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Social life cycle assessment of a desalination and resource recovery plant on a remote island: Analysis of generic and site-specific perspectives

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ABSTRACT

The sustainable supply of water is crucial, especially on islands where water is scarce. Our study applied the social life cycle assessment (S-LCA), under the organizational approach, to assess industrial water production on the island of Lampedusa, Italy. A novel plant for industrial water production considering a circular concept was compared with the existing linear production plant based on reverse osmosis. An online survey, brief literature review and generic analysis were conducted to prioritize impact subcategories selection for site-specific analysis that regarded six organizations in the system boundaries. These subcategories were Local employment, Access to material resources, Promoting social responsibility, End-of-life responsibility, Health and safety (Workers), and Public commitment to sustainability issues. The social performance of organizations involved was assessed based on equal weighting and weighting with cost values. The generic analysis showed that wastewater treatment in Italy is underdeveloped, and water scarcity can become a serious problem in the future. The site-specific analysis based on equal weighting showed that the novel water plant results in improving social performance for all considered impact subcategories by 88 % to 91 % due to co-production when compared with the existing plant. Even increasing impacts allocation to industrial water production social benefits are still expected due to co-production. The type of weighting based on cost values showed that two organizations are the main contributors to the social performance of the novel system, and improving their corporate conduct can result in improving impacts up to 25 %, such as Public commitment to sustainability issues. To conclude, the novel plan does provide social benefits but mainly due to co-production, thus, it should be investigated more how to apply the S-LCA to linear production systems as they become more circular.
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1. Introduction

Clean, circular and sustainable water supply systems are top priorities to reach a more sustainable society and counteract the increasing pressure on water depletion and ecosystems due to urbanization processes (Re et al., 2021), and other human activities. Furthermore, the reliable supply of sustainable industrial water can be even more critical and challenging in remote islands (Post et al., 2021) where diesel engines are used for electricity generation. This study deals with the application of the social life cycle assessment (S-LCA) on demineralized water production on the Italian island of Lampedusa to understand better the social sustainability of an existing reverse osmosis plant and a circular water plant.

Water is an indispensable good in modern society since it is necessary for various purposes, from human drinking and use as an energy carrier, to the cooling of operating machines (Trapanese and Frazitta, 2018). Thus, the European Union water policy prioritizes access to good quality water in sufficient quantity for all Europeans and sustaining the good status of all European water bodies. The focus is on river basins, freshwater ecosystems and biodiversity, water scarcity, flood risk management, the integration of the Water Framework Directive in other policies, but not on ultra-pure demineralized water which is used in industrial purposes (Dettori et al., 2022). In addition, the supply of clean and sustainable water is one of the priorities of the sustainable development goals (SDG) (Mironenko et al., 2015), as well as for the Italian agenda to achieve a circular economy (Re et al., 2021). However, water losses of the distribution network are a major global problem and

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one of the crucial problems of the Italian water system which performs worse than global average (Laspidou, 2014). Approx. 37 % and 45 % of Italian water is not received by end-users on average at national scale and in the southern islands, respectively (Re et al., 2021).

Desalination is an energy intensive process which is crucial for water supply in islands located far away from the mainland. Islands, such as Cyprus, consume up to 240 GWh of electrical energy per year to produce the desalinated water required, leading to approx. 169 ktons of CO_2 eq. (Xevgenos et al., 2021). However, such remote islands are often not connected to the national grid. Therefore, they typically use a local electricity mix that is largely based on diesel engines (Franzitta et al., 2018). which require a large amount of water for cooling purposes (Shafieian and Khiadani, 2020). The quality of the cooling water used in power plants located on islands can vary significantly. In Lampedusa, desalinated water with conductivity of approx. 400 μS/cm is used. Water for cooling purposes (referred to as industrial water hereinafter) can be produced from seawater with various technologies, such as multi-effect distillation, multistage flash distillation, mechanical vapor compression, electro dialysis reversal, and reverse osmosis (Trapanese and Frazitta, 2018). These technologies or related desalination plants have been investigated for their environmental (Lee and Jepson, 2021) and economic performances (Moossa et al., 2022). However, the social perspective is still underrepresented.

S-LCA is in its infancy and it is still under development (Iofrida et al., 2018). S-LCA employs the same framework as environmental LCA and is promoted by the United Nations for use within the holistic approach of life cycle sustainability assessment (Wulf et al., 2019). S-LCA assesses social and socioeconomic impacts of products, and it consists of four steps (UNEP, 2020). In the first step, the system under study is described in terms of its goal and scope. Next organizational-based (for Type I approach) and/or process-based (for Type II approach) data are collected and organized by impact subcategory on a generic and/or site-specific level of analysis. The generic level of analysis is used for national or sectorial societal "hotspots", while the site-specific level of analysis concerns societal data about specific organizations and/or processes within the system boundaries. In the third step, collected data are characterized into impact subcategories and aggregated into impact categories and/or stakeholder categories. Finally, results are discussed and conclusions and recommendations are presented based on the goal and scope of the study (UNEP, 2020; UNEP/SETAC Life Cycle Initiative, 2013).

Four S-LCA studies have assessed the social impacts of desalination systems with case studies and a perspective study about the application of S-LCA on circular system was recently published (Table 1). Opher et al. (2018) performed a site-specific analysis and investigated the social impacts due to the use of reclaimed domestic wastewater in urban households. Desalinated seawater was the source of their domestic water. These authors selected impact subcategories based on a literature review that included national scale surveys and considered self-developed impacts as well. They concluded that domestic water reuse results in social benefits, mainly due to water savings. Two studies (Tsalidis et al., 2020; Tsalidis and Korevaar, 2019) performed a site-specific analysis to investigate the expected social benefits of four European cases and a generic analysis to investigate social benefits on the national scale for a case that treated industrial wastewater with a high salinity level to recover materials. These authors concluded that site-specific analysis of cases in developed countries results in positive social performance of the companies involved in case studies due to strict national laws. However, Tsalidis et al. (2020) mentioned that the "water consumption" indicator was an area of concern, and Tsalidis and Korevaar (2019) concluded that employing S-LCA may not result in the expected social benefits because local communities and workers may not benefit if the analyzed system has large geographical boundaries. Serreli et al. (2021) employed the PSILCA S-LCA database to assess social impacts of a full-scale plant that treats various kinds of wastewater. They concluded that industrial sectors upstream the full-scale plant are major sources of social burdens. Lastly, a recent perspective study (Tsalidis, 2022a) investigated the application of Type I S-LCA when a linear production desalination plant is converted into a circular desalination plant through the treatment of its wastewater for materials recovery. This study concluded that the quality and quantity of involved organizations is crucial when the Type I approach is applied to compare products or systems.

Hence, to the best knowledge of the authors, there are still no published studies assessing social impacts derived from a seawater desalination system for industrial water production which recovers materials to minimize waste generation, nor have compared the conversion of an actual linear production plant to a circular production plant or have prioritized impact subcategories selection based on water industry expert consultation. This study aims to assess, for the first time, the social impacts of the desalination process for industrial water production in Lampedusa, a remote Italian island. Desalination was represented by two systems, an existing reverse osmosis plant, and a more circular and novel plant. The social impact assessment is carried out using the S-LCA method and both levels of analysis are investigated.

2. Material and methods

The S-LCA guidelines (UNEP, 2020) were followed for the assessment of the social performance and stakeholder categories and impact subcategories were selected based on a literature review and an online survey.

2.1. Case study

Lampedusa is a small remote Italian island of 5000 inhabitants (Faust, 2015) located between Sicily and northern Africa which depends on one single power plant for its electricity generation. The power plant generates electricity with diesel engines and converts seawater into industrial-quality water in a reverse osmosis plant which is integrated into the power plant (Franzitta et al., 2018). The reverse osmosis also

Table 1
Literature overview of S-LCA studies that concerned saline water treatment.

Study	Object of analysis	Level of analysis	Key findings
(Opher et al., 2018)	Reuse of domestic wastewater	Generic	Distributed urban water reuse was socially beneficial due to the promotion of public commitment to conservation of water resources and advancement of community engagement.
(Tsalidis and Korevaar, 2019)	Treatment of saline industrial wastewater	Generic	Social benefits in one country may results in social burdens in another country.
(Tsalidis et al., 2020)	Treatment of saline industrial wastewater	Site specific	National regulations are crucial in positive organizational code of conduct.
(Serreli et al., 2021)	Treatment of industrial wastewater	Generic	The use of a social life cycle assessment database shows that most of the social risks derive from supply sectors.
(Tsalidis, 2022a)	Production of industrial water from seawater	Site specific[a]	Weighing the contribution of organizations to S-LCA results provides valuable insights. The quality and quantity of involved organizations is crucial when the Type I approach is applied.

[a] With imaginary life cycle inventory data.

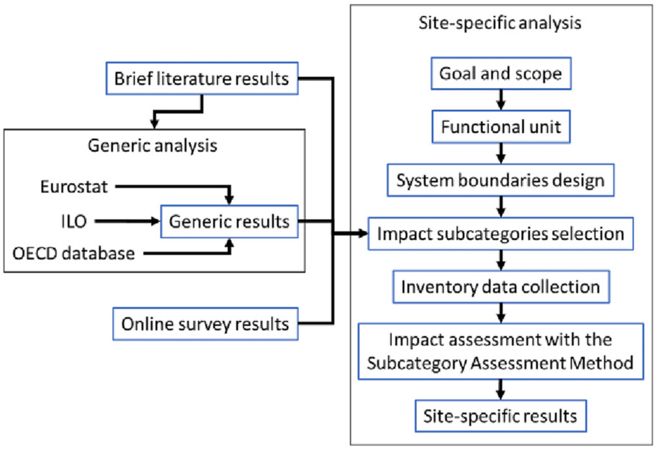

Fig. 1. Block diagram of how the Social LCA was applied.

generates brine which is discharged to the sea. The population of Lampedusa increases greatly, more than 50,000 tourists arrived during the holiday season (ANSA, 2020) resulting in an increased electricity consumption. The industrial water requirements, for the operation of the power plant, demonstrates a seasonal variation from approx. 60 m^3/d in January–February, to 170 m^3/d during summer months. To produce this quantity, a reverse osmosis unit with a capacity of 180 m^3/day is used, with a micro-filtration unit to pretreat seawater. For comparison purposes, the total reverse osmosis capacity to cover the drinking water needs of Lampedusa Island is approx. 3500 m^3/day. However, this system falls outside the scope of our work.

The owner of the power plant aims to replace the industrial water produced by the reverse osmosis plant with a novel desalination plant that produces industrial water and co-products. The novel plant has a capacity of approx. 2.25 m^3/h and employs seawater, while the capacity of the multiple effect distillation unit that recovers industrial water is approx. 2 m^3/h and its design with a forward-feed multiple-effect distillation configuration is presented elsewhere (Xevgenos et al., 2015).

2.2. Social LCA

The application of S-LCA combined the generation of generic analysis results, literature review results and online survey results to better identify impact subcategories for the site-specific analysis. Fig. 1 illustrates the adopted methodology.

2.2.1. Goal and scope definition

The novel plant regards the desalination of seawater to produce industrial water for the local power plant. Industrial water will replace industrial water production from the reverse osmosis plant in the power plant owned also by SELIS Lampedusa S.p.A. Therefore, since both plants are expected to provide the same function, i.e., supply industrial water for the SELIS Lampedusa S.p.A. power plant, the selected functional unit is 1 m^3 of industrial water. Furthermore, sodium chloride, magnesium hydroxide, and calcium hydroxide will also be recovered from seawater in the novel plant.

The system boundaries of the novel system comprised the following chemical processes: nanofiltration, magnesium and calcium crystallization, multi-effect distillation, thermal crystallization, eutectic freeze crystallization, and electrodialysis with bipolar membranes. These processes consume chemicals and electricity, which were identified after consultation with the novel plant operators. More details about the products and the technologies applied to recover such secondary raw materials can be found in (Culcasi et al., 2022) and (Morgante et al., 2022). In contrast, the reference system consists of only one process unit and generates waste (brine) during operation. Fig. 2 shows the system boundaries for the selected functional unit.

2.2.1.1. Multifunctionality. The novel system is multifunctional because it produces six co-products in addition to industrial water (Fig. 1). Two of the six co-products, i.e., hydrochloric acid and sodium hydroxide, are internally consumed. Thus, multi-functionality handled here for the remaining four co-products with economic allocation according to the ISO standard (International Organization for Standardization, 2006). Table 2 shows the allocation factors and the quantities of the salts recovered. These quantities have been calculated using a simulation model for a full-scale plant.

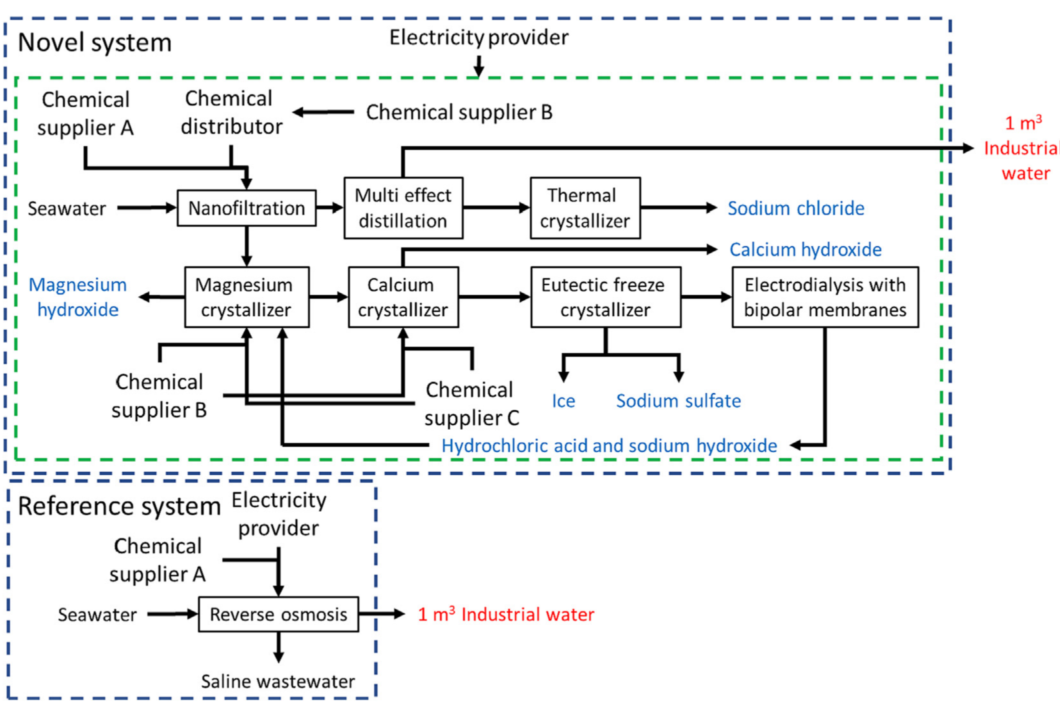

Fig. 2. System boundaries and functional unit of designed systems (FU: 1 m^3 industrial water). (Blue text means co-products of the novel system).

Table 2
Economic allocation factors of the novel system.

Co-product	Price (€/unit)	Amount per FU	Economic allocation factor
Industrial water	1.50 €/m^3	1 m^3	11.1 %
Sodium chloride	0.06 €/kg	58.6 kg	26.1 %
Magnesium hydroxide	1.50 €/kg	5.1 kg	56.8 %
Calcium hydroxide	0.18 €/kg	0.7 kg	0.9 %
Sodium sulphate	0.06 €/kg	11.1 kg	4.9 %

Table 4
Weighting factors for each organization of the novel system.

Organizations	Factor based on cost
Chemical supplier A	0.12 %
Chemical supplier B	0.53 %
Chemical distributor	0.17 %
Chemical supplier C	0.57 %
Electricity provider	43.5 %
Plant operator	55.1 %

2.2.1.2. Social impacts. An initial list of pre-selected social impact subcategories was first gathered from a brief literature review on studies dealing with S-LCA from a generic and site-specific perspective for the chemical industry and circular economy (Tsalidis and Posada, 2021). For instance, occupational health and safety, employment, and access to material resources were investigated by half of the S-LCA studies reviewed (see Fig. S1 in the Supplementary Material). The pre-selected list was then consulted for the final selection of social impacts to be assessed through an online survey distributed between March and April 2022 (Tsalidis, 2022b) to experts in the water sector. The survey considered four characteristics of social and governance issues: simplicity, importance, practicality, and uncertainty. The survey was directly shared with more than 100 experts, and it was completed by 35 respondents from multiple sectors, and primarily European countries. The entire survey can be found in the Supplementary Material. The selected social impact subcategories for the site-specific analysis are presented in Table 3, and the impact subcategories with their indicators used in this study can be found in Table S1. Among the subcategories, only the "End-of-life responsibility" could not be addressed by all considered organizations because consumption of electricity does not result in end-of-life processes.

2.2.1.3. Weighting step. During the weighting step, the practitioner applies weighting factors (values) to reflect the relative importance of inventory, impact subcategory, stakeholder category results. These factors are different from allocation factors because the former regard organizations and the latter co-products. For instance, inventory results derived from contributing organizations that are deemed more significant will have greater weights, so that their associated results show a higher contribution in the impact subcategory results. Even when the step is not mentioned, an implicit form of weighting is still applied, because all contributing organizations are assumed to have equal importance (UNEP, 2020). The weighting factors were calculated based on monetary flows according to prices (see Table 1) and quantities of consumed and recovered materials (see Tables 1 and S1). Table 4 shows the weighting factors for the novel system, which are multiplied with impact subcategory scores per organization. Weighting factors and equal weighting will be presented with stacked bar graphs to show the relative contribution of each organization to the impact scores.

2.2.2. Life cycle inventory

The life cycle inventory for the generic analysis regarded data at national level and the site-specific analysis regarded qualitative and semi-quantitative data collection for involved organizations. Data collection for the generic analysis was performed via public online databases, such as Eurostat, International Labour Organization and OECD, and it corresponds to the years 2017–2020, except for "fatal occupational injuries" and "wastewater treatment" which correspond to 2015 due to the absence or more recent data. The site-specific analysis considered organizations which are crucial for the operation of the novel plant. These organizations are: 1) the Plant operator, 2) Chemical supplier A supplies

Table 3
List of identified impacts subcategories by the literature review, considered impact subcategories of site-specific analysis by this study, and employed indicators (UNEP, 2020).

Stakeholder categories	Impact subcategories	Identified subcategories	Considered subcategories	Considered indicators
Local community	Local employment	X	X	1) Percentage of workforce hired locally, 2) Strength of policies on local hiring preferences, 3) Percentage of spending on locally based suppliers
	Access to material resources	X	X	1) Organizations should establish effective policies, waste management systems and procedures to ensure proper management of unavoidable pollution and waste, 2) Organizations should avoid or minimize the release of hazardous materials, 3) Organizations and suppliers should meet environmental standards or certification schemes
	Safe and healthy living conditions	X		
Value chain actors	Promoting social responsibility		X	1) An organization should make reasonable efforts to encourage organizations in its sphere of influence to follow responsible labor practices. 2) Suppliers and sub-contractors are expected to comply with a code of labor practice or contractual obligations, 3) An organization may find it useful to participate in, or use tools of, one or more initiatives for social responsibility
Consumer	End-of-life responsibility		X	1) Presence of internal management systems ensure that clear information is provided to consumers on end-of-life options
Workers	Health and safety (Workers)	X	X	1) Occupational accidents, incidents and diseases should be notified and reported, 2) Adequate general occupational safety measures are taken. 3) Medical assistance and first-aid should be provided, 4) Access to drinking water should be ensured 5) Documents related to procedures to detect, prevent, minimize, eliminate, or otherwise respond to potential risks to the health and safety of personnel should be delivered and available
	Hours of work	X		–
	Fair salary	X		–
	Freedom of association and collective bargaining	X		–
	Equal opportunities	X		–
	Child labor	X		–
Society	Public commitment to sustainability issues		X	1) Organizations are encouraged to engage in high quality standards for nonfinancial information, including environmental and social aspects, as a commitment to the contribution of sustainable development of the community or society, 2) An organization should, at appropriate intervals, report about its performance on social responsibility to stakeholders affected

Table 5
Involved organizations' characteristics in system boundaries development of the novel system.

Company	Product	Format for data collection
Plant operator	Industrial water	Questionnaire
Electricity supplier	Electricity	
Chemical supplier A	Antiscalant	Questionnaire and reports[a]
Chemical supplier B	Hydrochloric acid	Reports[b]
Chemical distributor	Transportation	Reports[c]
Chemical supplier C	Sodium hydroxide	Reports[d]

[a] (Kurita Group, 2021a, 2021b; Kurita Water Industries Ltd., 2018, n.d.).
[b] (Altair Chimica S.P.A., 2022a, 2022b, 2021, 2019, 2017, n.d.).
[c] (Brenntag, 2021, 2020a, 2020b, 2020c, 2017, 2015, n.d.).
[d] (Solvay, 2021; Solvay Chimica Italia S.p.A., 2021; Solvay, n.d.-a, n.d.-b).

antiscalant employed at the nanofiltration unit, 3) Chemical supplier B and 4) Chemical distributor manufactures and distributes hydrochloric acid employed at the nanofiltration and magnesium and calcium crystallization units, respectively, 5) Chemical supplier C supplies sodium hydroxide employed at the magnesium and calcium crystallization units, and 6) Electricity provider. According to interviews, only the supplier of hydrochloric acid was not identified. Therefore, Chemical supplier B, which is a large Italian chemical manufacturer, was selected for the sake of completeness in this study and complemented with a chemical distributor. The latter shows the effect of the supply chain on social impacts due to distribution. These organizations were contacted and information on company conduct was collected via interviews based on a developed questionnaire and/or sustainability reports. The questionnaire can be found in the Supplementary Material and the inventory data can be found in Table S3. In contrast, the involved organizations in the existing system are the Chemical supplier A, Electricity provider, and the Plant operator. Tables 5 and 6 present the organizations involved and their role in the systems.

2.2.3. Impact assessment

The social life cycle impact assessment (S-LCIA) for the generic analysis investigated national-level indicators, such as labor rights (freedom of association and collective bargaining), fair salary, working hours, occupational safety, circular economy, employment, degree of integrated water resources management (IWRM) implementation (used for SDG indicator 6.5.1), basic sanitation activities, annual freshwater withdrawals (% of internal resources), exports-to-imports ratio, and manufacturing employment as a proportion of total employment (used for SDG indicator 9.2.2). When it was possible these indicators regarded relevant industrial sectors to the case study, such as the a) electricity sector due to the local power plant and electricity consumption, b) manufacturing sector due to the consumption of chemicals, and c) water supply sector due to the wastewater treatment and provision of industrial water. Alternatively, they were assessed on a national scale. In both cases, the European Union was considered a benchmark to identify social hotspots.

The site-specific S-LCIA was performed with data collection from questionnaires and/or sustainability reports from the organizations involved. Using the Type 1 SLCIA approach implies defining reference scales for considered subcategories (Traverso et al., 2022). The Subcategory assessment method (SAM) (Ramirez et al., 2014) was used to perform the site-specific analysis. With SAM qualitative data can be converted into semiquantitative data. This way, SAM can compare different data types in a standardized manner and arrive at meaningful results. For this purpose, score value points were calculated based on basic requirements which were certifications based on ISO, national and international agreements. Therefore, the organizational performance is calculated at four levels (A = 1, B = 2, C = 3, or D = 4) for each social impact subcategory based on the achievement of the basic requirement, as presented in Table 7, and peers' organizational conduct. Score value A = 1 shows the best social performance while D = 4 shows the worst social performance. The basic requirements and description of score values per subcategory can be found in Table S2 and Tables S3–10, respectively. Lastly, for both novel system and existing system, organizational performance was aggregated by subcategory to assess the systems' social performance. The aggregation occurred by averaging the indicators results in each subcategory and organization and summing up the indicators averages to calculate the impact subcategory score.

Table 6
Involved organizations' characteristics in system boundaries of the existing system.

Company	Product	Format for data collection
Plant operator	Industrial water	Questionnaire
Electricity supplier	Electricity	
Chemical supplier A	Antiscalant	Questionnaire and reports[a]

[a] (Kurita Group, 2021a, 2021b; Kurita Water Industries Ltd., 2018, n.d.).

Table 7
Score (value points) for SAM levels.

Value points	SAM levels
D = 4	The organization does not comply with the basic requirement in a positive context
C = 3	The organization does not comply with the basic requirement in a negative context
B = 2	The organization complies with the basic requirement
A = 1	The organization has positive and proactive behavior beyond the basic requirement

3. Results and discussion

3.1. Generic analysis results

The literature review showed that Workers and Local community are the most investigated stakeholder categories in S-LCAs of chemical industry cases (Tsalidis and Posada, 2021). Furthermore, the results of the online survey showed that the experts evaluated ‘human health and safety’, ‘human right’, and ‘responsibility’ as the most important issues, ‘employment’ and ‘training’ as the most practical to measure, and ‘human right’, ‘standard of living’, ‘corporate ethics’, ‘accountability’, and ‘responsibility’ as the least practical to measure and most uncertain. These results can be found in the Supplementary Material. Therefore, social indicators from Workers, Local community, and Society stakeholder categories were compared with the average of the European Union to identify social

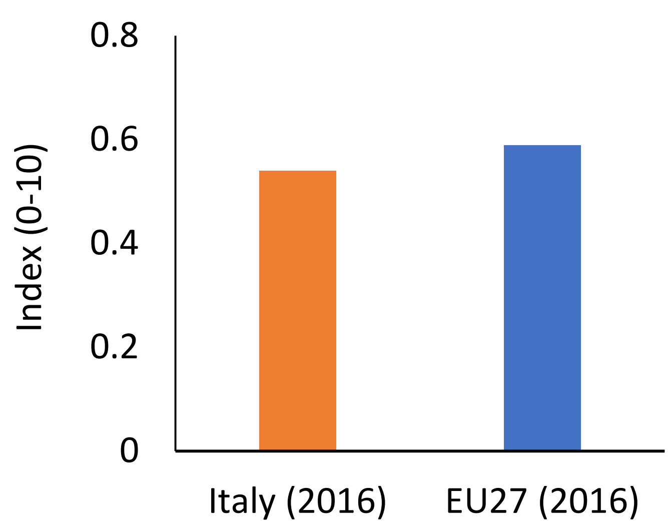

Fig. 3. Level of national compliance with labor rights (freedom of association and collective bargaining [FACB]) for Italy and the EU27 average, with 0 being the best possible score (indicating higher levels of compliance for FACB rights) by 2016 (International Labour Organization, 2022b).

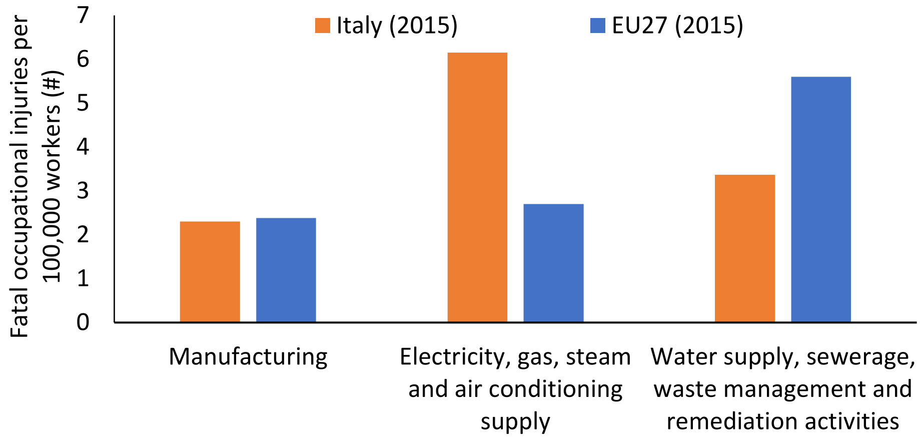

Fig. 4. Fatal occupational injuries per 100,000 workers in Italy (orange bars) and in the EU27 (blue bars) for relevant economic sectors in 2015 (International Labour Organization, 2022a).

hotspots (Eurostat, 2020a, 2020b, 2020c, 2018; International Labour Organization, 2022a, 2022b, 2022c; OECD, 2022; Simpson et al., 2020) to screen impact subcategories for the site specific analysis.

Figs. 3 and 4 refer to indicators of the Workers category. Fig. 3 shows that the level of national compliance with fundamental labor rights in Italy which is approximately the same as the European Union average. The constitutional rights of employment are laid out in the Italian constitution (International Labour Organization, 2011) which gives all citizens the right to work and receive fair pay, and also dictates the maximum work hours and guarantees paid vacations. Furthermore, Italy's minimum wage is larger than 68 % and 39 % than the lower and upper bounds of living wage, respectively. Since 1987, the Italian Department of Labor limits the maximum work hours to 48 h a week. On average Italian employees work more than the average of the European Union (Fig. S2) (OECD, 2022). This corresponds to 2 % higher work hours annually. However, in particular for the economic sectors related to the organizations indicated in Table 1, Italian employees work in average less time than the European average (International Labour Organization, 2022c), which is an opposite trend compared to the national average of all sectors included. This difference is minimal for the manufacturing and electricity sectors, but it is approx. 2 h/week for the water supply and treatment sector.

In addition, employees in manufacturing, water supply and treatment sectors work more safely with fewer fatal occupational accidents compared to the average EU27 (Fig. 4). In contrast, fatal occupational accidents in the Italian electricity sector are more than double the average in the European Union, which might be attributed to Italian firms (in general) not complying with tougher safety measures (Giuffrida, 2021). Furthermore, the Italian average of fatal accidents is higher than the European average due to the electricity, construction, agriculture, forestry, and fishing sectors combined.

Figs. 5–7 show hotspot social indicators regarding the Local Community and Society stakeholder categories. Similarly, to the indicators analyzed for the Workers category, the hotspot results for the Local Community category are compared to those of the European Union average. In general, in Italy more people use at least basic sanitation services than the average of the European Union (Fig. 5). The objective of basic sanitation services is to maintain hygienic conditions, through services such as garbage collection, industrial/hazardous waste management, and/or wastewater treatment and disposal. However, the use of wastewater treatment is lower in Italy than the average in the European Union, where Italy ranked 11th place in European Union according to Wolf et al. (2022). Generated Italian urban wastewater is collected by individual systems, such as domestic treatment plants and septic tanks, instead of centralized collecting systems and treatment plants. Furthermore, in 342 municipalities, which correspond to approx. 1.4 million inhabitants (2.4 % of the total population), the urban wastewater treatment service is absent. Advanced purification plants represent 12.9 % of the total plants, while treating 66.7 % of the actual generated polluting loads (Italian National Institute of Statistics, 2018). In addition, the Italian freshwater withdrawal is higher than the European Union average (Fig. 6). The Italian household water use from public water supply per citizen was the third highest in Europe, after Greece and Cyprus (Eurostat, 2022).

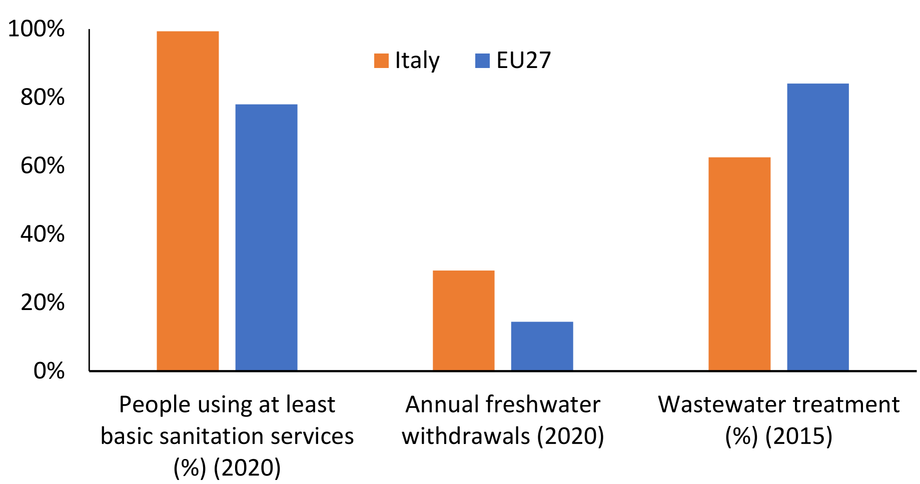

Fig. 5. Water consumption and treatment based on: a) percentage of citizens using at least basic sanitation services, b) wastewater treatment, and c) annual freshwater withdrawals (Simpson et al., 2020).

According to SDG target 6.5, by 2030 IWRM should have been implemented at all levels (United Nations, n.d.). Fig. 7 shows that Italy ranks lower than the European Union average according to the degree of IWRM implementation (Fig. S3) (Simpson et al., 2020). Italy scores high according to the UN in indicators “Enabling environment”, “Institutions and participation”, and “Management instruments”, but much lower in “Financing”.

According to the European Commission (2021), there are 137 products in the most sensitive ecosystems where the EU is highly reliant on imports from third-party countries. Therefore, material security is important, and the EU plan for circular economy has identified critical raw material, as well as fostering efficient use and recycling. Fig. 6 shows that there is an increasing trend in using recycled material and feeding back into the economy both in Italy and Europe. In Italy, there is larger use of recycled material than the European Union average. However, Italy was below the EU average in 2018 with respect to private investments, jobs, and gross value added related to the sectors of the circular economy (Fig. S4) (Eurostat, 2018), while still being a bigger net importer than EU average by approx. 30 % in 2020 (Eurostat, 2020b) (Fig. S5).

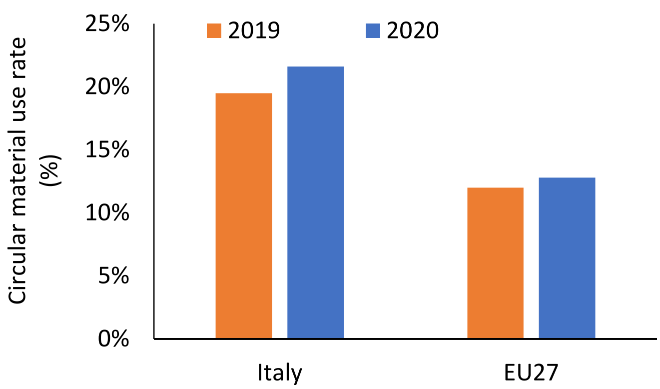

Fig. 6. Percentage of material recycled and feedback into the economy (Eurostat, 2020a) in 2019 and 2020.

Italian unemployment has risen dramatically in the last 10 years, it reached of 21 % at a rate of 10 % (Montanini and Barbabella, 2021). In 2020, the unemployment rate decreased in Italy, while the opposite occurred in EU27 (Fig. 7). Nevertheless, the unemployment rate is higher in Italy than EU27. In particular, Italy has the 3rd highest unemployment rate among the EU27 (after Greece and Spain), reaching 9.2 % (2.3 million unemployed people) in 2020, against the EU27 average of 7.1 % (Eurostat, 2020c).

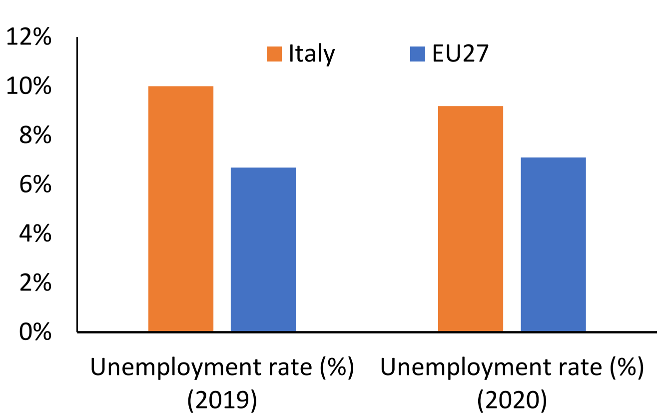

Fig. 7. Unemployment rate (%) in Italy and EU27 (Eurostat, 2020c) in 2019 and 2020.

According to the generic analysis, working conditions, working hours, and employment in Italy, and minimization of waste production while secondary materials are recovered are potential social impacts which should be investigated. Therefore, “Health and Safety (Workers)”, “Local employment” and “Access to material resources” will be investigated by the site-specific analysis.

3.2. Site-specific analysis results

Fig. 8 compares the production of industrial water by the novel system with industrial production by the existing reverse osmosis plant. The industrial water production by the novel plant results in an improvement of the six considered social impact subcategories, in the range of 87 % to 91 % compared to the reverse osmosis plant. One of the reasons for the lower social impacts of the novel system (which is a positive feature) is the fact that it generates several co-products and industrial water has a lower price than the co-products, even though it is produced in greater quantity. Furthermore, social impacts are allocated to these co-products with the economic allocation factors (Table 1). In particular, industrial water is assigned to the second largest allocation factor, and most social impacts are allocated to the recovery of magnesium hydroxide. Fig. S1 in Supplementary Material shows the total score if multi-functionality is not considered, and therefore if the entire social performance was attributed to the industrial water.

For the novel system, “Public commitment to sustainability issues” and “Local employment” are the impact subcategories that perform the worst with 1.8 and 1.7, respectively. The “Local employment” score for each involved organization is slightly higher than level B (on average) because the organizations did not have policies to hire locally or spend on local suppliers, which in both cases would benefit the local community. Among them, only the Chemical supplier A spent a large percentage (approx. 79 %) on local suppliers. In contrast, other organizations mentioned that it is of minor significance to their business model to invest in local or regional purchasing, or they did not have policies of preferences for hiring employees coming from close by communities or did not mention criteria for local suppliers in the core suppliers' assessment.

Regarding “Public commitment to sustainability issues” most organizations complied with the basic requirement and got a B = 2 score on both indicators, but none of the organizations exceeded level B on average. Only, chemical supplier B scored A = 1 on engaging in high quality standards for nonfinancial information (including environmental) indicator because they voluntarily joined the European “Eco-Management and Audit Scheme” to evaluate and improve their environmental performance. In contrast, the Electricity provider and Plant operator scored D = 4 because they do not encourage organizations/suppliers to engage in high-quality standards for non-financial actions, including environmental and social aspects, nor produce reports at appropriate intervals (e.g., yearly).

In contrast, “End of life responsibility” gets the best averaged results with 0.9 (or B = 2 score when all co-products are considered), due to Chemical supplier C engaging with major customers on common high materiality aspects and involved organizations having the certification for quality management systems. Missing data for the Electricity provider and Plant operator may have an effect. However, it is not possible to quantify the “End of life responsibility” for a non-physical product such as electricity.

The scores of the rest of the subcategories range between 1.4 and 1.6, in descending order, “Promoting social responsibility”, “Occupational health and safety”, and “Access to material resources”. The “Health and safety (Workers)” performance is acceptable because organizations have acquired ISO or Occupational Health and Safety Assessment Series (OHSAS) certifications for occupational health and safety, and work takes place in Europe where national laws are strict. The Chemical distributor is an outlier since it does not publicly report occupational accidents neither document procedures related to risks minimization; at

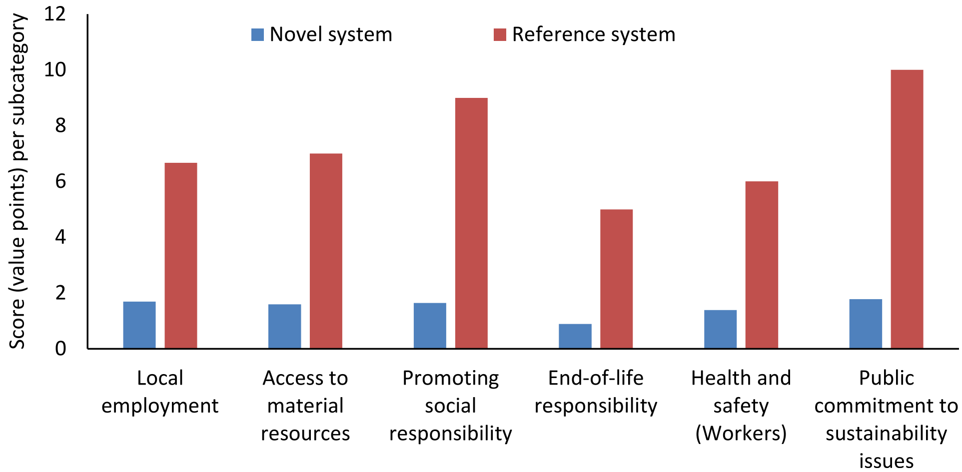

Fig. 8. Subcategory assessment results of the site-specific analysis, with equal weighting factors.

the same time, they were the only organization that involved employees directly by asking their own safety representatives' opinions.

The "Promoting social responsibility" performance is mainly influenced by the Electricity provider and Plant operator since no information could be publicly found about the organizations making reasonable efforts to encourage organizations in their sphere of influence to follow responsible labor practices. In contrast, the Chemical supplier C has the suppliers' code business and suppliers fully cooperate in ensuring that they can responsibly source minerals that do not support conflict or human rights abuses. The rest of the organizations comply with the basic requirements of having a supplier code of conduct where audits are carried out to confirm that the suppliers respect the code.

Additionally, the "Access to material resources" performance is affected by the Chemical supplier C, Electricity provider, and Plant operator. Although the Chemical supplier C acquired ISO 9001 for environmental management, it is currently being investigated for criminal activity with respect to the disposal of hazardous waste in the local river in Italy (Martinuzzi and Silver, 2022). The Electricity provider and Plant operator do not meet environmental standards or certification schemes because none is acquired. The rest of the organizations comply with the basic requirement due to the acquisition of certifications, such as ISO 14001 Environmental management systems (Kurita Water Industries Ltd., 2018), or explicitly requesting suppliers to meet environmental criteria (Solvay, n.d.-b) or assessed with EcoVadis (Brenntag, 2020a).

Lastly, the reference system (i.e., the reverse osmosis and its suppliers) shows similar performances per subcategory because it comprises a smaller group of the same organizations with the novel system. For instance, similar to the novel system, the reference system performs the worst in the "Public commitment to sustainability issues", and results in the best scores regarding "End-of-life responsibility" and "Health and safety (Workers)". One worthy difference regards the "Local employment" and "Promoting social responsibility" scores. "Local employment" is among the better scores because Chemical supplier A performs much better than the other organizations of the novel and reference systems. Similarly, "Promoting social responsibility" is among the worse scores because the additional organizations performed relatively better than Chemical supplier A, Electricity provider, and Plant operator.

As explained in Section 2.2.3, the aggregated scores presented in Fig. 9 are composed of the contribution from each organization to each of the six social impact subcategories. Fig. 10 shows a stacked bar graph of the contribution analysis for equal weighting. All organizations

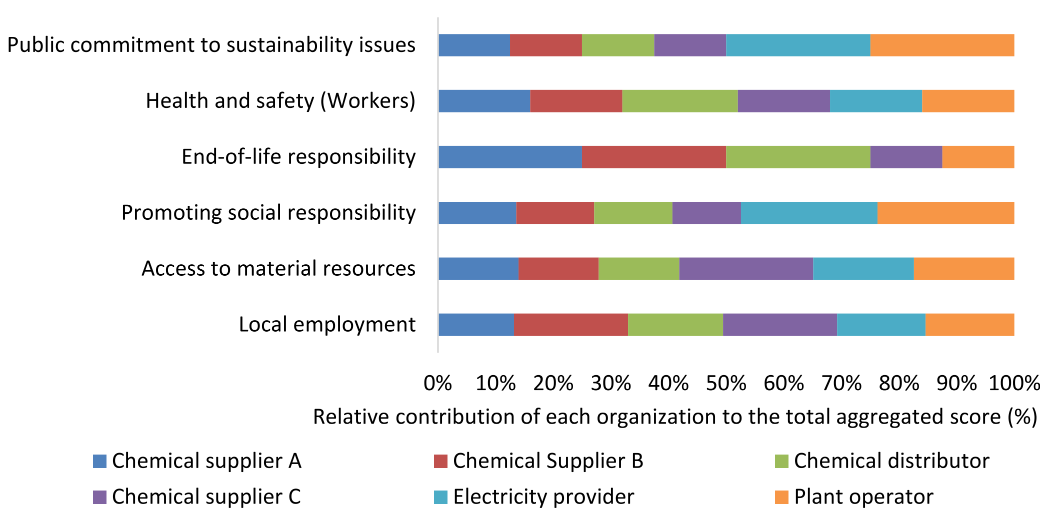

Fig. 9. Contribution analysis of social impact subcategories results for industrial water production (FU: 1 m^3) via seawater desalination with the novel system under the site-specific analysis, with equal weighting factors.

contribute to all impact subcategories. The Chemical suppliers A and B, and the Chemical distributor have comparable contributions to the Chemical supplier C and Plant operator due to equal weighting factors and achieving the basic requirement. Contributions range between 13 % and 25 %, i.e., no organization contributes less than 13 %, and no organization contributes more than 25 % without the use of weighting factors. The average contribution is 17 % due to having six organization comprising the system boundaries.

Fig. 10 shows a stacked bar graph of the contribution analysis results for each of the six subcategories when cost weighting factors are applied. Due to weighting, the results changed. The results are affected mainly by the Electricity provider, approx. 44 % (for five out of the six assessed social impact subcategories), and the Plant operator, approx. 55 % (for five out of the six assessed social impact subcategories). Furthermore, the contribution of the latter is approx. 96 % for "End of life responsibility" due to not assigning a score to the Electricity provider. The "Promoting social responsibility" and "Public commitment to sustainability issues" scores became higher than Fig. 12 (equal weighting) because the Electricity provider and Plant operator score relatively low on these subcategories, while the other subcategories improved or remained the same. In particular, the "End-of-life responsibility" improved but this is a result of not assigning a score to the Electricity provider for "End-of-life responsibility". The low amounts of chemicals usage (due to recovery), combined with low overall cost contribution of antiscalant, sodium hydroxide, hydrochloric acid, and distribution of the latter, resulted in low financial weighting factors for these suppliers making their contributions to the aggregated social impacts virtually irrelevant (in the range of approx. 0.1 %–0.6 %) for all assessed subcategories.

3.3. Sensitivity analysis of uncertain parameters

3.3.1. Effects of major contributors

Among the considered organizations, the Chemical supplier B and Chemical distributor were the only proxy organizations used due to not identifying a supplier of hydrochloric acid during the interviews. Chemical supplier B was selected because it is a large Italian chemical manufacturer, and the Chemical distributor is a large German company that distributes chemicals with offices and warehouses in various European locations (Italy included). Both organizations and the Chemical supplier A contribute to the subcategory results when equal weighting is used. However, when financial weighting factors are used, these organizations do not affect the results due to the low amount of hydrochloric acid and antiscalant purchased. Therefore, a sensitivity analysis is focused on the Chemical supplier C, Electricity provider and Plant operator.

The Electricity provider and Plant operator perform in general worse than the rest organizations because of their size and no promotion of social responsibility to their value chain actors. However, both organizations perceive social responsibility as an important aspect, thus, a future development of suppliers' code of conduct and acquisition of ISO certifications could improve the social performance of the novel system. In addition, the Chemical supplier C is under investigation for criminal activity (Martinuzzi and Silver, 2022) affecting its score on "Access to material resources". Fig. 11 shows how the social impacts assessment for the six subcategories would result, under the site-specific analysis and with equal weighting factors, if the Chemical supplier C is found not guilty and if it improves its conduct in Italy, and if the Electricity provider and Plant operator will develop a suppliers' code of conduct based on human rights, occupational health and safety, and acquire ISO 45001 and 9001. Fig. 11 illustrates this effect on the subcategories whether the Electricity provider and Plant operator, and Chemical supplier C improve develop policies and improve their conduct, respectively, i.e., a decrease on the impacts, with rectangles with straight diagonal lines. The score of "Access to material resources" is reduced by 16 % mainly due to Chemical supplier C improvement. "Promoting social responsibility" and "Public commitment to sustainability issues" are reduced by 14 % and 25 %, respectively, mainly due to the Electricity provider and Plant operator. Therefore, there is significant room for improvement for both Electricity provider and Plant operator.

3.3.2. Effect of economic allocation factors

The selected prices of the products correspond to the desired qualities. However, the targeted quality of magnesium hydroxide as a product of the novel systems may be challenging or result in additional costs due to other consumables needed. Therefore, in this section, we analyze how sensitive the impact subcategory results are with respect to the recovery of magnesium hydroxide. The price of recovered magnesium hydroxide was reduced significantly in case the highest purity cannot be achieved in the recovery steps and some impurities may still exist. Therefore, its price was reduced from 1.5 €/kg to 0.5 €/kg. This change resulted in an increase in the economic allocation factors for industrial water and other co-products (i.e., sodium chloride, calcium hydroxide, sodium sulphate). In particular, for industrial water the economic allocation factor increased from 11.1 % to 17.9 %. Furthermore, the new economic allocation factors are 42.1 %, 30.5 %, 1.5 %, and 8.0 % for sodium chloride, magnesium hydroxide, calcium hydroxide, and sodium sulphate, respectively. The new allocation factor for industrial water resulted in an increase of all impact subcategories by 62 %. Fig. 12 shows that there are still social benefits even when lower quality magnesium is recovered.

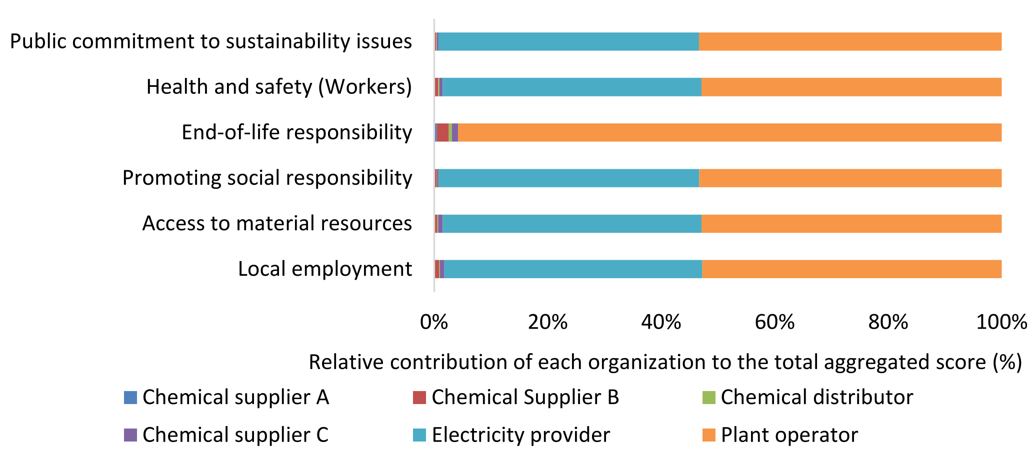

Fig. 10. Contribution analysis of social impact subcategories results for industrial water production of the novel system (FU: 1 m^3) via seawater desalination with the novel system under the site-specific analysis, with financial weighting factors.

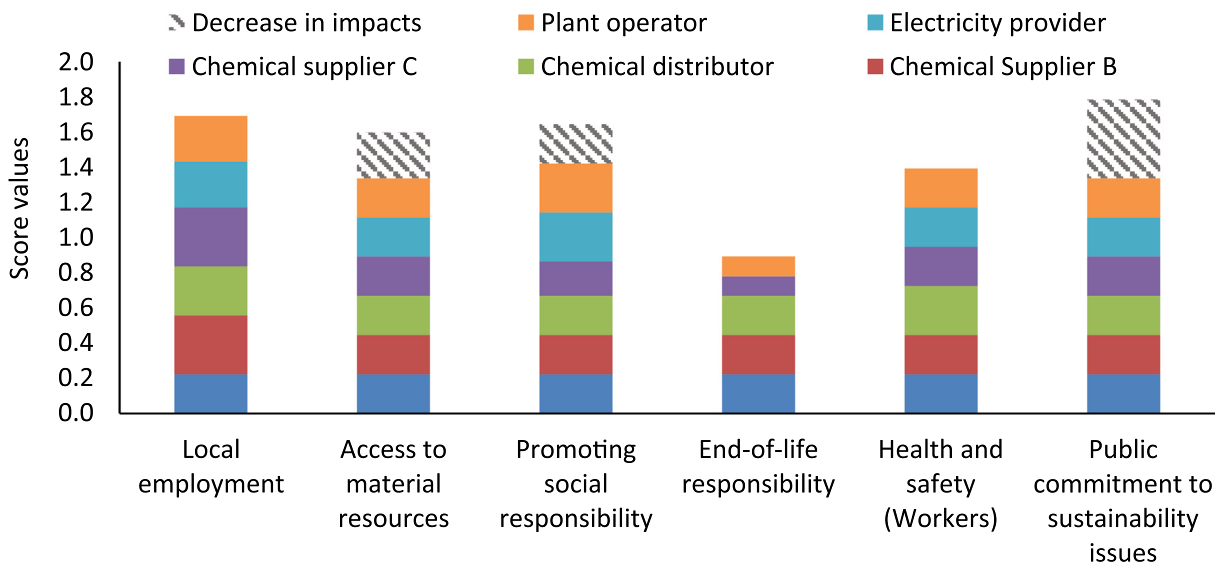

Fig. 11. Sensitivity analysis of social impact subcategories results for industrial water production of the novel system (FU: 1 m^3) via seawater desalination with the novel system under the site-specific analysis, with equal weighting factors, and decrease in impacts (rectangle with straight diagonal lines).

3.4. Limitations

The results of this study provide a social performance assessment of the organizations involved in the supply chain of the analyzed product line. A limitation is the number of investigated impact subcategories. Although these impact subcategories were considered the most relevant for the case based on generic analysis, literature review, and online survey, these six subcategories still represent a small fraction of all subcategories in the Guidelines. Furthermore, when data collection with the questionnaire was not possible, data was collected from public annual reports focusing on specific plants where consumed chemicals were manufactured. On the other hand, when the questionnaire was distributed, only one person from the organization filled it in. Both facts constitute limitations due to the potential omission of plant-specific data and personal bias. However, it is impossible to include all impact subcategories in the assessment due to data needs, and data collection from more than one person in an organization is challenging when the organization is not directly collaborating with the S-LCA practitioners. The S-LCA method comes with a significant limitation when site-specific analysis is performed; no database can be built for site-specific analysis. This results in great data needs for the S-LCA practitioners. Lastly, a major limitation is allocation. In environmental-LCA, handling allocation is a standard solution to allocate system inputs and outputs to co-products. However, in the case of S-LCA, allocating social effects to co-products may not be needed. The Guidelines mention that the allocation depends on the nature and scope of the social data. For instance, allocation may be irrelevant when assessing indicators and impacts that are not measured at the product level (e.g., external effects, such as disrespect of indigenous rights, delocalization of local communities, etc.) (UNEP, 2020). Fig. S1 shows the S-LCA results without applying allocation. In this case, and since the novel system consists of more involved organizations, the organizational-based approach results in worse social performance than the reference system. Finally, the selection of allocation type will affect the social impact scores. This study applied economic allocation because one product exiting the water plant gate is in liquid form, while the rest are solids. Instead, if mass allocation were applied then according to Table 2, 99.5 % of the social impacts would be allocated to industrial water and the results would be very similar to Fig. S1.

4. Conclusions

This study assesses the social impacts of a novel desalination plant to produce industrial water from seawater, and also compares the social

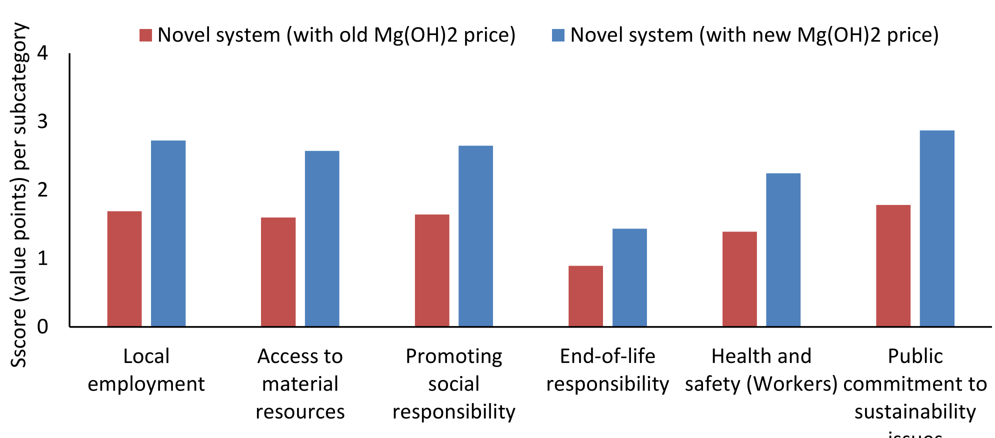

Fig. 12. Sensitivity analysis of subcategory assessment results for lower prices of magnesium hydroxide of the site-specific analysis for industrial water production of the novel system (FU: 1 m^3) via seawater desalination with the novel system under the site-specific analysis, with equal weighting factors.

impacts of the novel plant with respect to a conventional industrial water plant based on reverse osmosis, at Lampedusa (Italy) through the application of the social-LCA method. Surveying water experts and the literature review in combination with the generic analysis provided insights regarding which impact subcategories should be selected for the site-specific analysis. The novel desalination plant provides social benefits even if the recovered products will be sold at a lower value than expected and two are the stakeholders which contribute to the results highly.

The generic analysis showed that wastewater treatment in Italy is underdeveloped, and water scarcity can become a serious problem for Italy. Additionally, Italian employees work less but less safely than European average, and the Italian economy is still a net importer of goods. Therefore, for S-LCA case studies of the Italian water supply and treatment, “Local employment”, “Access to material resources” and “Occupational health and safety” subcategories should be investigated.

The site-specific analysis showed that the novel system results in social benefits with respect to the reference system for all impact subcategories due to co-production. The use of weighting factors shows that two organizations are the main contributors to social performance (i.e., Electricity provider and Plant operator). Furthermore, a sensitivity analysis showed that improving specific aspects of the conduct of these organizations can result in benefits in “Promoting social responsibility”, “Public commitment to sustainability issues”, and “Access to material resources”. According to the generic and site-specific results, the Plant operator and the Electricity provider should be certified for health and safety of employees.

It is recommended to aim and collect more site-specific data from the involved organizations in the system boundaries, and to develop scenarios for the supply of hydrochloric acid based on former suppliers of the Plant operator. This way, the used S-LCA results can provide additional valuable insights to decision makers of the Plant operator and Electricity provider in order to select a supplier that can help to improve the social performance of the novel system. Finally, due to the fact that the novel plan provides social benefits due to co-production, it is recommended to investigate further how to apply the type I approach of S-LCA to linear production systems as they become more circular.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.03.017.

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