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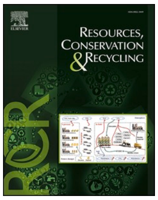

Full length article

Resource recovery from desalination, the case of small islands

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ABSTRACT

This work explores resource recovery coupled to seawater desalination in small islands. As small islands depend on seawater desalination for water access, they make an excellent ground for exploring the trade-offs associated to resource recovery, like potential economic gains, energy use, and environmental impacts. Here, we investigated these tensions in the context of Lampedusa, in Italy. We then developed and evaluated scenarios for the recovery of additional water, Mg, and other resources from brines, to identify if and how resource recovery is an interesting approach for the island vis-à-vis these tensions. We have found that the potential to increase water production with water recovery from brine is an interesting alternative for small islands, especially when harnessing waste heat. However, while some technologies offer possibilities for recovering additional resources, in places like small islands the potential benefits from additional recovery do not seem to justify the costs to the local system.

1. Introduction

Seawater desalination (SWD) has been gaining prominence in water scarce areas to satisfy water demand. However, as water demands are met, questions over the impacts of desalination emerge: it requires vast amounts of energy with associated costs and greenhouse gas emissions, and it produces a brine effluent that can affect aquatic eco-systems (Missimer and Maliva, 2018). In this context, resource recovery approaches have been suggested as a means to reduce these impacts and contribute to circular economy objectives. Besides table salt (NaCl), SWD brines are rich in Ca and Mg salts, the latter having being identified as a critical raw material in the European Union, for example (Magnus Gislev and Milan Groho, 2018). However, questions remain about the potential trade-offs that resource recovery in the context of seawater desalination brings (Palmeros Parada et al., 2022). For example, recovering resources implies additional processing steps that can increase energy and capital costs, or bring additional economic benefits depending on the resources to recover. To reduce the impacts of energy use, some have proposed integration to alternative energy sources, however these can bring additional issues, such as land use or renewable energy availability and costs.

In this paper we discuss the case of desalination in the specific context of small islands, which often face water scarcity due to climatic and topographical characteristics that do not allow for storage (Falkland and Custodio, 1991). Recently, SWD has gained prominence for producing freshwater in small islands, becoming the main or only source of freshwater in some cases (Gómez-Gotor et al., 2018; Rossi, 2014). In this context, small islands where SWD takes such a prominent role for society – providing water access – make an excellent ground for exploring the tensions mentioned above. That is, when desalination is so critical for water access, is resource recovery desirable, and how?

To investigate this question, we took as case study the demonstration of a resource recovery system in the island of Lampedusa, in Italy. The pilot-plant is based on a battery of technologies for the recovery of water, Ca, Mg and other chemicals from SWD brines, and was developed within the WATER MINING H2020 project. The technologies in the pilot-plant have been tested in previous R&D projects, and in this work they were implemented within the local power plant to use waste heat on-site. Our analysis takes a Responsible Innovation perspective, which aims to make the innovation process more anticipatory, reflexive, and

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responsive by promoting participation of stakeholders (Marques Postal et al., 2020). To engage in the innovation process, we followed a “context-sensitive design approach”. This approach is based on Value Sensitive Design (VSD), a design methodology to proactively integrate societal values in the design of technologies. In contrast to VSD, which is typically applied for the design of technological products and often with direct contact with end users, in this work we use elements of this approach as a Responsible Innovation exercise. That is, the aim of this work is to use the design of a resource recovery system to gain first insights on its societal implications in the context of small islands, with explicit recognition of emerging tensions between societal values around it.

2. Methodology

The context-sensitive design approach incorporates elements of VSD (Davis and Nathan, 2015; Friedman et al., 2017), sustainable design and participatory assessments (Barron et al., 2021; Gamboa et al., 2016; Palmeros Parada et al., 2020, 2018). Two participatory phases were followed: Phase 1 (months 1–10), when societal (i.e. stakeholder values, value tensions and uncertainties) and technical aspects (i.e. design variables and evaluation indicators) around the resource recovery system are identified; and phase 2 (months 11–35), when technical scenarios for the full scale implementation of the system were developed and brought to stakeholders. In the next subsections we describe the case study, the different roles in the project, the conducted activities along the two project phases (see Fig. 1), and the data analysis method.

2.1. Case study

Lampedusa is a small island of about 6000 inhabitants located in the southern Italy, between Sicily and northern Africa. Lampedusa suffers water scarcity and for a long time it depended on water imports. Freshwater is currently produced by an in-situ reverse osmosis desalination plant (Trapanese and Frazitta, 2018), which in small islands can constitute around 30% of the total electricity use (Giudici et al., 2019). The island is not connected to the Italian energy grid, and relies on a boat service to deliver diesel to a local power plant. As result, power and potable water production are more expensive than in the mainland, and have relied on public incentives to equalize costs to users with the mainland (Curto et al., 2020). An increasing population in the summer (reaching more than 50,000 tourists (Tsalidis et al., 2023)) leads to increased electricity and water consumption, so water supplements by boat are sometimes needed (Trapanese and Frazitta, 2018).

Fig. 2 shows the resource recovery system at the pilot-plant, which uses waste heat from the local power plant where the pilot-plant is located. Seawater or seawater brine pass through a nanofiltration unit (NF) that splits the stream into a permeate rich in NaCl and a retentate where divalent salts, such as Mg and Ca, are concentrated. From there on, the system has two sides: the concentration side where the waste heat from the power plant is used to obtain pure NaCl (i.e. table salt) and water from the NF permeate stream by using the Multiple Effect Distillation (MED) and Evaporative Crystallization (EC); and a separation side to recover other salts (e.g. $Mg(OH)_2$ and $Ca(OH)_2$ from the MF-PFR; Na_2SO_4 from the EFC) and chemicals (HCl, NaOH from the EDBM) from the NF concentrate rich in divalent ions.

2.2. Researcher and stakeholder roles

In this work, ‘researchers’ refer to the scientists within the project responsible of the research design and coordination for this work, with experience on VSD and participatory approaches. ‘Technical partners’ are researchers within the project responsible for the design and testing of the technologies. Researchers designed surveys and interviews with stakeholders, and technical partners conducted them in Italian. ‘Project partners’ refer to other project partners not directly involved with this work or the technological system in question. Stakeholders are referred to a broad category of organizations and individuals, especially those beyond the project who may affect or be affected by the WM technologies.

2.3. Main activities

2.3.1. Phase 1

A literature review was conducted during the first year of the project, with the aim to identify social values around resource recovery from desalination brines and support the development of surveys and interview guides. The results of the review have been published elsewhere (Palmeros Parada et al., 2022) and are not elaborated here.

Interviews were carried out to identify stakeholder values. For this, identified stakeholder organizations were invited for interviews. While the interviews followed this guide, they remained flexible to attend to any emerging topic. Interviews were recorded and transcribed and, when needed, translated to English. Transcripts of the interviews are available by contacting the corresponding author.

VSD Meetings with technical partners and researchers were held during the first year of the project. These meetings had the aim to familiarize researchers and project partners with their different backgrounds, and to support the identification of technical and societal aspects around the system.

First stakeholder meeting (SM1) was held online at the end of the first year of the project to present to stakeholders the demonstration system in the case study, and to open a discussion around the identified values and tensions.

2.3.2. Phase 2

Technical scenarios were developed to explore different ways of implementing the WM technologies at large scale. The scenarios explore different technical configurations to respond to the identified value tensions directly (e.g. varying product qualities that result in different costs) or indirectly (i.e. as basis to elicit a discussion about value tensions with stakeholders). In this way, the scenarios are a means to explore different technology development pathways, allowing to anticipate potential impacts and explore the identified tensions more concretely. Although in this work all identified tensions are presented, here we only develop technical scenarios for one of the presented

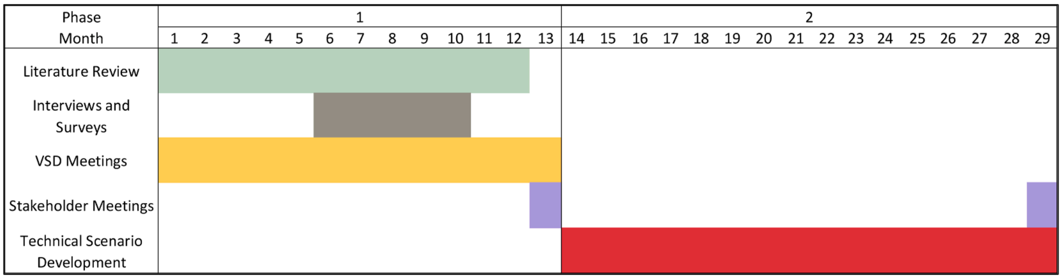

Fig. 1. Main activities for the context-sensitive design of a resource recovery system for SWD.

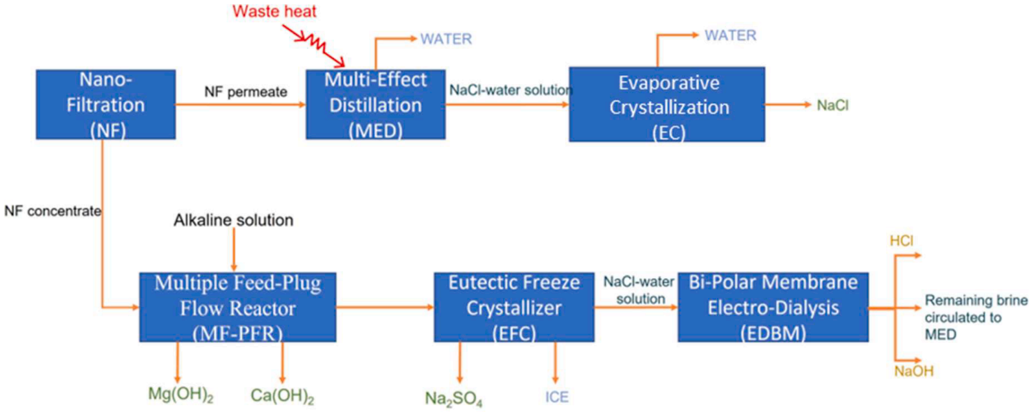

Fig. 2. Diagram of the resource recovery process within the Water Mining project, indicating recovered resources: salts (green), chemicals (yellow) and water (blue). The concentration side is the processing train at the top; the separation side is the processing train at the bottom.

tensions due to the scope of this work and time constraints. Nevertheless, recommendations for further research and implementation are given for the other two tensions in Section 4.

Scenario development and evaluation: A desk study to develop, model and simulate technical scenarios was carried out in an interdisciplinary team of researchers and technical partners. The process started with the analysis of how identified tensions could be explored through technical scenarios and their evaluation. Scenarios were then developed taking as basis the Water-Mining system being demonstrated in Lampedusa, and exploring four main variables: (1) process and technology, (2) product and by-products, (3) scale and supply chain, (4) raw materials and utilities (Palmeros Parada et al., 2018). The scenario development relied on data obtained from the demonstration system as well as from literature, and was brought for discussion with technical partners in month 15 and with project partners in month 25. Main considerations are included in Appendix 1, and the “Water Mining Scenario” comprises the original set-up of the Water-Mining system. The description and design parameters of the demonstration system in Lampedusa can be found in Xevgenos et al. (2022), and technical details are available at Xevgenos et al. (2022). Further analyses on bench-scale tests are reported in Culcasi et al. (2022) and performance of individual process steps at pilot scale in (Cassaro et al., 2023; Herrero-Gonzalez et al., 2023; Morgante et al., 2022). Additionally, a separate manuscript is now being prepared to report the results from the integrated demonstration in Lampedusa island.

Second stakeholder meeting (SM2): A second online meeting with stakeholders took place on month 29, where the identified tensions and the technical scenarios were presented to stakeholders with aid of the indicators identified in Phase 1. During the meeting participants were divided into three groups and were asked to discuss which scenario would be the most suitable for Lampedusa. The groups were pre-selected seeking to have stakeholders with different backgrounds in each group and based on a list of confirmed participants. The aim was that, by having participants from different backgrounds, they would have to debate their choice and make explicit their judgements and assumptions.

2.4. Data analysis

2.4.1. Value analysis

Values were identified from the surveys and interview outcomes, as well as from project documents. All documents and transcripts were analyzed with open coding, focused on objectives, expectations, hopes, concerns around the project and case study. Coded segments were contrasted to each other to form value categories vis-à-vis the literature review findings. This was done iteratively as new documents were retrieved and analyzed. Based on this analysis, value tensions were identified from aspects of the technology or ways to implement it that can contribute and oppose several values at the same time. At the end of Phase 1, the identified values and value tensions were reviewed by all VSD researchers and technical partners. These values and value tensions were the basis to construct the multicriteria structure presented in the following section.

2.4.2. From social values to indicators

Indicators were identified to allow the comparison of performance in relation to identified values. In this case, the technical scenarios are the alternatives to be evaluated and compared under a set of criteria derived from identified social values. The information is structured in a $m \times n$ multicriteria impact matrix (i.e., with m rows and n columns), where n is the number of alternatives and m the number of criteria. The element g_{ij} of the matrix is the criterion score of alternative i under criterion j. This information was used to foster discussion among stakeholders about the trade-offs in resource recovery from desalination brines in small islands.

To populate the impact matrix, we defined alternatives as explained in Section 2.3.2 Phase 2. The criteria were defined following Gamboa et al. (2020, 2016). Social values, concerns and expectations were translated into a set of multi-dimensional criteria, and indicators representing different views present in society. Criteria are the elements used within a specific narrative to describe a system: a description of an observable relevant quality. For example, the assertion that “water desalination technologies are highly energy intensive” contains a value judgment, which is used to identify “energy consumption” as a criterion within it. To perform a quantitative characterization of the system under study, indicators were identified as a means of representing a criterion, as an attribute of the system. They can be defined as the image of an attribute, formalized in terms of a specific measurement (Gallopín, G., 1997) For example, the “amount of MJ used as energy input to desalinate water” can be used as the indicator for the criterion “energy consumption”. The value of the indicator provides information about the condition and/or the trend of the attribute of the system.

3. Results and discussion

3.1. Stakeholder interviews and SM1

From the interviews and the first stakeholder meeting an initial identification was made of how stakeholders respond to the proposed resource recovery system in the island context. Particularly, stakeholders stated the importance of desalination plants for covering water needs in the islands and expressed that projects that improve the performance of such plants are positive. At the same time they showed concerns regarding the illegal extraction of underground and seawater by some consumers, worsening the global availability and putting the system at risk, since seawater may enter into the aquifers and pollute them. While some stakeholders see the potential of extracting new resources from desalination as something positive, especially when it comes to avoiding brine discharge and when it could economically benefit the final consumer, some considered this a threat to their business or doubted its economic feasibility. Additionally, the high consumption of energy was seen as a prominent issue to tackle, and they considered the use of waste heat as an opportunity to reduce the global footprint of the plant.

These findings are generally in agreement with the Water Mining project, and little disagreement emerged from the gathered data. This result can be explained by the limited participation of local stakeholders despite efforts to engage them. An overview of participants can be found in Appendix 2, where it can be seen that, e.g., no representatives of the local administration nor environmental organizations attended the activities). Therefore, for the value analysis, these results were contrasted with the findings from the literature review as mentioned in Section 2.4.

3.2. Value tensions

3.2.1. Tension 1, between water and energy security, and sustainability

The investigated system brings a tension between the values of water security, energy security and sustainability. Particularly, the system would increase water availability and self-resilience, but would come at a cost on energy security by increasing the need for energy imports. Additionally, impacts on different sustainability aspects are expected, such as reducing brine discharge into the sea, increasing GHG emissions due to higher energy use, and an uncertain impact on the cost of water. Although a large part of the energy demand would be provided by waste heat from the local power plant, the system would nevertheless require electrical energy to, e.g., operate membrane equipment and pump streams through the system. Considering that even if only a small fraction of energy demands is not covered by waste heat, this demand would add to the energy requirements of the island and increase energy imports and the associated GHG emissions under the current energy system (see Tension 2 for a discussion on renewable energy sources (RES)). The impact of that additional energy on overall GHG emissions vis-à-vis impacts on water security, therefore needs to be investigated. With regards to impacts on the cost of water, there are uncertainties on the impact of resource recovery process on the production cost of water, and on how much (and how) the recovered salts can compensate the cost of the process. In a context where public support to keep water or energy cost low is uncertain, this is a very relevant question to the stakeholders in this case study. As these aspects can be explored quantitatively through techno-economics and carbon foot-printing, it was decided to base the development of technical scenarios on this tension, and to bring to discussions with stakeholders in Phase 2 of the project.

3.2.2. Tension 2, between efficiency and long-term sustainability

Integration with waste heat is being proposed for the sake of energy efficiency (i.e. less primary energy is needed for obtaining a given amount of water when using waste heat), as an aspect contributing to the overall sustainability of desalination and power production. However, as the waste heat has fossil origins (i.e. diesel transported by boat), a risk of promoting a fossil energy lock-in was identified. That is, investing in equipment integrated with fossil resources could deter or slow-down the adoption of renewable energies, as noted for other sectors, e.g. (Janipour et al., 2020). When this issue was brought up to discussion with stakeholders, it was pointed out that in Lampedusa there are limited areas for Renewable Energy Sources (RES), leading to expectations that fossil resources are the only large-scale energy alternative in the short to medium term. This situation has also been discussed in the literature, when RES potential is limited by landscape protection laws in addition to the surface limitation in small Italian islands (Giudici et al., 2019). Nevertheless, an expansion of RES in Lampedusa is already under consideration in local planning (with, e.g., photovoltaics and solar thermal expansion (Beccali et al., 2020), even if in practice it has been slower than expected as discussed by some stakeholders.

Another long-term issue that arises is that as drinking water needs are mostly covered by SWD already, and the effects on water consumption when providing extra water are unknown. There is a potential to increase water consumption due to higher efficiency in the provision of water, as discussed, for example, around irrigation in the agricultural sector (Sears et al., 2018). In the case of Lampedusa, the effect could be through tourism expansion, which is a prominent economic activity in the island, and lead to larger environmental impacts even at higher efficiencies (i.e. what is commonly referred to as a 'rebound effect' (Makov and Font Vivanco, 2018)).

3.2.3. Tension 3, with the ownership of water, recovered resources and technology

This tension is related to the ownership of seawater, of desalinated water, and of the technology developed with public funds. From the review of the literature, debates regarding the ownership and management of water were identified (i.e. who should be benefitted and who is responsible for the management of resource recovery?) (Palmeros Parada et al., 2022). As this case study relates to seawater as a common good, and is being partly developed with public funding, the question about who owns, manages and benefits from implementing this system becomes relevant. For example, cost associated to the process of resource recovery can be distributed differently across the recovered resources, or be compensated through public support. In this way, how costs are distributed will affect the competitiveness of resource recovery and the affordability of water in a water scarce region, or the public budget allocated to it.

3.3. Performance indicators

Indicators are considered here as the technical translation of social values, concerns and expectations. The next Table 1 presents the criteria and indicators derived from the social values presented in the previous section.

3.4. Technical scenarios

Considering the identified tensions and the scope of the WM system, technical scenarios were developed around Tension 1, between water security, resource security and sustainability. Therefore, while all scenarios aim to use waste heat to increase water recovery from seawater and reduce brine discharge (compared to a typical SWD), they do so

Table 1
Selected indicators for CS1 and associated criteria and values.

Value	Criteria	Indicators	Unit	Direction[a]
Water security	Water availability	Volume of water production	Hm^3/year	↑
Sustainability - Resource security	Recovery Efficiency	Amount of recovered minerals	%	↑
Sustainability - Energy security	Energy consumption	Electrical Energy consumption	kWhel/year	↓
Sustainability - Energy security	Energy consumption	Thermal Energy consumption	kWhth/year	↓
Sustainability - Climate Change Mitigation	CO_2 emissions	Tons of CO_2 equivalent	tCO_2eq/year	↓
Economic viability of the plant	Investment costs	CapEx	€/year	↓
Economic viability of the plant	Operational costs	OpEx	€	↓

[a] Direction has two options: For maximizing higher is better, and for minimizing lower is better.

differently: Scenario 1 maximizes water and resource recovery as in the demonstration project and integrated to a reverse osmosis plant, Scenario 2 does the same but as a standalone system (without RO), Scenario 3 focuses only on water recovery to keep energy requirements low, and Scenario 4 balances water and resource recovery with electricity requirements. The scenarios are summarized in Table 2, and block schemes of each scenario are included in Appendix 3.

3.4.1. Technical scenario performance

The estimated performance of the technical scenarios is summarized in Table 3. Scenario 3 on water recovery performs yields the most water and performs better under most of the indicators except economic margin and thermal energy requirements. Scenarios 1, 2 and 4 require higher amounts of electricity and imply large CO_2 emissions than scenario 3. Nevertheless, due to the recovery of multiple valuable products (high resource efficiency) with high revenue potential, their economic margin are much higher than for Scenario 3, which has a negative margin. The differences in water recovery are related to the consideration of evaporation ponds to reduce energy demand in Scenario 4, and the internal use of produced water within the systems to recover chemicals in the EDBM unit (Scenarios 1, 2 and 4). Despite that scenarios 1 and 2 have similar designs, they perform differently in economics due to the different equipment capacities associated the volume reduction with an initial RO step. Scenario 4 focused on the recovery of Magnesium yields the highest economic margin despite showing the highest OPEX and CAPEX too. In this scenario, the potential for recovering and selling magnesium (Mg) and chemicals compensates for these high investments, resulting in a profitable scenario with a significant economic margin. The production rate of chemicals (NaOH, HCl) is higher than the internal demand, allowing for additional profits. Despite the integration of fewer technologies and the use of evaporation ponds for NaCl recovery, Scenario 4 exhibits values for electrical energy consumption and CO_2 emissions in the same range as in Scenarios 1 and 2. This is primarily attributed to the upscaling of energy-intensive technologies, such as EDBM.

In relative terms, scenario 3 yields about 33 m^3 per each kWh_{el} consumed, whereas scenarios 1, 2 and 4 deliver about 7 m^3/kWh_{el}; likewise, Scenario 3 yields about 17 m^3 of recovered water for each emitted tCO_2eq, whereas scenarios 1, 2 and 4 deliver about 5 times less. In economic terms, while Scenario 3 yields between 0.6 to 3 times more water per invested euro than the other scenarios, it yields the lowest profitability since it has less revenues from additional resources. However, it must be noted that the estimated economic margin carries large uncertainties as the prices of recovered resources depend on achievable qualities and on market characteristics under uncertainty.

3.4.2. Stakeholder discussion in SM2

Participating stakeholders to SM2 included potential users of technology and recovered resources, research organizations in the engineering and policy domains, and engineering companies (see Appendix 2). Participants, who were divided in three discussion groups, largely agreed on their preference for a water recovery scenario (Scenario 3) in the context of Lampedusa. In their discussions, they referred to energy consumption, efficiency and availability, technology reliability and demand for recovered products in the deliberation. Particularly, two participants of the first discussion group argued that from an energy efficiency point of view, Scenario 1 is the best one. They also referred to reverse osmosis (part of Scenario 1) as the safest option in terms of it being a technology with known performance. Participants in the second group additionally referred to the advantages of Scenario 1 in terms of economics, having a higher revenue potential. Nevertheless, low CO_2 emissions, as well as plant footprint and having Lampedusa as location, determined the preference for Scenario 3 in all groups. For the latter issue, participants in all groups discussed that a desalination plant in the small island of Lampedusa would not be a preferred alternative considering the local energy constraints and the limited local industrial activities (i.e. no chemical demand). When reflecting over the perspectives of stakeholders who were not present in the workshop (i.e. reflecting on what the perspectives of, e.g., civil servants and environmental protection agencies would be), they responded that they would likely prefer plants with an 'environmentally friendly' approach that relies on a circular system, implicitly referring to local production and use. They then suggested it as a potential attractive point for the island. Lastly, Scenario 1 with the largest resource recovery potential and integrated with RO, and Scenario 4 with Magnesium recovery were discussed as a desirably system for other locations without the energy, land, and/or chemicals demand characteristics of Lampedusa.

Table 2
Description of technical scenarios.

Scenario		Technologies	Products
1	Integrated scenario	RO, NF, MED, ThCryst, MFPR, EFC, EDBM	$Ca(OH)_2$, HCl, Ice, $Mg(OH)_2$, NaCl, NaOH, Na_2SO_4, Water
2	Water mining scenario	NF, MED, ThCryst, MFPR, EFC, EDBM	$Ca(OH)_2$, HCl, Ice, $Mg(OH)_2$, NaCl, NaOH, Na_2SO_4, Water
3	Water recovery scenario	NF, MED, ThCryst	Water, Mixed salts
4	Magnesium recovery scenario	NF, MED, EvPond, MFPR, EDBM	$Ca(OH)_2$, HCl, $Mg(OH)_2$, NaCl (lower purity), NaOH, Water

EDBM: Electrodialysis with bipolar membranes; EFC: Eutectic freeze crystallization; EvPond: Evaporation Pond; MED: Multi-effect distillation; MFPR: Plug-flow reactor; NF: Nanofiltration; RO: Reverse Osmosis, ThCryst: Thermal crystallizer.

4. Discussion and conclusions

The presented work shows an exploration of the societal desirability of resource recovery for small islands, taking as case study Lampedusa. It was found that resource recovery scenarios outperform substantially the water focus scenario in terms of economics, however they lead to lower water recoveries, additional energy requirements, carbon emissions, and they carry market uncertainties associated to the recovered resources. That is, water, energy, and land are critical resources in Lampedusa and a system focused on water recovery, like in Scenario 3, yields the most water resources per amount of energy spent, emitted emissions, and required capital. This result, as well as the discussions with stakeholders who pointed to a limited industrial demand for recovered resources, indicate that a water recovery focus is most suitable for Lampedusa. Thus, based on this work, a potential higher profitability from recovered resources, like in Scenarios 1, and 4, does not seem to compensate for the additional energy requirements in Lampedusa and the lack of local demand for the resources. Newer technologies, such as membrane distillation have the potential to lower the energy and emission impacts of desalination (Abdel-Karim et al., 2021), however the comparison across scenarios would likely yield a similar conclusion for Lampedusa when factoring in the recovery and demand of salts and chemicals.

This finding holds in the current Lampedusa context, where the availability of RES is limited and its development has been slower than anticipated. Nevertheless, RES remains in long term regional plans (Beccali et al., 2020). The eventual availability of RES would not lead, nevertheless, to an automatic desirability for a wider resource recovery from brine in the island, even with higher water recovery and profitability. If in the current state, intensive resource recovery is not desirable due to a large energy use with associated emissions, as well as reliability and energy security implications, the availability of RES brings additional questions around priorities for energy use. That is, what would be the most desirable uses of limited RES, considering the trade-off between its negative impacts (e.g. burdens on landscape or economic requirements) and the benefits of its possible uses, like house-hold electricity, transportation, water supply and sanitation, and

Table 3
Summary of results of the evaluation of technical scenarios in CS1.

Indicator	Unit	Direction[a]	Scenario 1: RO-SWD integration	Scenario 2: water mining	Scenario 3: water recovery	Scenario 4: Mg recovery
Water production	1000m3/year	↑	100 690	102 509	122 674	57 735
Resource efficiency	%	↑	96.19	92.06	94.41	79.64
Electricity consumption	GWh/year	↓	13.39	13.21	3.79	12.42
Thermal energy consumption	GWh/year	↓	223.76	349.52	403.24	280.58
CO_2 emissions[b]	kton/year	↓	26 516	26 152	7 500	24 582
OPEX	M€/year	↓	5.07	7.29	6.09	9.16
CAPEX	M€	↓	32.11	40.11	24.55	37.77
Economic margin[c]	€/m3 distillate water	↑	19.29	11.32	-5.38	42.10

[a] Direction has two options: For maximizing higher is better, and for minimizing lower is better. [b]Emissions are those associated to energy use within the process and transportation of brine. [c] Economic margin represents the yearly potential revenues minus annualized production costs per amount of recovered water. Revenues are estimated for already marketed resources, considering average prices.

industrial resources? These questions bring a component of environmental justice that should be further explored, especially if economic and environmental costs are taken by the public (e.g. (Levenda et al., 2021)).

The presented results, nevertheless, indicate that in contexts where RES and demand for recovered chemicals are readily available, the recovery of additional resources like $Mg(OH)_2$, HCl and NaOH would be an interesting development, especially when coupled to RO SWD as in Scenario 1. The latter is emphasized by a possible use of HCl and NaOH within the desalination process. Such a location could be, for instance, larger Mediterranean islands or desertic areas that also face water scarcity but that have more alternatives for renewable energy sources, and where there is infrastructure to use or trade the recovered resources, like for plastic production in which $Mg(OH)_2$ could be used as fire retardant (Rothon and Hornsby, 2014). However, a more detail analysis would be necessary to identify how different sustainability aspects would be affected in that context, and thus identify the most suitable configuration. A priori, targeting the recovery of only water, HCl and NaOH in Lampedusa could be interesting for the local desalination plant. However, to recover these chemicals there is a need to pre-process the streams before the EDBM equipment, which would turn the process into something like Scenarios 1 and 4.

A possible argument in favor of intensive resource recovery from desalination brines in the Lampedusa context could be additional water recovery with the potential benefits from the export of recovered resources. However, such potential economic benefits carry large uncertainties, especially if markets for recovered resources need to be developed as has been discussed elsewhere (Kehrein et al., 2020), and would need to be further studied, as well as how they would contrast vis-à-vis overall environmental impacts, including energy for export. Even more, such a scenario would challenge a circular economy that benefits from short supply chains, bringing users and producers closer (Kiss et al., 2019). Some authors have discussed the role of ports in a 'global circular economy', where they allow to take advantage of existing infrastructure and industrial symbiosis to bring benefits to local economies (Gallaud and Laperche, 2016), however for small islands like Lampedusa the availability for infrastructure and connectedness seems limited.

In any case, flexibility has to be designed into the energy integration approach, to avoid lock-ins with fossil resources as discussed for tension 2. Particularly, a flexible integration between thermal equipment and waste heat is recommended for large scale implementation. That is, heat exchange equipment for the resource recovery system should be suitable or easily adaptable to take heat at the conditions available at an existing power plant and heat deliverable from renewable sources in the planning for Lampedusa (e.g. at certain temperature and pressure). For the resource recovery system as in the discussed in the research project, the ideal would be to have thermal energy directly from RES. However, the type of heat delivered can vary largely between, e.g., solar collectors, concentrated solar power plants and flue-gas from power plants. Therefore, the design of the thermal equipment (MED and crystallizer) should have in perspective the type of thermal RES in regional plans.

While Tensions 2 and 3 remained beyond the scope of this work, some recommendations for future study are extracted from this work. Particularly, it has been found that rebound effects can be avoided through policy and water management measures (Freire-González, 2021). Possibilities to consider are, e.g., allocating the extra water to users during peak demand only, and the rest of the time to substitute desalinated water capacity. However, the feasibility of this or other policy measures depends on contracts and arrangements between local entities, and their impacts should be investigated in more detail. To explore Tension 3 around the ownership of resources and technology, a possible approach could be to combine the economic evaluation of technical scenarios like presented here, and 'what-if' analyses that explore the impacts of, e.g. incentives, distribution of costs, and elicit stakeholders responses. Such an exploration would be helpful to identify, with concrete examples, what are desirable policies or acceptability factors for recovered resources (e.g. willingness to pay, perceived required subsidies…).

Overall, the presented results give an ex-ante estimation of the tradeoffs involved in resource recovery from SWD, and the perspective of stakeholders on what is desirable for the small island of Lampedusa. While resource recovery technologies offer many possibilities for recovering resources with high potential economic benefit, a simple resource recovery system with a focus on additional water recovery from SWD brines seems to be the most suitable alternative for places like small islands (i.e. with limited chemical demand, limited land to implement RES, and dependence on fossil fuel imports).

CRediT authorship contribution statement

Mar Palmeros Parada: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Serena Randazzo:** Investigation, Writing – review & editing. **Gonzalo Gamboa:** Formal analysis, Investigation, Methodology, Writing – original draft. **Rodoula Ktori:** Formal analysis, Investigation, Methodology, Writing – original draft. **Britte Bouchaut:** Investigation, Methodology, Writing – review & editing. **Andrea Cipolina:** Funding acquisition, Project administration, Writing – review & editing. **Giorgio Micale:** Funding acquisition, Project administration, Writing – review & editing. **Dimitrios Xevgenos:** Funding acquisition, Project administration, Writing – review & editing.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2023.107287.

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