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Contribution of capital goods production to social impacts: A life cycle perspective for a circular desalination plant

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ABSTRACT

The production of capital goods is often ignored in the life cycle inventory phase of life cycle assessment studies. In this study, we investigated whether capital goods production, i.e., manufacturing of capital equipment and construction of infrastructure, and operation affect the results of the social life cycle assessment (S-LCA), using a case study of a desalination plant with multiple co-products in Lampedusa, Italy. The assessment was conducted using the PSILCA database to evaluate 20 impact subcategories and four stakeholder categories: Workers, Value chain actors, Society and Local community. Monetary data were collected for the manufacturing of equipment, labor and miscellaneous work during plant construction, working hours of employees during operation, consumed electricity and chemicals, and recovered materials during operation. Furthermore, multi-functionality was addressed through substitution, system expansion, and economic allocation to examine how these approaches affected the results. The functional unit was 1 m^3 industrial water. Equipment manufacturing and plant construction contributed up to 15% to stakeholder categories and between 2% and 75% to impact subcategories of the substitution approach, and up to 51% for impact subcategories of system expansion and economic allocation. Equipment manufacturing and plant construction contributed to a high extent to "Health and safety" (of Workers), "Discrimination" and "Local employment" due to the construction and electrical sectors. Credits in substitution lead to a lower contribution of the operational stage and negative societal impact values. If S-LCA practitioners must limit the considered impact subcategories, for generic or site-specific analysis, the "Health and safety" (Workers), "Local employment", and "Fair salary" should be investigated.

1. Introduction

The transition to a more circular economy is essential to the EU's efforts to develop a sustainable, low-carbon, resource-efficient, and competitive economy. However, the construction of a circular economy infrastructure is not tracked (Green Alliance, 2019), current industrial infrastructure operates primarily for a linear economy, and the construction stage of infrastructure is often ignored in the life cycle inventory phase of environmental life cycle assessment (LCA) studies (Martín-Gamboa et al., 2020) and social life cycle assessment (S-LCA) (Pollok et al., 2021; Tragnone et al., 2022). The former may be valid if the analyzed product systems have direct emissions throughout their life cycle but can be misleading for product systems with no direct emissions or circular systems that recover materials from waste. In this study, we investigated the validity of including capital goods production in S-LCA. Our objective was to provide a starting point for discussion on whether S-LCA practitioners should disregard the social impacts derived from labor due to the construction of infrastructure and manufacturing of equipment in production systems. Therefore, we modeled a case study in which we considered the construction of infrastructure, equipment manufacturing, and the operation of a circular water plant.

Environmental LCA is a standardized method for quantitatively assessing the environmental impacts of products throughout their life cycle (International Organization for Standardization, 2006a, 2006b). However, the ISO standardized only the LCA phases. As a result, most environmental LCA studies systematically disregard certain processes,

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such as 1) extraction and conversion of raw materials used for construction and/or operation of capital goods (buildings, installations and machinery), 2) construction and production of capital goods, and 3) demolition and disposal of capital goods (Yang et al., 2021). However, these life cycle stages associated with the construction, use, and disposal of capital goods may still significantly contribute to the overall environmental or social impacts of a product.

For simplicity, in the remainder of the document, the term "capital goods" will include the supply chain, i.e., extraction and conversion of raw materials needed to produce capital goods (such as infrastructure and equipment), and labor and miscellaneous tasks required to produce such capital goods. Furthermore, the term "plant construction" refers only to labor and miscellaneous tasks during the plant construction stage.

This omission or consideration of capital goods production in environmental LCA studies depends on the Goal and scope definition phase. As a general rule of thumb and since LCA is data intensive, environmental LCA practitioners were recommended to cut-off contributors smaller than 5% to environmental impacts (Zampori et al., 2016). Therefore, LCA systems with direct emissions, such as fossil-based systems (Laurent et al., 2018), biofuel-based systems (Mann and Spath, 2001; Mukoro et al., 2021), and agricultural systems (European Commission, 2018), often ignore environmental impacts due to infrastructure construction and the production of capital goods. For instance, the recent European product environmental footprint category rules for wine production (European Commission, 2018) recommend disregarding the production of tractors within the system boundaries. In contrast, environmental LCA studies of renewable energy (Mukoro et al., 2021) and buildings (Bahramian and Yetilmezsoy, 2020) have shown the significance of the infrastructure construction stage.

S-LCA employs the same framework as environmental LCA, and the United Nations recently published the second version of the S-LCA guidelines (UNEP, 2020). One of its differences from environmental LCA is the fact that analysis occurs on two levels, on a macro-level with a generic assessment and/or on a micro-level with a site-specific assessment. The generic assessment investigates national or sectoral societal "hotspots". The site-specific assessment investigates societal data about specific organizations and/or processes in the supply chain. Consequently, databases exist only for generic assessments. Two commercial S-LCA databases are available, the Social Hotspot Database (Benoit-Norris et al., 2012) and Product Social Impact Life Cycle Assessment (PSILCA) database (Maister et al., 2020). Both databases assess social impacts at the national sectoral level, but only PSILCA aligns with the S-LCA guidelines in terms of social impact subcategory calculation.

Since 2018, 12 peer-reviewed studies have used the PSILCA database. These studies investigated societal issues that occur during the operation of waste treatment (Martin and Herlaar, 2021; Serreli et al., 2021), mining (Di Noi et al., 2020; Muller et al., 2021), energy (Werker et al., 2019; Martín-Gamboa et al., 2020), mobility (Bouillass et al., 2021), educational (Erauskin-Tolosa et al., 2021), and product manufacturing systems (Hannouf and Assefa, 2018; Herrera Almanza and Corona, 2020; Andrade et al., 2022; Wang et al., 2022). However, most of these studies excluded equipment manufacturing and infrastructure construction. For instance, Bouillass et al. (2021) and Werker et al. (2019) considered the manufacturing of cars or electrolyzers in their system boundaries but not the machinery that produced these products. Furthermore, Werker et al. (2019) did not report any contribution to the manufacturing of the electrolyzer in the final results. Except for the study by Martín-Gamboa et al. (2020), Muller et al. (2021), and Wang et al. (2022), no other studies mentioned impacts due to equipment or infrastructure. Martín-Gamboa et al. (2020) included the plant construction stage and assessed five social impacts. These authors concluded that plant construction contributes only to "Women in the sectoral labor force" due to the high number of working hours for construction which results in increased working hours of workers. Muller et al. (2021) reported that manufacture of mining equipment in the UK led to off-site social impacts, such as "Indigenous rights", "Minerals consumption", "Association and bargaining rights", "International migrant stock", and "Biomass consumption". Finally, Wang et al. (2022) included capital goods, and they were the only study that considered labor costs. These authors reported that activities related to the house construction (including labor) dominate important social issues, such as "Association and bargaining rights", "Industrial water depletion", "Fair salary", and others. However, the extent to which labor costs affect these social issues has not yet been reported. Table 1 lists the relevant key parameters in the systems design.

Therefore, it is unclear whether the inclusion of the capital goods production stage (including labor) in the system boundaries affects the S-LCA results. Furthermore, to the best of our knowledge, no study has assessed the effect of equipment manufacturing and labor during plant construction on the production of industrial water. This study aims to showcase, for the first time, whether the production of capital goods, plant construction, and labor due to operation should be considered as important contributors to social impacts in S-LCA studies. Therefore, a case study was designed for an innovative desalination plant in Italy. The PSILCA database is used to assess the societal impacts of capital goods production, plant construction, and operations.

2. Methodology

2.1. Case study

Desalination plants produce drinking or industrial water from seawater. However, in the circular economy context, desalination plants can also recover valuable materials such as magnesium or calcium salts,

Table 1
Peer-reviewed studies that used the PSILCA database.

Study	Object of analysis	Plant construction cost	Capital goods	Operation
(Hannouf and Assefa, 2018)	Polyethylene production	Not considered	Not considered	Considered
(Werker et al., 2019)	Hydrogen production	Not considered	Only the electrolyzer	Considered
(Di Noi et al., 2020)	Raw materials industries	Not considered	Not considered	Considered
(Herrera Almanza and Corona, 2020)	Shirt retailing in the Netherlands	Not considered	Not considered	Considered
(Martín-Gamboa et al., 2020)	Electricity generation	Considered	Considered	Considered
(Serreli et al., 2021)	Wastewater treatment	Not considered	Not considered	Considered
(Martin and Herlaar, 2021)	Waste wool valorization	Not considered	Not considered	Considered
(Muller et al., 2021)	Mining cerussite ore	Not considered	Considered	Considered
(Erauskin-Tolosa et al., 2021)	University operation	Not considered	Only computers	Considered
(Bouillass et al., 2021)	Mobility	Not considered	Only the vehicle	Considered
(Andrade et al., 2022)	Agricultural product	Not considered	Not considered	Considered
(Wang et al., 2022)	Industrial LED lighting	Considered	Considered	

which can be sold to local markets. The case study concerns an innovative integrated process implemented in Lampedusa, a small island in the Mediterranean. The plant had a capacity of approx. 2.25 m^3/h, treats seawater to produce industrial water for the local power plant, and recover added value chemicals, such as magnesium hydroxide, calcium hydroxide, sodium sulfate, sodium hydroxide, and hydrochloric acid. Therefore, the desalination plant consists of nanofiltration, multi effect distillation, crystallization, and electrodialysis process units. Detailed information on this case study can be found in the work of Tsalidis et al. (2023).

2.2. PSILCA

This study was conducted using the PSILCA database v3.0 (Maister et al., 2020). PSILCA is available in the open-source LCA software, OpenLCA (www.openlca.org). PSILCA employs the EORA multiregional input/output database (Anon, 2015) to provide social indicators for 189 countries and approximately 15,000 sectors, based on monetary flows among sectors. 65 qualitative and quantitative social indicators are structured according to the Guidelines for S-LCA (UNEP, 2020). These indicators are quantified in medium-risk-hours (mrh), i.e., hours with an average risk of occurrence of a social impact. PSILCA employs worker-hours as the activity variable to represent the time needed to produce 1 USD of output of a sector and to quantify the impact indicators of a product throughout its life cycle. To use the PSILCA, economic data were collected regarding the materials and energy used to build and operate the circular desalination plant.

2.3. Social LCA

This study followed the Guidelines. Thus, the LCA framework of the 1) Goal and Scope Definition, 2) Inventory Analysis, 3) Impact Assessment and 4) Interpretation phases are presented in the following sections.

2.3.1. Goal and scope of the study

This study aims to assess the social impacts of capital goods and the operation of a circular desalination plant in Lampedusa (Italy). The analysis considered the monetary flows of equipment, labor, materials, and the electrical input of a large demonstration plant. The plant produces industrial water for the power plant and recovers secondary materials. In total, the plant will operate for 20 years at 8000 h per year. Therefore, all flows and impacts were normalized to the functional unit of 1 m^3 of industrial water.

Fig. 1 shows the boundaries of the cradle-to-gate system, where the green dotted line represents the technical aspects of the desalination plant, while the blue dotted line represents the entire system under study, desalination plant, and labor for its operation. Black, purple, and blue fonts represent consumables, waste, and products, respectively. Seawater is treated with nanofiltration to generate a retentate stream rich in magnesium and calcium, and a permeate stream rich in sodium chloride. The retentate was sequentially treated with magnesium and calcium crystallization units to recover magnesium hydroxide and calcium hydroxide, respectively. The remaining flow from the crystallizers was treated by eutectic freeze crystallization and electrodialysis with bipolar membranes to recover the remaining minor quantities of sodium sulfate, hydrochloric acid, and sodium hydroxide. The permeate was treated by multi-effect distillation and thermal crystallization units to separate and recover industrial water and sodium chloride.

The objective of the desalination plant is the production of industrial water. However, the plant produces several marketable co-products as well. It was not possible to subdivide processes per co-product as suggested by ISO (International Organization for Standardization, 1998, 14,041). Therefore, multifunctionality is handled in three ways, 1) substitution, 2) system expansion, and 3) economic allocation. Regarding substitution, the co-products are assumed to replace the same commercial products; thus, calculations include the avoided social issues in the form of credits. Moreover, system expansion resulted in an expansion of the functionality of the system to consider all the co-products. Finally, economic allocation concerned the distribution of the inputs and outputs of the desalination plant among the co-products based on the economic values of the recovered quantities. The economic allocation factors are listed in Table 2.

Table 2
Economic allocation factors of the desalination plant system; prices were obtained from (Tsalidis et al., 2023).

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%

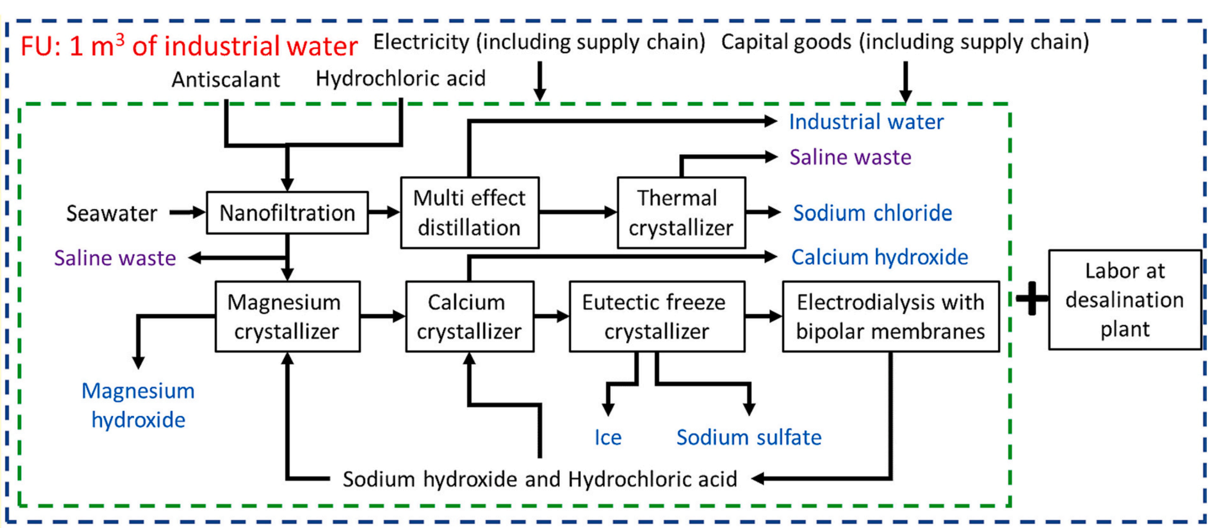

Fig. 1. System boundaries for S-LCA of desalination plant. Black, purple, and blue fonts represent consumables, waste, and products, respectively. FU stands for functional unit.

2.3.2. *Inventory analysis*

The datasets were collected from the PSILCA database to model the product system. These data regarded the kind of input materials for capital goods production and operation (see Table S1), the origin of materials for capital goods production and operation, the EORA MRIO database category where the materials for capital goods production and operation belong to, the total cost of each input material for capital goods and operation, and the working hours needed to operate the desalination plant. Only in the case of the nanofiltration unit, the unit's price was communicated by the commercial supplier in The Netherlands instead of considering its materials inventory. Tables 3 and 4 summarize the input data, country of origin, and EORA economic sector for capital goods and operations, respectively. A detailed version of Table 3 with the specific material requirements per process unit is provided in Table S1 of the Supplementary Material.

2.3.2.1. *Assumptions.* The material inputs for the equipment are listed in Table S1 and were provided by technology suppliers. The material inputs for consumables and energy inputs can be found in (Tsalidis et al., 2023). All material inputs were entered into openLCA as monetary values. The technology suppliers of the thermal crystallization and eutectic freeze crystallization units did not exist in the project consortium, and it was not possible to collect material input data from commercial suppliers of these technologies. Therefore, material inputs for the manufacturing of thermal crystallization and eutectic freeze crystallization units were assumed to be the same as those for the magnesium and calcium crystallization units because they had similar input volumes. Furthermore, the recovered magnesium hydroxide and sodium chloride were expected to be of commercial grade purity, which means that they are marketable at competitive prices (see Table 1). In addition, the relationship between labor and material costs in the built construction industry varies widely depending on the sub-sector and the type of work being completed. Therefore, we assumed the labor and miscellaneous costs of plant construction to be approx. twice the cost of equipment (Austin, 2021). Last, it was impossible to collect data on the average salary of the employees of the circular water plant owned by the power plant. Therefore, based on the functional unit (1 m^3) and capacity, the working time was calculated and converted to monetary flows according to the median salary in the Italian water sector (Instituto Nazionale Previdenza Sociale, 2023).

2.3.3. *Sensitivity analysis*

A sensitivity analysis was performed to determine the effect of the labor cost of the desalination plant and Labor and miscellaneous costs due to construction on the results. The effects of increasing or decreasing the annual salary by 20% (Table 4) was investigated. Moreover, the effect of the labor and miscellaneous costs (Table 3) being the same as the equipment cost or three times the equipment cost, instead of two times, was investigated.

Table 3
Input cost data for capital goods production and plant construction.

Equipment	Flow (USD 2015)	Origin	EORA sector
Nanofiltration (NF)	43,275	Netherlands	Machinery & equipment n.e.c .[a]
Multi-effect distillation (MED)	38,229	Italy	Machinery & equipment n.e.c. [a]
Thermal crystallizer	2943 [b]	Italy	Machinery & equipment n.e.c.[a]
Mg and Ca crystallizers - Multiple Feed – Plug Flow Reactor (MF-PFR)	2943	Italy	Machinery & equipment n.e.c.[a]
Eutectic freeze crystallizer (EFC)	2943 [b]	Italy	Machinery & equipment n.e.c.[a]
Bipolar membrane electrodialysis (EDBM)	21,857	Italy	Machinery & equipment n.e.c.[a]
Labor and miscellaneous	224,382	Italy	Construction

[a] n.e.c. stands for "not elsewhere classified".
[b] Assumed to be the same cost as magnesium and calcium crystallizers.

Table 4
Input and output monetary flows for operation, per operation hour; prices were collected from (Tsalidis et al., 2023).

	Flow (USD 2015)	Origin	EORA sector
Inputs			
Antiscalant	0.04	Italy	Chemicals, chemical products & man-made fibres
Hydrochloric acid	0.20	Italy	Chemicals, chemical products & man-made fibres
Sodium hydroxide	0.16	Italy	Chemicals, chemical products & man-made fibres
Electricity	12.49	Italy	Electrical energy, gas, steam & hot water
Labor	29,214[a]	Italy	Sewage, sanitation and similar activities
Outputs			
Industrial water	1.98	Italy	Chemicals, chemical products & man-made fibres
Sodium chloride	2.44	Italy	Chemicals, chemical products & man-made fibres
Magnesium hydroxide	8.99	Italy	Chemicals, chemical products & man-made fibres
Calcium hydroxide	0.18	Italy	Chemicals, chemical products & man-made fibres
Sodium sulfate	0.92	Italy	Chemicals, chemical products & man-made fibres

[a] The labor cost (salary) is presented on an annual basis.

2.3.4. *Impact assessment*

This characterization step is provided in PSILCA by the "social impacts weighting method". Moreover, the risk level for a sector is provided by the database and is entered on the output side. The activity variable was then used to "characterize" the indicators. The characterization factors are expressed on an ordinal scale and classified into six levels based on the sector and the origin country: "no risk" = 0, "very low risk" = 0.01, "low risk" = 0.1, "medium risk" = 1, "high risk" = 10, "very high risk" = 100 and missing values (no data) equal to "very low risk". The social impacts weighting method assigns characterization factors to the various indicators per sector. The working hours of each process were used as activity variable to quantify the social risk. The social impacts weighting method employs the characterization factors of each input (specific to sector and country) and the working hours of every process to calculate the social risk, in medium-risk-hours (mrh). For instance, let us assume that the forced labor indicator for process A has a low-risk characterization factor of 0.1, and that the working hours of process A correspond to 10 h to manufacture product A, which corresponds to 1 USD. Then, to calculate the impact of manufacturing 3 USD for product A, 0.1 is multiplied by 10 and 3 to result in 3 mrh. Table S2 lists the stakeholders, subcategories, and indicators used in our study from the database (Maister et al., 2020). Finally, Fig. 2 shows how the characterization results are calculated and aggregated by stakeholder category based on equal weights and three multifunctionality handling approaches: 1) economic allocation, 2) system expansion, and 3) substitution.

3. Results

The results were grouped by multi-functionality handling approach, i.e. substitution, system expansion and economic allocation (see Figs. 3–5, respectively) and aggregated by impact subcategory (see Figs. 6–9). Detailed (i.e., not aggregated) results are also presented by social indicators per subcategory as required by the Guidelines (UNEP,

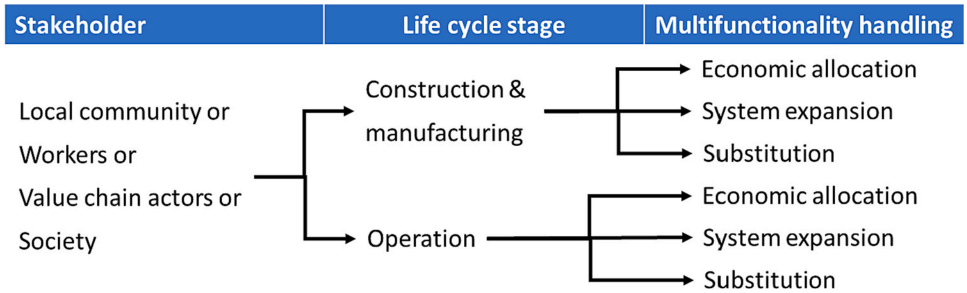

Fig. 2. The stakeholders, subcategories, and indicators from the PSILCA database (Maister et al., 2020).

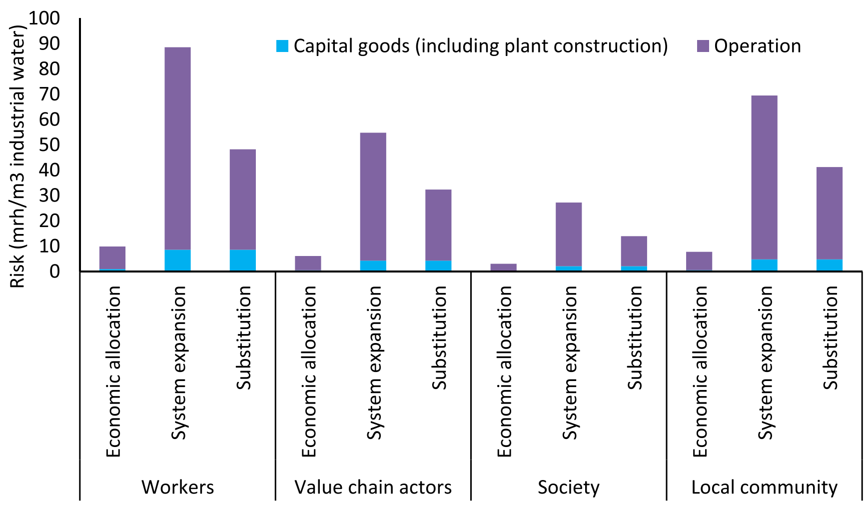

Fig. 3. Contribution of capital goods production and operation to risk results by stakeholder category and multifunctional handling approach.

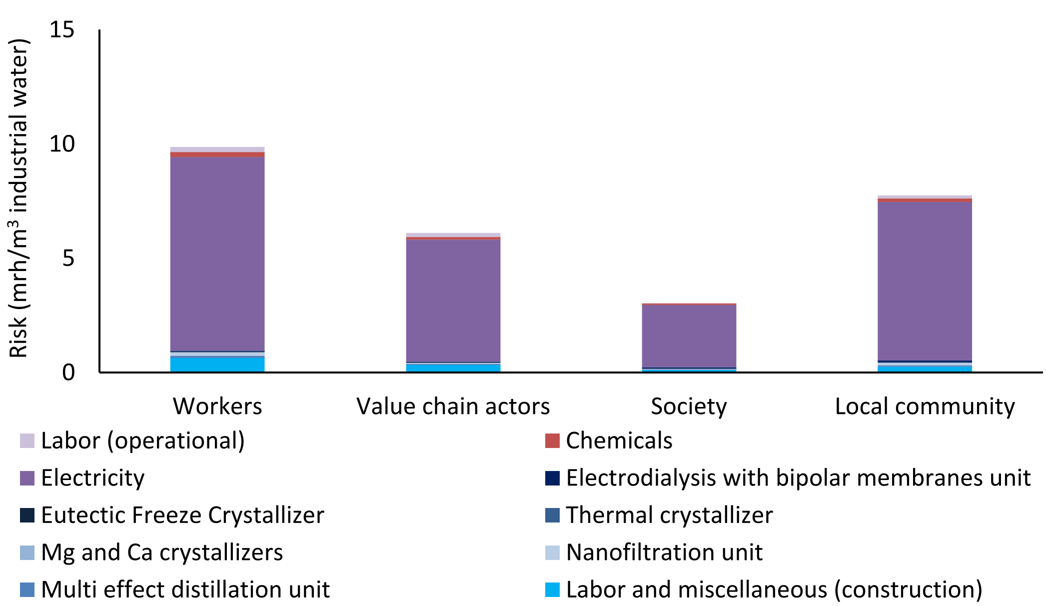

Fig. 4. Contribution of capital goods production and operation to economic allocation results by stakeholder category.

2020) to avoid "losing" information during aggregation and ensure the transparency of the study. The non-aggregated results can be found in the Supplementary Material Tables S3-S5.

3.1. *Stakeholder categories*

Fig. 3 shows the total risk results due to capital goods production and construction and operation based on all the multifunctionality handling approaches and grouped by stakeholder category. The production of capital goods affects all stakeholder categories, to a certain extent. This

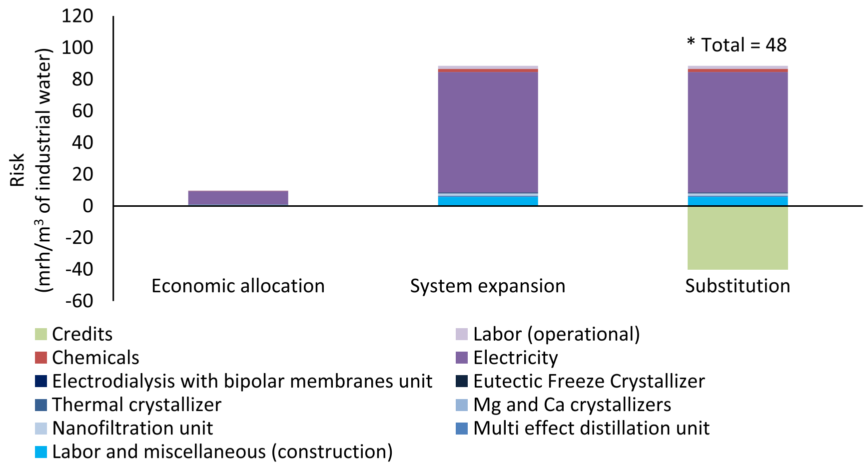

Fig. 5. Contribution of capital goods production and operation to Workers results by multifunctionality handling approach.

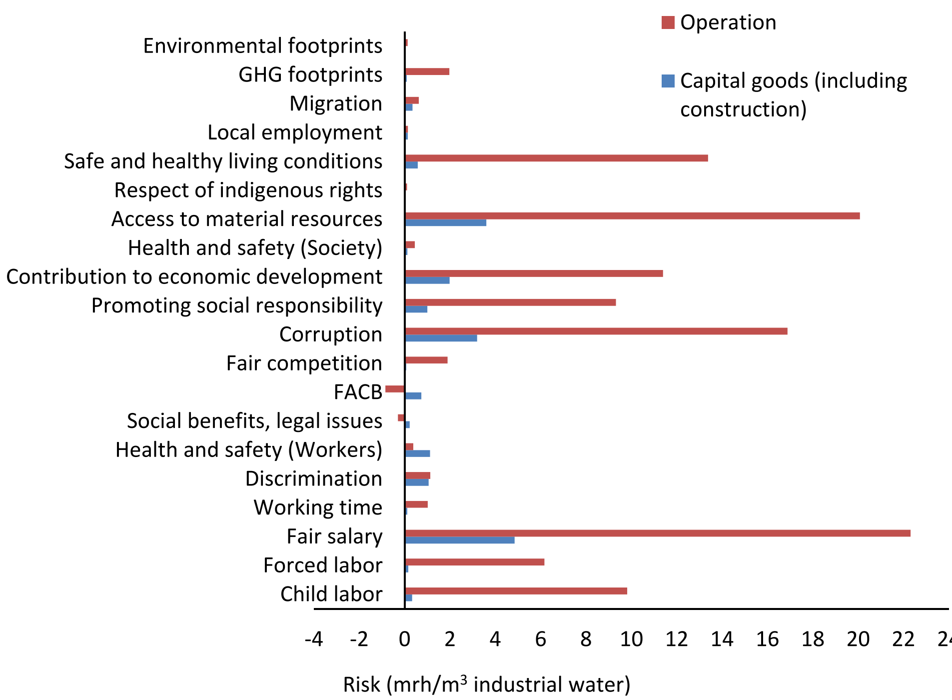

Fig. 6. Results by impact subcategory for capital goods production and operation of the desalination plant according to the substitution approach; FACB stands for Freedom of association and collective bargaining.

contribution ranges between 12% and 18% for substitution with the inclusion of avoided risk hours (due to credits) (see Fig. S2) and between 7% and 10% for system expansion (see Fig. S1), and between 7% and 10% for economic allocation (Fig. 4). Fig. 4 shows the contribution of infrastructure construction, equipment manufacturing, operational parameters, and credits due to chemicals avoided to risk results when economic allocation is performed. Figs. S1 and S2 in the Supplementary Material show the same parameters when the system expansion and substitution are applied, respectively. These ranges depend on the absolute risk values for construction stage, equipment manufacturing, and operational stage. In absolute values, the risk hours due to capital goods production are the same for the substitution and system expansion approaches, whereas for economic allocation they are scaled down by approx. 89% due to the economic allocation factor of industrial water (Table 2).

For all stakeholder categories, the calculated risks for operation are higher when the system expansion approach is applied, followed by the substitution and economic allocation approaches (see Fig. 3). Substitution results in higher risks than economic allocation with respect to capital goods production for all stakeholders. Economic allocation results in the lowest risk for all stakeholders owing to industrial water isolation. These risk results differ by approach, because the multifunctionality problem stems from the fact that LCA isolates a product in a production system, wherein various products can be brought forward by single processes or systems (Heijungs et al., 2021). The system-expansion approach expands the goal and scope of the system to include all consumables and products. The substitution approach also included all consumables and co-products in the form of societal credits (i.e., negative numerical values). In contrast, the application of economic allocation isolates industrial water production according to the recovered amount and price from co-products.

Substitution results in the largest relative (%) contribution of capital goods to subcategories results because credits are subtracted by the risk values derived from operation. Fig. 5 shows that the contribution of

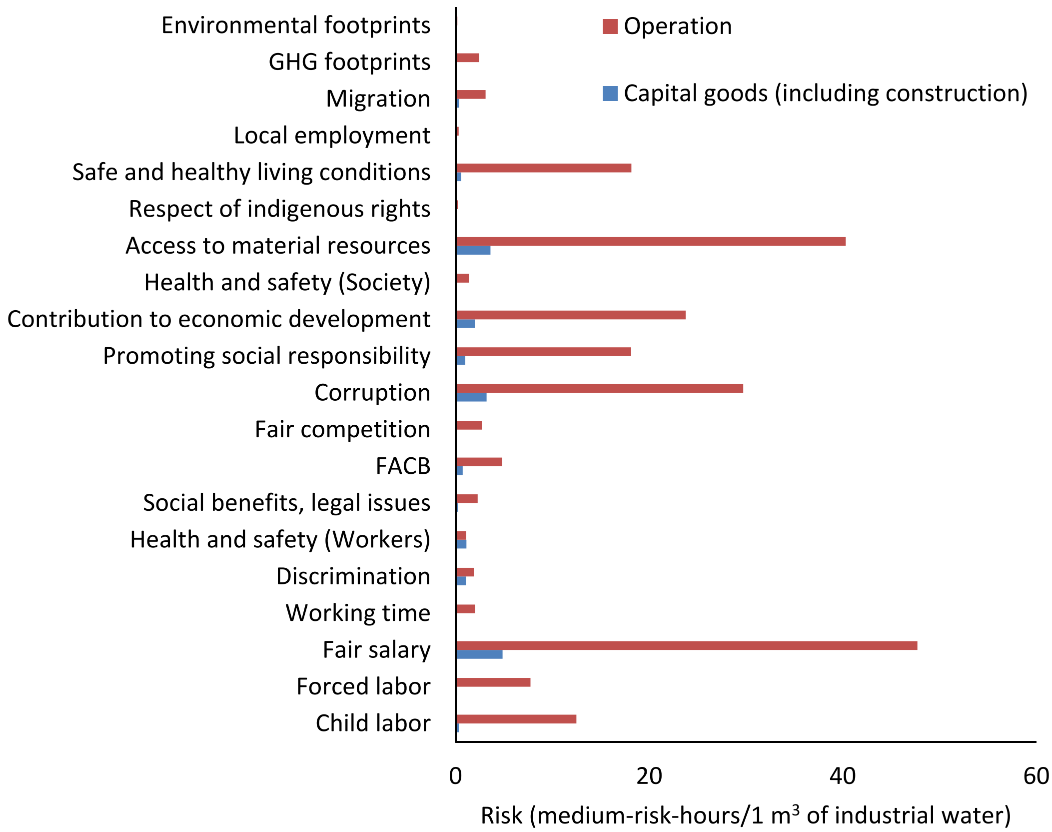

Fig. 7. Results by impact subcategory for capital goods production and operation of desalination plant according to the system expansion approach; FACB stands for Freedom of association and collective bargaining.

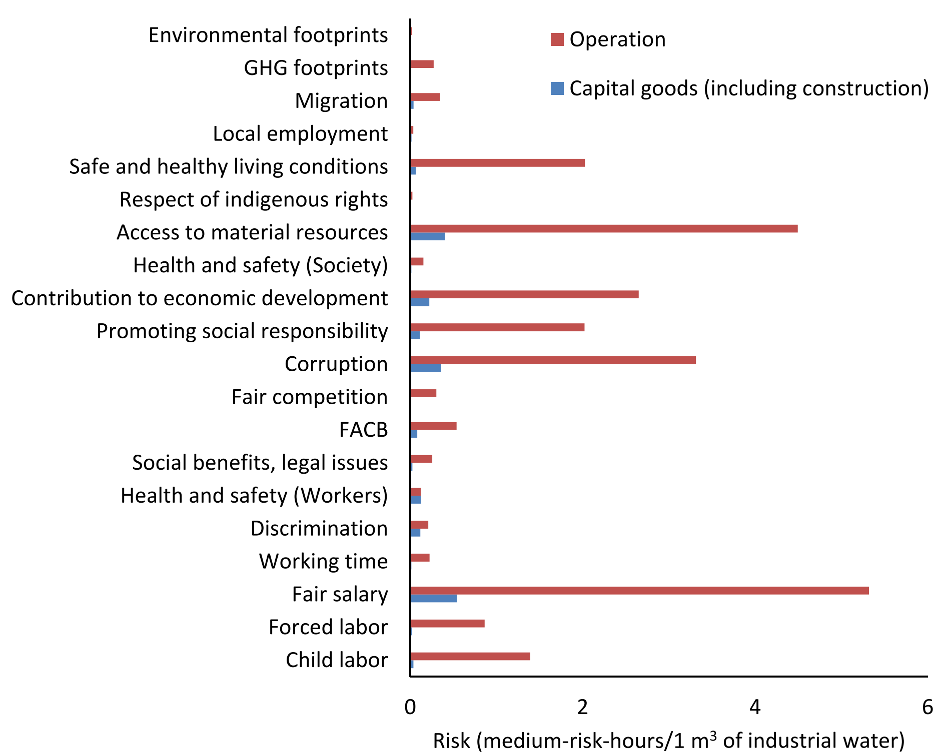

Fig. 8. Results by impact subcategory for capital goods production and operation of desalination plant according to economic allocation approach; FACB stands for Freedom of association and collective bargaining.

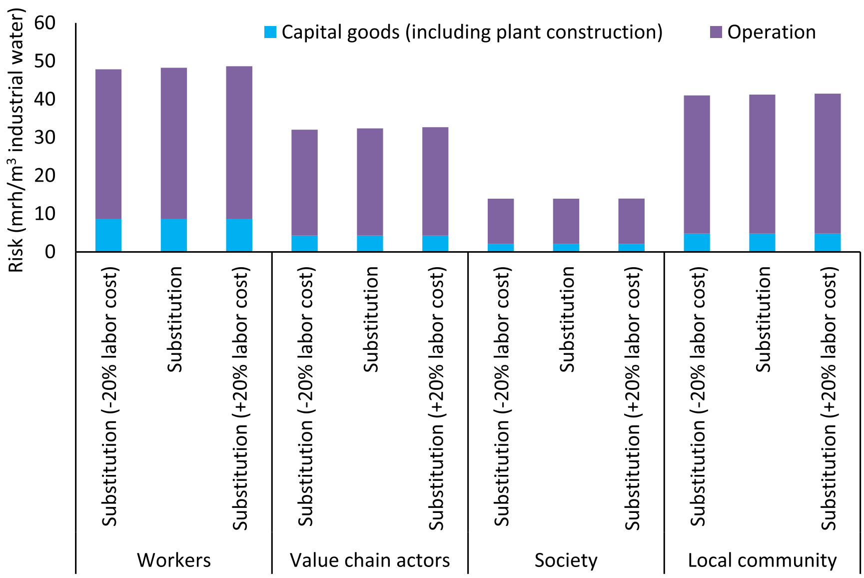

Fig. 9. Sensitivity analysis results of labor costs of substitution approach.

capital goods production ranges between 10 and 18% for the Workers stakeholder category; the other stakeholders can be found in Supplementary Material Figs. S3-5. A recent review of environmental LCAs of circular systems concluded the same effect, because practitioners consider environmental credits and reduce environmental indicator scores to very low or negative values (Ingrao et al., 2018). In such cases, capital goods production may significantly contribute to the overall impact. However, system expansion and economic allocation approaches result in the same relative (%) contributions to all impact subcategories for capital goods production and operation. However, this was expected because allocation employs weighting factors to isolate a product in a production system, and risk hours due to capital goods production and operation are allocated to each co-product in an equal manner.

The Workers, Local Community, and Value chain actors categories have the highest risks, in decreasing order for all approaches. On the one hand, the Workers and Local Community comprise the most impact subcategories in the integrated 'social impacts weighting method' in PSILCA. On the other hand, the Value chain actors comprise only three impact subcategories but these impact subcategories comprise indicators with medium to very high risk levels that result in high indicator results. In particular, the electricity supply and plant construction contribute highly to "Fair salary" which is a social hotspot for Workers category. Furthermore "Corruption" and "Promoting social responsibility" are also identified as hotspots for Value chain actors, and "Access to material resources" and "Safe and healthy living conditions" are hotspots for Local Community, despite the credits due to material recovery.

3.2. Subcategories with substitution approach

Fig. 6 presents results by impact subcategory according to the substitution approach. The non-aggregated results are presented in Table S3. In this case, the operation stage dominates 17 out of 20 subcategories, such as "Child labor", "Forced labor", "FACB", and "Safe and healthy living conditions". Consumables during the operation contributed between 37% and 82% of the total. The "Electrical energy, gas, steam & hot water" sector is the largest contributor in positive risk-hours values due to electricity supply, while the "Chemicals, chemical products & man-made fibres" sectors are the largest contributors in negative risk-hours values (i.e., credits) due to the recovery of chemical products which are categorized to the operation stage. This categorization of the operation stage results in a decrease in the total social risk of operation due to the subtraction of credits and consequently increases the relative contribution of capital goods production (i.e., manufacturing of equipment and plant construction).

In contrast, subcategories with lower risk values, such as "Working time", "Local employment", and "Health and safety" (Workers), have capital goods production in Italy as a large contributor. Plant construction (labor and miscellaneous work, see Table 3) is the second largest contributor to "Discrimination", "Migration", "Fair salary", "Corruption", and "Access to material resources" subcategories due to risks occurring in Italy. Indicators contributing to the "Migration" subcategory have a high risk value because the net migration rate in Italy was the second largest in Europe (World Bank, 2018). In addition, the Italian construction sector scores badly in terms of "Corruption" and "Fair salary". The subcategory "Access to material resources" consists of risk indicators for "Fossil fuel consumption", "Level of industrial water use", "Minerals consumption", "Biomass extraction", and "Certified environmental management system", and "Biomass extraction" is the most contributing indicator. It is worth noting that the construction sector uses various materials, such as bioplastics and composites, and chemical compounds. These products can be obtained from different types of biomass, including oil and protein crops, starch and sugar plants, forestry resources, herbaceous plants, and organic industrial co-products or by-products. Last, regarding the overall contribution of plant construction to capital goods, plant construction dominates "Fair salary" (69%), "Corruption" (81%), "Health and Safety" (Workers) (88%), and "Discrimination" (92%) subcategories.

In this study, the recovered materials are regarded as chemical products that replace the same products produced by the chemical sector in the Italian market. Hence, such replacement results in negative results for "Social benefits, legal issues" and "FACB" subcategories (in Fig. 6). The resulting risk values of these negative flows are a combination of *i)* the recovered materials in monetary units (see Table 2), *ii)* the number of indicators per subcategory, and *iii)* the risk levels of Italian indicators. In particular, large societal benefits due to credits are calculated for "Fair salary", "Access to material resources", "Corruption", "Contribution to economic development", and "Promoting social responsibility". For the Workers category, the Italian "Fair salary" consists of five indicators and shows a very high risk level due to low "Living wage per month" and "Living wage, Lower bound" indicators. Furthermore, regarding Local community category, "Access to material resources" has seven indicators (see Table S3) and shows a very high risk level for

"Extraction of biomass" and high risk level for "Level of industrial water use" and "Certified environmental managements systems" indicators. For the Value chain actors category, "Corruption" comprises two indicators and shows a very high risk level of the Italian "Public sector corruption" indicator, and "Promoting social responsibility" comprises only one indicator "Membership in an initiative that promotes social responsibility along the supply chain" which shows a very high risk level. Last, for the Society category, "Contribution to economic development" results in a high positive value due to having nine indicators. In contrast, minor societal benefits due to credits are calculated for "Migration", and "Health and safety" (Society) due to these subcategories having low or very low risk levels. The social issue "Health and safety" (Society) was expected to be high because the current Italian health expenditure per capita was 11th in Europe (World Bank, 2020). Nevertheless, it should be noted that even though chemicals production will not be "avoided" in different countries, such as China, India, etc., it is uncertain if local communities and workers of those countries will be affected due to the large distances from Italy (Tsalidis and Korevaar, 2019).

3.3. Subcategories with system expansion approach

Fig. 7 presents results by impact subcategory according to the system expansion approach. In this case, the operation stage dominates the results of almost all subcategories, except for "Health and safety" (Workers) (49%). The main contributors of "Health and safety" (Workers) are plant construction and electricity, with expected risks occurring in Italy, not in foreign countries which belong to the supply chain for raw materials supply. Other impact subcategories with relatively high contribution of capital goods are "Discrimination" (36%), "Local employment" (30%), "Respect of indigenous rights" (15%), "Corruption" (10%), and "Fair salary" (9%). Once more, plant construction is the main contributor to the social risks of capital goods, but social risks due to operation are so high that the contribution of capital goods becomes insignificant. Based on system expansion, absolute risk values due to capital goods production are the same as in the substitution approach, but the exclusion of credits results in higher relative positive risk values at the operation stage. This increase was not linear, and ranged from 7% to 127%. The largest average increase (39%) by stakeholder is found for Workers, followed by Society (37%) and the Local Community (18%). In particular, "Social benefits, legal issues" and "FACB" show an increase greater than 121%, "Health and safety" (Society) an increase of 50%, and "Respect of indigenous rights" and "Migration" an increase of 29% and 91%, respectively. In general, the supply of electricity and chemicals contributed between 49% and 98% of the results of the operation stage (see Fig. 3 and Table S4).

3.4. Subcategories with economic allocation approach

Fig. 8 presents results by impact subcategory according to the economic allocation approach. In this case, the operation dominates the results of almost all the subcategories, except for "Health and safety" (Workers) (49%). In this case, the relative results are the same as in the case of the system expansion approach (for both capital goods production and operation); they are all scaled down by 89% of the initial value, and no negative risk values (due to credits) exist. Similar to the relative results of the system expansion, the supply of electricity and chemicals contributes from 49% to 98% to the results of the operation stage.

4. Discussion

4.1. Analysis of indicators

The analysis of the results according to the indicators shows that for the three applied multifunctionality handling approaches, "Living wage, Lower bound", "Biomass extraction", "Public sector corruption", "Active involvement of enterprises in corruption and bribery", "Social responsibility along the supply chain", "Value added (total)", "Pollution level of the country", "Trade union density", and "Industrial water depletion" had the highest scores (see Tables S2-S4). Furthermore, except for Italy, which is the country where the case is located, risks are found in supply chains related to Russia, Iran, Saudi Arabia, Cameroon, and Libya. Iran is a major exporter of iron, steel and non-alloy steel to Italy. The main products exported from Russia to Italy are petroleum gas, crude and refined petroleum (United Nations, 2022). Saudi Arabia, Cameroon and Libya export to Italy crude petroleum, refined petroleum and ethylene, aluminum and petroleum oils, respectively, according to the latest data from the Observatory of Economic Complexity (Simoes and Hidalgo, 2011).

The "Living wage Lower bound" indicator belongs to the "Fair salary" subcategory of the Workers stakeholder. In our study, the "Living wage Lower bound" is linked to the electrical, machinery and equipment, electrical energy, gas, steam and hot water and construction sectors, which are characterized by "very high risk" in PSILCA. This was confirmed in 2018 by the Italian Ministry of Labour and Social Policies (Ministry of Labour and Social Policies, 2018). However, this may change in the upcoming version of the database because in March 2022 a new collective agreement for the Italian construction sector was signed to address training, safety and sustainable development, and tackle illegal unregulated work (mind RH, 2022). Manufacturing of the multi-effect distillation and nanofiltration units and labor for plant construction contribute during capital goods production and plant construction, while the electricity provider and the plant operator contribute during the operation stage. Although Italy is the main location of expected risks due to electricity supply and capital goods production, risks are also expected in Iran and Russia due to the supply of resources. If credits are considered for chemicals, avoided risks are expected mainly in France and to a lesser extent in Germany due to chemical imports according to the PSILCA database.

The "Public sector corruption" indicator belongs to the "Corruption" subcategory of the Value chain actors stakeholder. It was calculated based on the Corruption Perception Index (Transparency International, 2017). Corruption typically affects public institutions or governments. The locations of expected risks are (primarily) Italy due to electricity and capital goods production and (secondarily) Iran and Russia. In the case of credits, avoided risks are expected to occur in China and India, but the values are much smaller than risks in Russia. In our study, "Public sector corruption" is linked to the "electrical, machinery and equipment" sector and "construction" sector, both of which are characterized by "very high risk" in PSILCA. Manufacturing the multi-effect distillation unit and plant construction contributes to capital goods production and plant construction, while electricity provision and the Plant operator contribute to the operation stage. The manufacturing of other technology units contributes to a small extent to "Public sector corruption".

The "Social responsibility along the supply chain" indicator belongs to the "Promoting social responsibility" subcategory of the Value chain actors stakeholder. It is calculated based on the UN Global Compact (United Nations, 2018) and evaluates the extent to which social responsibility is taken seriously and assured by organizations within specific sectors. The location of expected risks is Italy due to electricity. In our study, "Social responsibility along the supply chain" is linked to the "electrical, machinery and equipment" sector and construction sector, which are both characterized by "very high risk" in PSILCA. Manufacturing of the multi-effect distillation unit and plant construction contribute to capital goods production, while the electricity provider and Plant operator contribute to the operation stage. Similar to the "Public sector corruption", the manufacturing of the other technology units contributes to a small extent to "Social responsibility along the supply chain".

The "Biomass extraction" indicator belongs to the "Access to material resources" subcategory of the Local Community stakeholder. It is calculated based on the Global Material Flows Database (International

Resource Panel, 2018). The exploitation and destruction of bioresources can result in resettlements, poverty, cultural uprooting, and ultimately, conflicts with local people (Maister et al., 2020). In our study, "Biomass extraction" is linked to the "electrical, machinery and equipment", and construction sectors, which are both characterized by "very low risk" in PSILCA. Manufacturing of the multi-effect distillation, nanofiltration, and EDBM units and plant construction contributes to capital goods, while electricity and desalination plant operator contribute to the operation stage. The main location of expected risks is Italy, but some risks can occur in Iran due to "collection, purification and distribution of water" due to basic metals in equipment manufacturing, and Russia due to "mining and quarrying". Both of these are background processes. If credits are considered for chemicals, avoided risks are expected mainly in France and to a small extent in India.

The "Active involvement of enterprises in corruption and bribery" indicator belongs to the "Corruption" subcategory of the Value chain actors stakeholder. It is calculated based on the Foreign Bribery Report (OECD, 2014) and evaluates the extent to which an organization engages in corrupt behavior or whether it has implemented appropriate measures (Maister et al., 2020). In our study, "Active involvement of enterprises in corruption and bribery" is linked to the electrical and construction sectors, which are characterized by "low risk" and "very high risk", respectively, in PSILCA. Plant construction contributes to capital goods, whereas electricity contributes to the operational stage. The main location of expected risks is Italy due to the construction sector, but some risks can occur in Russia due to "mining and quarrying".

The "Pollution level of the country" indicator belongs to the "Safe and healthy living conditions" subcategory of the Local Community stakeholder. It is calculated based on the Numbeo pollution index (Numbeo, 2019) and evaluates garbage disposal, cleanliness and tidiness of the city, noise pollution and light during the night in the city, and green and parks in the city (Maister et al., 2020). In our study, the "Pollution level of the country" is linked to the "electrical, machinery and equipment" and construction sectors, which are both characterized by "medium risk" in PSILCA. Manufacturing of the EDBM unit and plant construction contributes to capital goods, while electricity contributes to the operation stage. The main location where the risks are expected is Iran mainly due to "collection, purification, and distribution of water", which is a background process due to the supply chain of equipment manufacturing processes.

The "Industrial water depletion" indicator belongs to the "Access to material resources" subcategory of the Local Community stakeholder. It is calculated based on Aquastat: Food and Agriculture (FAO, 2017) and evaluates the level of industrial water use that is withdrawn for industrial purposes related to total water withdrawal and total actual renewable water resources (Maister et al., 2020). In our study, "Industrial water depletion" is linked to the "electrical, machinery and equipment", and construction sectors, which are both characterized by "very low risk" in PSILCA. The manufacturing of the nanofiltration unit and plant construction contributed to capital goods, whereas electricity contributed during the operation stage. The main location where risks are expected is Italy, but some risks can occur in Saudi Arabia and Libya as well due to "mining and quarrying" which is a background process. If credits are considered for chemicals, avoided risks are expected mainly in France.

The "Trade union density" indicator belongs to the "Freedom of association and collective bargaining" subcategory of the Workers stakeholder. It is calculated based on "ILO: Trade unions and Collective bargaining" (International Labour Organization, 2016), and assesses how liberal and vivid trade union culture is, and, to what extent the right to organize freely is assured in different sectors (Maister et al., 2020). In our study, "Trade union density" is linked to the "electrical, machinery and equipment", and construction sectors, which are both characterized by "high risk" for Italy in PSILCA. The manufacturing of the nanofiltration unit and plant construction contributes to capital goods, while electricity contributes to the operation stage. The locations where impacts occur are (primarily) Italy due to electricity and capital goods production and (secondarily) Iran and Cameroon due to "mining and quarrying". In the case of credits, this avoided impact is expected to occur in India and France.

The "Embodied value added (total)" indicator belongs to the "Contribution to economic development" subcategory of the Society stakeholder. It is calculated based on Eora Labor, GHG, and other environmental footprints by sector (Eora Global MRIO, 2015), and reflects an average value of the difference between the sale price and the production cost in relation to 1 USD of the output product within various sectors (Maister et al., 2020). In our study, "Embodied value added (total)" is related to the "electrical, machinery and equipment", and construction sectors, which are both characterized by "high risk" in PSILCA. The manufacturing of multi-effect distillation and nanofiltration units and plant construction contribute to capital goods, whereas electricity contributes to the operational stage. The location where impacts occur is Iran due to "collection, purification and distribution of water" which is a background process.

4.2. Sensitivity analysis

According to Fig. 5, substitution results in the largest contribution of labor costs during operation owing to the subtraction of credits from the risk results. Fig. 9 shows the results of the sensitivity analysis for the labor costs of the desalination plant for the substitution approach. The sensitivity analysis showed that the salary of employees of the desalination plant affected the total risks and risks due to operation negligibly. The operational risks of Workers and Local community stakeholders were affected by ±1%, and Value chain actors and Society risks were affected by ±2%. Figs. S6 and S7 show the sensitivity analysis results of system expansion and economic allocation, respectively. Regarding system expansion and economic allocation, the sensitivity analysis showed that only the Workers and Value chain actors risks were affected by ±1%.

Furthermore, Fig. 10 shows the results of the sensitivity analysis for the labor and miscellaneous costs of the desalination plant for the substitution approach. Fig. 10 shows that assuming that the labor and miscellaneous costs are the same or three times the equipment costs, instead of two times, affected the total risks by 3–6% and risks due to capital goods production to a large extent. The influence is proportional to the contribution of risks due to labor and miscellaneous to total risks. The total risks of Workers stakeholder was affected by ±6%, Value chain actors stakeholder was affected by ±5%, Society stakeholder was affected by ±4%, and Local community stakeholder was affected by ±3%. The risks due to capital goods for Workers and Value chain actors stakeholders were affected by ±65%, and Local community and Society risks were affected by ±76%. Figs. S8 and S9 show the sensitivity analysis results of system expansion and economic allocation, respectively. Regarding system expansion and economic allocation, the sensitivity analysis showed that Workers and Value chain actors total risks were affected by ±3% and total risks of Society and Local community were affected by ±2%.

4.3. Limitations

The limitations of our study exist on two levels: the structure of the PSILCA database and the input data. The PSILCA database employs sectoral data and calculates sectoral results that lower the accuracy of the results for the analyzed supply chain. This calls into question how much of the societal impacts can be attributed to supply chain activities and how much noise is generated by aggregated data. For instance, the selection of "Machinery and equipment n.e.c." for the manufacturing of process units did include the manufacturing of basic metals, chemical products, glass products, etc. in Italy and foreign countries, but not the only specific commodities employed because manufacturing industries

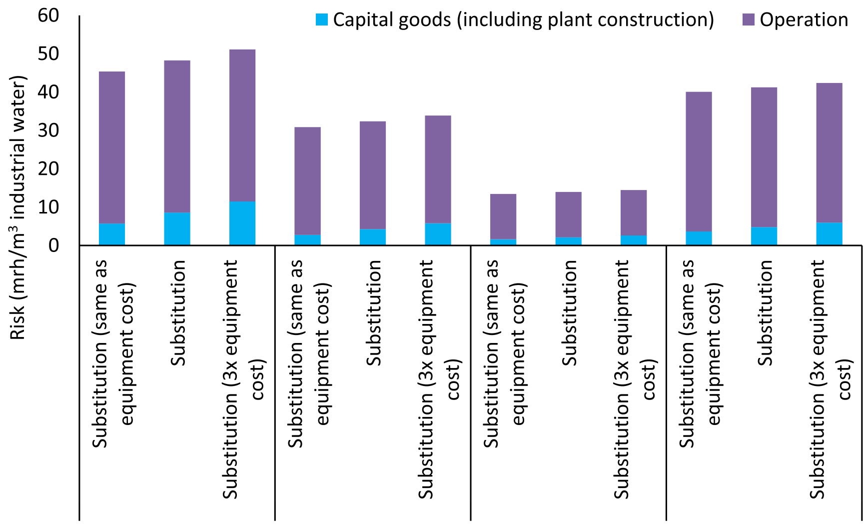

Fig. 10. Sensitivity analysis of labor and miscellaneous costs of substitution approach.

were aggregated on a sector level. In addition, it should be acknowledged that limitations derive from the uncertainty that is associated with the use of databases, e.g., the temporal coverage because data source of PSILCA is the EORA Input-Output database (Anon, 2015) which comprises data from 2015. Last, the mass and energy flows were scaled up to the operation of the large demonstration plant according to stoichiometry. In reality, energy and material consumption efficiencies during operation may be lower, which will result in lower societal risks owing to operation and fewer credits, particularly when the substitution approach is applied.

5. Conclusions

This study aimed to investigate whether the production of capital goods, and labor and miscellaneous tasks during plant construction contribute to social impacts as high as plant operation throughout the life cycle of a desalination plant. The results showed that the production of capital goods and the construction of infrastructure contributed to several impact subcategories that belonged particularly to Workers and Value chain actors stakeholder categories. If the SLCA practitioners would limit the selected impact subcategories for generic or site-specific analysis, the “Discrimination”, “Health and safety” (Workers), “Respect of indigenous rights”, and “Local employment” should be investigated. The electrical and construction sectors are the largest contributors to societal risks, and avoided chemical products result in high negative societal risk values (i.e., credits) when substitution approach is applied.

Furthermore, we found that the approach of handling multi-functionality does affect the contribution of capital goods to the overall impacts but not to the extent that practitioners should omit the inclusion of capital goods production in the system boundaries. Particularly the labor and miscellaneous costs during plant construction can contribute to total risks to a large extent. In addition, the use of credits (owing to applying substitution) leads to an increase in the relative contribution of capital goods to the overall impacts.

The PSILCA database is useful for modeling the social impacts of supply chain or product systems, but the data are aggregated at a sectoral level, which leads to uncertainty in the results. Therefore, it is recommended to further develop PSILCA with more site-specific data for economic sectors in Europe and impact subcategories that are not fully affected by national laws.

CRediT authorship contribution statement

Georgios A. Tsalidis: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Supervision, Writing - original draft, Writing - review & editing. **Akemi Kokubo Roche**: Writing - review & editing**. Serena Randazzo**: Data, Writing - review & editing**. John A. Posada**: Funding acquisition, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

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