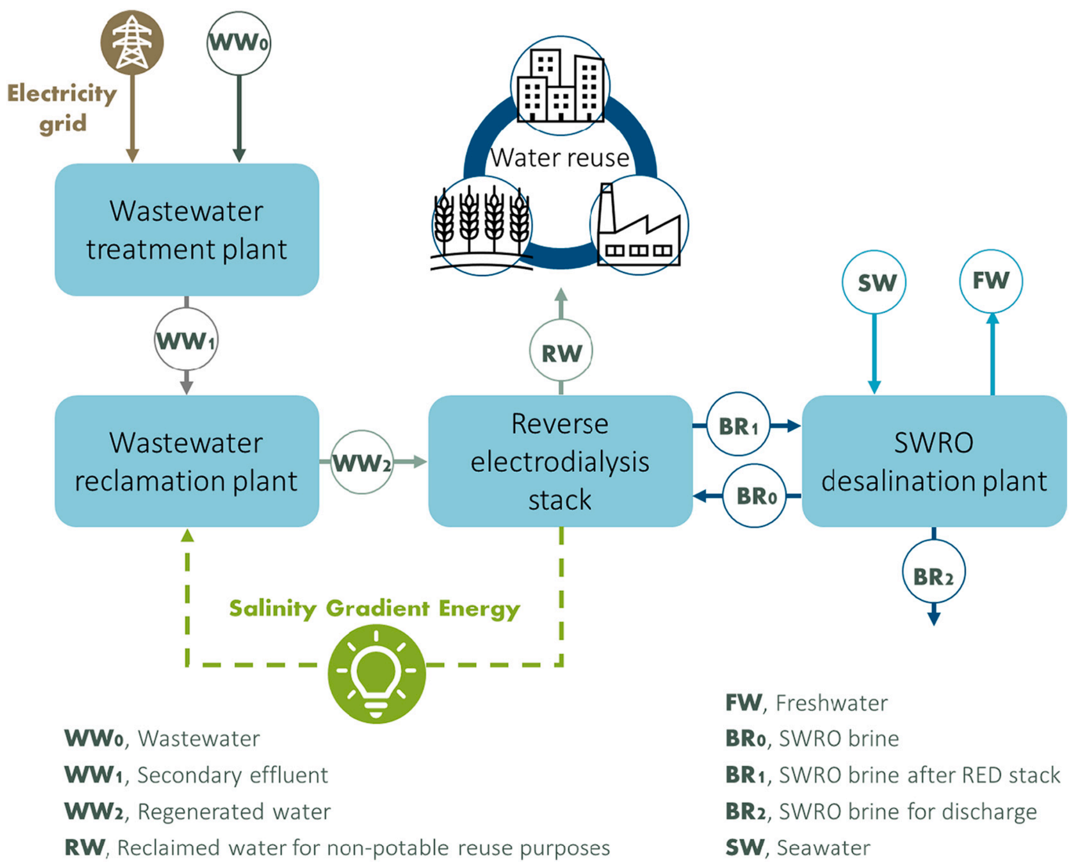

Fig. 1. Outline of the planned water reclamation and brine waste energy valorisation.

(LC) and brine from seawater RO (BR0) as high-concentrated solution (HC).

2.1. Main databases and tools

Spain has been targeted as a case study due to the large desalination capacity currently installed [44] and the current water scarcity issues suffered in the mayor part of its geography [45], accentuated in the Mediterranean area where there is a high risk of severe water shortages in the near future. The task of identifying Spanish UWWTPs and SWRO desalination plants has been done through the following sources of information:

(1) potential WWTPs have been identified through the "Urban Wastewater Treatment Directive site" [46], focused on managing the information according to the European Wastewater Treatment Directive 91/271/EEC [47]. It gathers the inventory of UWWTPs of >2000 population equivalents (p.e.) that exist in the countries of the European Union, as well as some of their most relevant characteristics (treatment capacity, types of treatment, …).
(2) potential SWRO desalination plants have been identified through The "EMODnet Human Activities Portal" [48], aims to facilitate access to information on activities taking place in EU waters. This information source is part of the European Marine Observation and Data Network (EMODnet) initiated by the European Commission. It is based on information provided by Global Water Intelligence through GWI DesalData on the global desalination industry sector.
(3) The geographical location of the pairs of facilities and the corresponding altitude and distance has been determined with the open access software Google Earth® (https://earth.google.com/web/), obtaining all the measurements with respect to the WWTP.

2.2. Guidelines for SWRO-WWTP pairs identification

Those seawater desalination facilities via reverse osmosis with a freshwater production capacity equal to or >25,000 m^3 per day have been addressed in this study. In this sense, the study has been limited to large or medium-sized treatment facilities in order to establish the WWTPs as the limiting flow rate.

According to previous studies that analysed the impact of the energy consumption of the pumping systems on the net power generated by RED [35], in this work those UWWTPs located in the vicinity of SWRO desalination plants within a radius of 2.5 km and with an altitude difference of a maximum of 15 m have been selected. In addition, only those effluents that comply with European regulations on discharge of treated wastewater (Directive 91/271/EEC [47]) were considered.

2.3. Assessment of attainable specific energy

The potential for SGE-RED energy recovery in the identified scenarios, in terms of specific energy, has been evaluated by means of a mathematical model that describes the performance of RED technology. Detailed information about the model is provided in the publication by Ortiz-Imedio et al. [32], where an in-depth description of the model fundamentals and equations is given [32]. The initial model has been improved to increase its predictive capability in different operating conditions, including the performance of up-scaled systems [28,33,35,49].

The model was implemented using Aspen Plus® V11 and Aspen Custom Modeler® V11, both developed by AspenTech. The specific details of the simulations, such as thermodynamic methods for the

Table 1
Characteristics of commercial RED module and IEMs.

Component	Parameter	Description	Value	Unit
RED Stack Fumatech GmbH®, Germany	N_{cp}	Number of cell pairs	1000	–
	b	Channel width	0.456	m
	L	Channel length	0.383	m
	δ_{sp}	Inter-membrane distance equal to spacer's thickness	270	μm
	ε	Spacer's porosity	82.5	%
CEM Fumasep® FKS-50	R_{CEM0}	Electrical resistance	1.8–2.5[a]	$\Omega \cdot cm^2$
	α_{CEM}	Permselectivity	97–99[b]	%
	δ_{CEM}	Thickness dry	50	μm
	$A_{m,eff}$	Active area	0.175	m^2
AEM Fumasep® FAS-50	R_{AEM0}	Electrical resistance	0.6–1.5[a]	$\Omega \cdot cm^2$
	α_{AEM}	Permselectivity	92–96[b]	%
	δ_{AEM}	Thickness dry	50	μm
	$A_{m,eff}$	Active area	0.175	m^2

[a] Measured in 0.5 M NaCl at 25 °C.
[b] Measured in 0.1/0.5 mol/kg KCl at 25 °C.

determination of solution properties and the main simplifications and assumptions, were collected in the Supplementary Material of Tristán et al. [35]. The simulations have been performed on the basis of a commercial RED stack consisting of cation exchange membranes (CEM, Fumasep® FKS-50) and anion exchange membranes (AEM, Fumasep® FAS-50) (Fumatech GmbH®, Germany). The characteristics of the commercial RED module and its components are listed in Table 1.

The following assumptions have been considered for the simulation of the SGE production potential in each scenario:

1. The concentration in the diluted compartment (C_{LC}) is equal to 0.02 M, salinity determined as optimal according to a previous work by Ortiz-Martínez et al. [33].
2. The typical water recovery rate at which SWRO facilities operate is in the range of 35 %–45 %. Accordingly, a recovery rate of 45 % has been assumed for the selected SWROs [50].
3. The whole wastewater flow rate (Q_{LC}) is used, being in all cases the limiting flow rate in the RED plant.
4. The average salinity of the brine in each scenario has been considered as the C_{HC} according to the data shown in Table 5.
5. The temperature of both water streams is equal and corresponds to the average sea temperature at the location of the assessed scenario. Sea water temperature data have been obtained from Copernicus Marine Service [51].

Therefore, the terms evaluated in this study are defined as follows:

— Gross power (W) Eq. (1), given by the stack voltage E (V) and the current intensity I (A).

$$P_{gross} = E \cdot I \tag{1}$$

— Net power (W) Eq. (2), defined as the difference between the gross and the pumping power.

$$P_{net} = P_{gross} - P_{pump} \tag{2}$$

where the power used in the pumping process in the RED stack defined by Eq. (3), depends on the pressure drop in both, the concentrated (HC) and the diluted (LC) compartments, Q (m^3/s) is the volumetric flow rate of both streams and η (−) is the pumping efficiency.

$$P_{pump} = \frac{\Delta P_{HC} \cdot Q_{HC} + \Delta P_{LC} \cdot Q_{LC}}{\eta} \tag{3}$$

— Net specific energy (kWh/m^3) Eq. (4), calculated as the ratio of the net power and the flow rate of the diluted stream.

$$SE = \frac{P_{net}}{Q_{LC}} \tag{4}$$

3. Results

This section presents the potential SWRO-WWTP pairs identified for the recovery of SGE in water treatment facilities in Spain and their characterization in terms of volume of water treated and geographical location. In addition, the potential of each scenario for the generation of energy through RED is analysed using a predictive model; besides, the potential to satisfy the energy demand of domestic water reclamation processes has been evaluated. In this regard, the challenges and opportunities for improvement of the RED technology for the selected application are discussed next.

3.1. SWRO-WWTP pairs identification

In 2021 DesalData collected a total of 3911 salt content reduction systems in water streams in Europe. Among the different water streams that can be subjected to these treatments, seawater desalination with 1311 installations throughout Europe is one of the preferred options after brackish water. 437 of these seawater desalination plants are located in Spain. Reverse osmosis is used in around 80 % of seawater desalination plants.

Regarding wastewater treatment facilities, Europe has a total of 20,098 WWTP units in operation, of which 2019 are located in Spain. A summary of the distribution of WWTPs and seawater desalination plants is presented in Table 2 [46,48].

Based on the set of seawater desalination plants, those using reverse osmosis technology and with a treatment flow rate greater than or equal to 25,000 m^3/day have been considered; a total of 35 Spanish facilities meet these criteria. Of these 35, those with a coastal WWTP in their vicinity (within a radius of 2.5 km and with a maximum altitude difference of 15 m) were selected, thus obtaining 16 pairs identified as potential sites to promote decarbonisation of wastewater reclamation treatments through the recovery of saline gradient energy for self-consumption.

The industrial pairs are distributed throughout the peninsular area bathed by the Mediterranean Sea and the Balearic and Canary archipelagos. SWRO-WWTP pairs geographical location is mapped in Fig. 2. Specifically, scenarios with identification numbers 1, 3, 4, 8–10, 12–15 are located in regions belonging to the Segura and Jucar river basins, strongly affected by water scarcity that require urgent planned strategies for the management of available hydrological resources in order to avoid the socio-economic impact of water shortages in a region with strong agricultural activity [52,53].

Each pair of industrial facilities represents a hypothetical scenario for energy extraction from the salinity difference between the two wastewater streams. Therefore, all the scenarios detected have been characterised in terms of water treatment capacity, end use of desalinated water, physical capacity for urban wastewater treatment and differences in geographical location (distance and altitude). An overview of all these features is provided in Table 3.

As an illustrative example of the geographical characteristics of the different scenarios, Fig. 3 shows the aerial view of the scenarios identified as 1 and 8 in this study, corresponding to the Torrevieja and

Table 2
Summary of treatment plant distribution by geographical area.

Type of water treatment facility	Europe	Spain
Seawater desalination plants	1311	437
WWTPs	20,098	2019

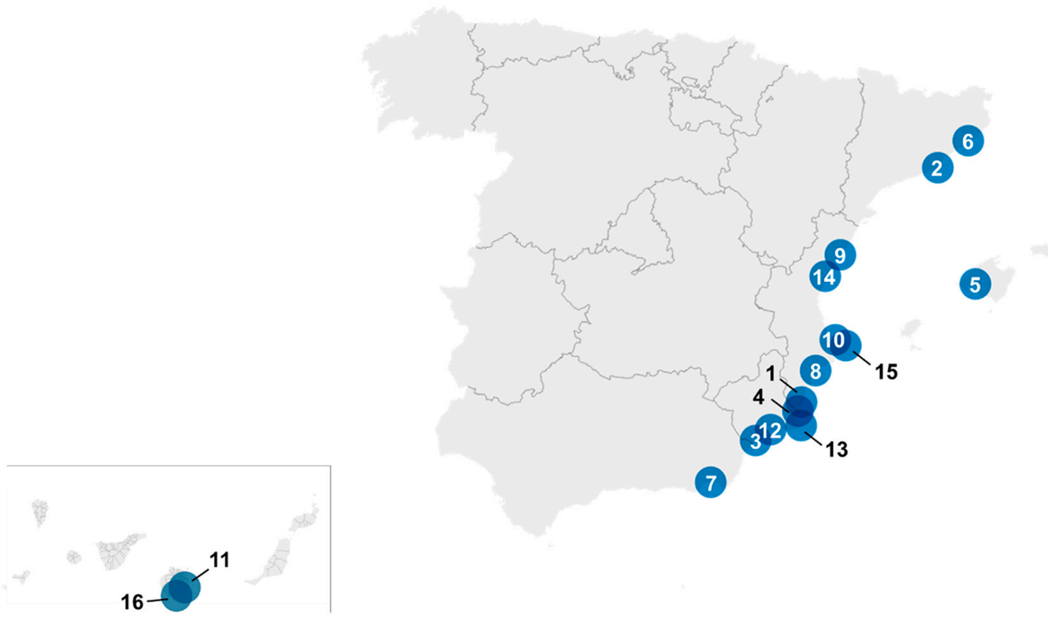

Fig. 2. Map of the location of SWRO desalination plants-Urban Wastewater Treatment Plants pairs in Spain.

Table 3
SWRO desalination facilities and WWTPs pairs main features.

Pair ID	SWRO desalination plant	Capacity (m^3/day)	Type of water produced	WWTP	Physical capacity (p.e.)	Flow rate (m^3/day)	Distance (m)	Altitude (m)
1	Torrevieja	240,000	Drinking water[a]	Torrevieja	490,000	18,480	800	1
2	El Prat de Llobregat	200,000	Drinking water[a]	El Prat de Llobregat	2,275,000	258,487	0	0
3	Aguilas Guadalentin	180,000	Drinking water[a]	Aguilas	86,667	5946	990	14
4	San Pedro del Pinatar I y II	130,000	Drinking water[a]	San Pedro del Pinatar	145,000	7184	550	1
5	Bahía de Palma	68,000	Drinking water[a]	Palma II	546,000	49,560	410	−3
6	La Tordera	57,600	Drinking water[a]	Blanes	120,000	9327	500	4
7	Almeria City	50,000	Drinking water[a]	El Bobar	315,000	22,880	650	5
8	Marina Baja/El Campello/Mutxamel, Alicante	50,000	Drinking water[a]	Alacantí Norte	112,500	6127	60	−14
9	Oropesa, Castellón	49,000	Drinking water[a]	Oropesa del Mar	113,750	11,614	680	−2
10	Desaladora Denia	42,500	Drinking water[a]	Denia-El Verger	7500	1079	290	0
11	Telde	37,700	Drinking water[a]	Telde (Hoya del Pozo)	66,666	6732	2300	3
12	Virgen del Milagro	37,000	Irrigation[b]	Mazarron	100,000	7430	1010	−13
13	Arco Sur	30,000	Irrigation[b]	Mar Menor Sur	541,667	9149	20	2
14	Moncofar	28,000	Drinking water[a]	Moncofar	28,000	4716	250	2
15	Jàvea	26,000	Drinking water[a]	Jàvea	39,200	5047	900	1
16	Maspalomas II	25,200	Drinking water[a]	Las Burras	100,000	10,630	220	8

[a] Drinking water (TDS 10 ppm–<1000 ppm).
[b] Irrigation (TDS <1000 ppm).

Alacantí Norte wastewater treatment plants, respectively.

It is noteworthy that in all cases, except for scenario with ID number 2, the lowest effluent flow corresponds to the WWTP, so it will be the limiting factor and will be fully utilised in the SGE-RED system. The exception occurs in the scenario with the highest baseline potential as it has the highest wastewater flowrate and is given by the SWRO and WWTP facility at El Prat de Llobregat. Scenario 2 is also the most favourable since the facilities are located at the same level and parallel to each other. Furthermore, it should be noted that two of the pairs reflected in this study include SWRO desalination plants specifically intended for the production of freshwater for agricultural use.

In the context of energy production and use to provide energy support to the treatment plants that enable WWTP effluent reclamation, a summary of the tertiary treatments already installed in the WWTPs that make up the selected pairs has been made. All the information collected is shown in Table 4, where nitrogen and phosphorus removal treatments, various disinfection treatments and filtration processes have been collected. Besides the WWTP of El Bobar, the rest of the WWTPs considered include some tertiary treatment in their facilities that improves the quality of the effluent. Thus, several beneficial opportunities arise for all the identified pairs. On the one hand, the implementation of SGE-RED technology can provide the necessary energy support to include reclamation treatment at the El Bobar WWTP. On the other hand, and considering the rest of the scenarios, the SGE-RED can decrease the dependence on the grid energy and thus increase the sustainability of the water cycle.

3.2. SGE-RED recovery assessment

This study focuses on the integration of SGE recovery in the reclamation of treated wastewaters using the RED technology. SGE is generated in the contact between SWRO concentrates and treated

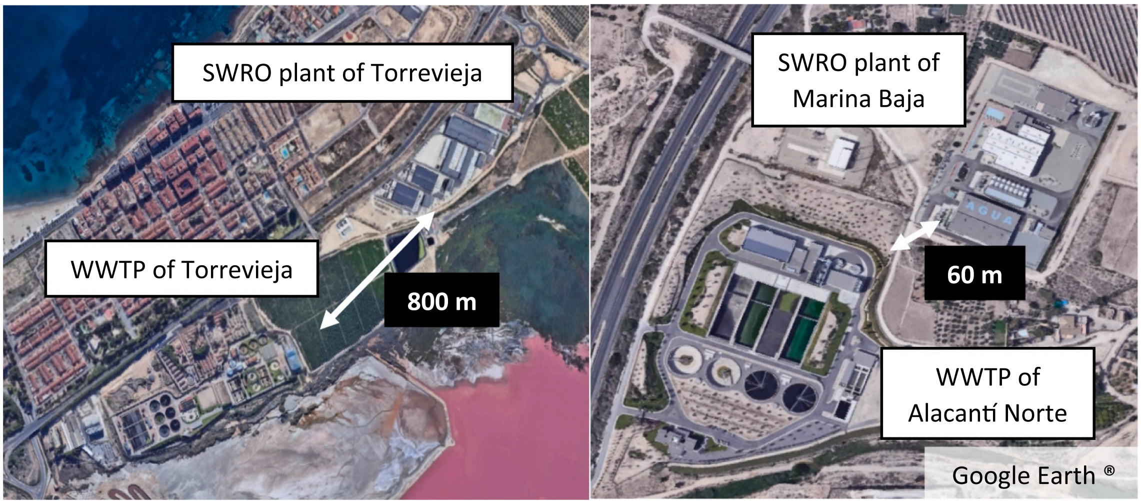

Fig. 3. Geographical characterization of scenarios ID number 1 (left) and ID number 8 (right).

Table 4
Description of WWTPs tertiary treatments.

WWTP	N removal	P removal	UV	CH	SF	PC	MF	UF	IP
Torrevieja	Yes	Yes	Yes	–	Yes	–	–	–	Yes
El Prat de Llobregat	Yes	Yes	Yes	–	Yes	Yes	–	–	–
Aguilas	Yes	–	Yes	Yes	Yes	–	Yes	–	–
San Pedro del Pinatar	Yes	Yes	Yes	Yes	–	–	–	Yes	–
Palma II	–	–	–	Yes	Yes	–	–	–	–
Blanes	Yes	Yes	Yes	Yes	–	Yes	–	–	–
El Bobar	–	–	–	–	–	–	–	–	–
Alacantí Norte	Yes	Yes	Yes	–	–	Yes	–	–	–
Oropesa del Mar	Yes	Yes	–	Yes	–	–	–	–	–
Denia-El Verger	Yes	Yes	–	Yes	–	–	–	–	–
Telde (Hoya del Pozo)	–	–	–	Yes	Yes	–	–	–	–
Mazarron	Yes	Yes	Yes	Yes	–	–	–	–	–
Mar Menor Sur	Yes	–	–	–	–	–	–	–	–
Moncofar	Yes	Yes	–	Yes	–	–	–	–	–
Jàvea	Yes	Yes	–	Yes	–	–	–	–	–
Las Burras	–	–	–	Yes	Yes	–	–	–	–

UV: ultraviolet disinfection, CH: chlorination, SF: sand filtration, PC: physico-chemical, MF: microfiltration, UF: ultrafiltration and IP: infiltration-percolation.

Table 5
SWRO effluent characteristics (C_{LC} equal to 0.02 M in all cases).

Pair ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
C_{HC} (M)	1.17	1.23	1.16	1.18	1.21	1.23	0.91	1.09	1.16	1.21	1.26	0.94	1.16	1.07	1.18	1.26
T (°C)	20	19	20.5	20	20.5	18.5	20	20	20	20	21	20.5	20	20	20	21

wastewater that after reclamation will be used for non-potable purposes. Therefore, information regarding the characteristics of SWRO effluents has been collected and is presented in Table 5, C_{HC} concentration and temperature. The salinity of the WWTP effluents discharging in the Mediterranean coast of Spain ranges from $5.9 \cdot 10^{-4}$ M to 0.02 M, as a consequence of seawater intrusions in the catchment and discharge systems. Previous studies have demonstrated that 0.02 M is the concentration of the low concentration stream that provides the optimal energy extraction scenario [33]. In this sense, the concentration of the LC stream has been assumed to be adjustable to reach the optimum value of 0.02 M by means of a by-pass from the HC compartment to the LC compartment, if necessary.

To compare different scenarios, several SWRO-WWTP pairs have been chosen for the analysis of the energy extraction potential representing the most favourable, unfavourable and intermediate conditions. Fig. 4 shows the results of net energy generated and specific energy of the six scenarios studied. The net energy generated at the El Prat de Llobregat treatment plant, facility with the highest treatment capacity in

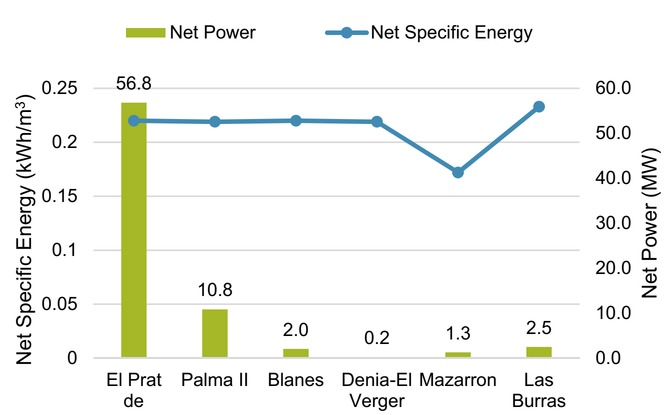

Fig. 4. Simulated net power and specific energy obtained in specific scenarios.

terms of volumetric flow, is 56.8 MW. For its part, the specific energy shows slight variations between 0.172 kWh/m^3 (Mazarron) and 0.233 kWh/m^3 (Las Burras). The electrical production capacity is closely conditioned by the gradient of salinity.

3.3. Analysis of energy use and improvement of the environmental profile in the WWTP

Besides to the potential chemical energy that can be harnessed, there is a growing interest in the regeneration and reuse of wastewater effluents. Furthermore, water reclamation processes are compatible with the pre-treatments applied for RED systems and sufficient to achieve the necessary water quality as demonstrated in a previous work by Gómez-Coma et al. [28]. In this sense, it arises the possibility of covering totally or partially the energy needs of water regeneration treatments with SGE harnessed.

The capacity of the SGE-RED technology to satisfy the energy requirements and reduce the carbon footprint in the selected pairs of WWTP-SWRO plants has been evaluated.

Table 6 summarises the average specific energy consumption for the most common tertiary treatments in operation at WWTPs [37,38,54]. This information has been used to estimate the energy consumption of the overall tertiary treatment installed in the WWTPs analysed, according to the description given in Table 4. Thus, the estimates for the specific cases are as follows: El Prat de Llobregat 0.84 kWh/m^3; Palma II 0.056 kWh/m^3; Blanes 0.79 kWh/m^3; Denia-El Verger 0.55 kWh/m^3; Mazarron 0.59 kWh/m^3 and Las Burras 0.056 kWh/m^3.

Fig. 5 shows the percentage of the specific energy consumption by each tertiary treatment applied in all the cases of study. Fig. 5 also indicates (◆) the percentage of tertiary treatment energy that can be supplied by SGE-RED in the case of full effluent flow recovery and considering the energy intensity of the plants as given in Fig. 4.

Fig. 5 confirms that there is a potential energy self-sufficiency capacity of tertiary wastewater treatment, which is around 30 % of the specific consumption in three scenarios (El Prat de Llobregat, Blanes and Mazarrón) in the case that the entire flow would be reclaimed. For the Denia WWTP, this value rises up to 40 %. This would currently allow the plants of El Prat de Llobregat, Blanes, Denia-El Verger and Mazarrón to reclaim a water flow equivalent to 67,206 m^3/day, 2518 m^3/day, 420 m^3/day and 2154 m^3/day, respectively.

And, specifically, at the Palma II and Las Burras WWTPs, estimated values of SGE-RED energy are around 4 times higher than the current specific energy consumption of the tertiary processes. Furthermore, this study highlights the opportunity to increase the effluent quality by installing new tertiary processes at low or zero additional energy expenses. All the results have been obtained from the specific intensity for SGE production simulated in each specific scenario and a theoretical estimation of the energy intensity of the regeneration treatment.

The energy recovery from water treatment plants effluents can contribute to reduce direct emissions of air pollutants of growing concern. WWTPs are mainly supplied by the energy grid of the Spanish power supply network, which in turn is dominated by non-renewable fossil energy sources [55]. In 2021 the average carbon intensity of the

Table 6
Average energy needs of different wastewater tertiary treatments [37,38,54].

Treatment	Energy consumption (kWh/m^3)
N removal	0.45
P removal	0.1[a]
UV	0.04
Chlorination	0.001
Sand filtration	0.055
Physico-chemical	0.2
Ultrafiltration	0.13

[a] Average consumption of an effective phosphorus removal process with microfiltration membranes.

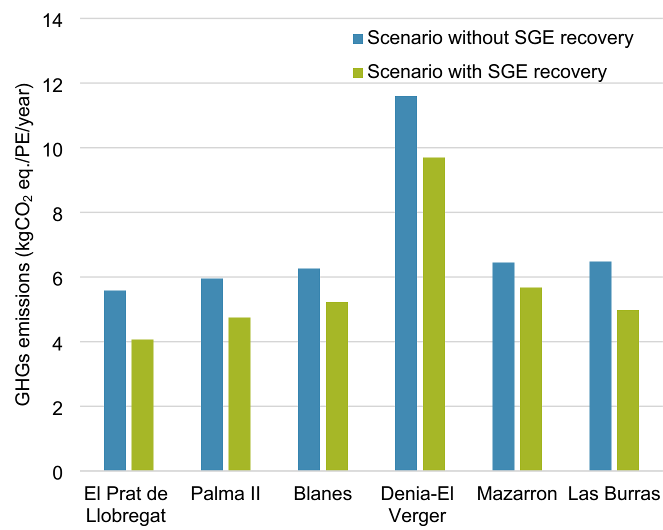

Fig. 6. Estimated carbon dioxide emissions present and in the future by implementing SGE energy recovery.

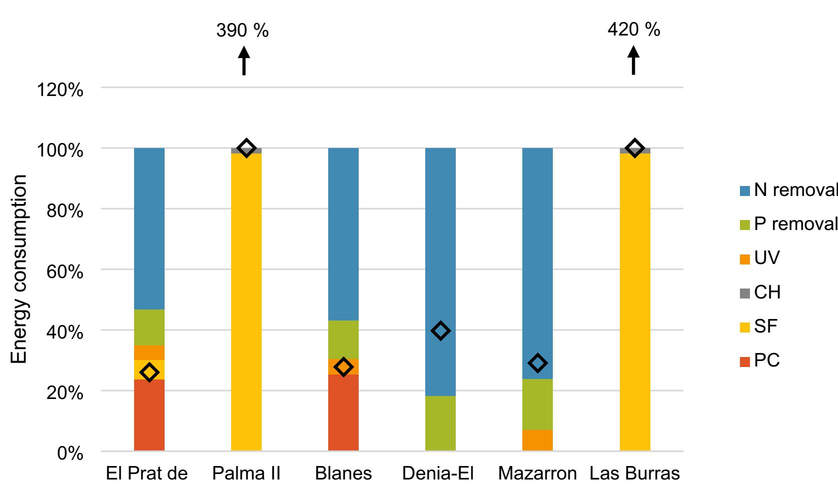

Fig. 5. Distribution of tertiary treatment energy by type of treatment and percentage of energy covered by SGE (◆).

Spanish energy sector was 166 g of CO_2 per kilowatt-hour generated [56].

On this basis, a comparison was made between the greenhouse gas (GHGs) emissions in the current situation of the WWTPs (scenario without SGE recovery) and in the potential scenario of SGE harnessing. The total specific energy consumption of the selected WWTPs has been forecasted based on the study of Ganora et al. [57] aimed at the prediction of electricity use in wastewater treatment by means of a statistical model that takes into account the economy of scale.

The results for the estimation of air pollutant emissions associated with WWTPs in the two scenarios studied are displayed in Fig. 6. Due to the substitution of the electricity provided by the Spanish electricity grid by a carbon neutral source of energy, such as SGE-RED, a significant reduction in total GHG emissions can be noted. In the large El Prat de Llobregat plant of 2,275,000 p.e. the estimated reduction in pollutants emissions could be up to 27 %. Whereas, for plants with a size in the range 546,000 p.e. to 7500 p.e., the variation is between 12 %–23 % of the total specific consumption. This reflects the potential of the technology to improve the environmental and social sustainability of wastewater treatment plants, simultaneously driving carbon neutrality. Nevertheless, these results are highly site-specific, as they may vary not only depending on the input load referred to in terms of p.e. but also on the treatment flow rate and the characteristics of the water streams that determine the amount of energy produced.

3.4. Environmental benefits of water reclamation and SGE harvesting

The environmental benefits of promoting WWTP secondary effluent reclamation and simultaneous SGE renewable energy recovery through membrane technology in the sixteen SWRO-WWTP pairs have been assessed through three Key Performance Indicators (KPIs):

— Water savings (m^3/day). The planned reclamation and reuse of treated wastewater leads to a reduction of water treatment for non-potable use equal to the volume of the reclaimed water. This study has estimated a potential water savings of 434,387 m^3 of water per day if all effluents of selected WWTPs were reclaimed and reuse.
— Water stress alleviation (%). The reduction in freshwater abstractions from renewable sources for subsequent conditioning has a beneficial impact on the reduction of water stress to which natural water resources are subjected. A reduction of 434,387 m^3/day of freshwater withdrawals represents a 0.5 % reduction in Spain's Water Exploitation Index of 23.71 (−) [9,58].
— Water cycle decarbonisation (%). The reduction in energy dependence on fossil fuels improves the environmental impact of WWTPs. It has been estimated that a reduction of 18 % of direct GHG emissions could be achieved with the recovery of SGE through RED on average in the WWTPs for the specific cases analysed.

4. Conclusions

The dichotomy between the need to promote water reclamation as a new source of water to meet the demand of a society with ever-increasing water needs and accelerate decarbonisation in the water sector demands sustainable energy sources suitable to specific water treatment scenarios. In this sense, the recovery of saline gradient energy at the discharge points of wastewater treatment plants opens up a niche of opportunities to provide an integrated solution to the problems of current and future society.

In this context, this study has identified and characterised 16 potentially optimal WWTP-SWRO desalination plant scenarios in Spain for the application of planned wastewater reclamation systems by exploiting the chemical potential difference between wastewater effluents and desalination concentrates. SGE-RED systems could provide energy support to water remediation allowing the decarbonisation of the regeneration of 434,387 m^3/day of wastewater.

The potential capacity of the SGE-RED technology has been demonstrated through the calculation of the SGE energy intensity generated in specific real scenarios. The net energy intensity simulated by mathematical modeling covering a range of temperatures and concentration gradients, was in the range of 0.17–0.23 kWh/m^3 of treated wastewater. This confirms its capacity to energetically satisfy the energy requirement of a tertiary regeneration treatment based on disinfection and solids removal process. However, future progress in RED technology will enable increasing the efficiency and performance in SGE recovery, further enhancing the carbon neutrality of WWTPs.

Finally, 10 of the 16 selected sites are of particular interest as they are located in the Segura and Jucar River basins, associated with extraordinary high WEI values. They are therefore situated in a strategic area from the point of view of the planned reuse of reclaimed wastewater for non-potable uses, due to the high-water consumption in agricultural activities and the water scarcity of the catchment areas to which they belong.

The replicability of the SGE-RED systems in wastewater reclamation plants will depend on the development of the technology, not only by improving the power density generated but also by optimising energy recovery using advanced computational simulation and optimisation tools.

CRediT authorship contribution statement

T. Sampedro: Methodology, Investigation, Writing – original draft, Visualization. **C. Tristán:** Methodology, Software, Formal analysis, Investigation. **L. Gómez-Coma:** Conceptualization, Investigation, Writing – original draft, Visualization. **J. Rioyo:** Funding acquisition, Project administration. **M. Sainz:** Funding acquisition, Project administration. **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.

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