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Definition, assessment and prioritisation of strategies to mitigate social life-cycle impacts across the supply chain of bioelectricity: A case study in Portugal

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ABSTRACT

A key goal in sustainable supply chain management is the minimisation of risk across supply chains. However, this is jeopardised by underdeveloped aspects such as social risk management, especially in the case of energy systems as they involve complex supply chains. This article constitutes the first time that Social Life Cycle Assessment (S-LCA) is used to lay the foundation for a methodological framework to define, assess and prioritise strategies oriented towards the minimisation of social life-cycle impacts across the supply chain of energy products. This framework combines S-LCA, a novel approach to the definition of alternative supply chain strategies, and multi-criteria decision analysis (MCDA). It was demonstrated through a case study of bioelectricity in Portugal by defining and assessing fifteen strategies on the specific supply chains of oil and fertilisers to check their suitability to enhance the system's social life-cycle performance. The weighted sum method (WSM) and Data Envelopment Analysis (DEA) were used as MCDA tools to further support decision-making by prioritising strategies. According to the results for a set of six social indicators, the strategies proposed on the supply of oil and nitrogen-based fertilisers were deemed suitable trade-off solutions to mitigate the social life-cycle impact of the bioelectricity system.

1. Introduction

Production processes often involve multiple countries, which has shaped a current context of interconnection and interdependence of sectors and companies on a global scale. Within a product's supply chain, information, material and capital flows are established between suppliers, focal company, and customers [1]. An optimal exchange of these flows is necessary for a favourable economic performance of the agents involved in the supply chain. Nevertheless, the success of an organisation should not be based only on profitability but also on protecting the environment and the welfare of society across supply chains [2]. In this sense, sustainable supply chain management (SSCM) is recognised as an emerging area of research [1–5].

Chowdhury and Quaddus [5] define SSCM as "managing the supply chain functions aligned with the social, environmental, and economic sustainability requirements of the stakeholders to reduce sustainability risks in supply chain and improve market performance". According to this definition, one of the pillars in SSCM is the minimisation of risk. In traditional supply chain risk management, companies usually take actions to prevent a loss of profitability [6]. However, supply chains usually encompass processes across numerous countries and tiers, which makes the intra-flows and operations involved in these systems opaque. This fact can lead to uncontrollable risks in terms of environmental degradation, human rights abuse and corruption, often found at second-tier suppliers or further upstream [7]. Stakeholders (customers, environmental agencies, policy-makers, etc.) are increasingly aware of this issue and put pressure on organisations to control such risks.

Regarding the energy sector as a driver of social welfare, its decarbonisation arises as an urgent milestone to be achieved through renewable energy systems that guarantee a sustainable performance across their entire supply chain. This task is especially

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challenging because the energy sector usually operates on a global scale and entails systems with complex supply chains [8]. The level of complexity is closely linked to the main feedstock used in the system, its conversion route, and background processes. Bioenergy systems illustrate such a complexity and the need to appropriately manage activities within the supply chain [9–11], especially in countries pursuing a sustainable energy context through a robust bioeconomy.

In order to implement an SSCM strategy, energy companies need to consider the main dimensions of sustainability, maximising profit while minimising environmental impacts and social risks across the supply chain [1]. In the last decades, significant contributions have been made to the development and application of methodologies (e.g., environmental life cycle assessment, LCA [12,13]) in the field of environmental management of energy supply chains regarding both fossil [14,15] and renewable [16–18] systems. In contrast, major challenges remain in the social risk management of energy systems across their supply chains, especially bioenergy systems [2,8]. According to Buckivc et al. [2] and Govindan et al. [7], the implementation of strategies to minimise the social risks of supply chains should be assessed and monitored through social life cycle assessment (S-LCA) [19,20]. In fact, there is a need for analyses that holistically integrate all tiers of a supply chain [21], beyond current evaluations focused on the first and second tiers [2,7]. Furthermore, there is a research gap regarding the application of scenario analysis and multi-criteria decision analysis (MCDA) to support decision-making towards social sustainability of supply chains [2,7].

Based on the abovementioned needs, the present study proposes and illustrates a framework for the definition, assessment and prioritisation of potential strategies to mitigate social life-cycle impacts across the supply chain of energy products through the case study of bioelectricity in Portugal. To the best of our knowledge, this article constitutes the first time that the S-LCA methodology, in combination with other tools, is applied for this purpose. This is expected to open the door for further case studies, thereby contributing to the progressive formulation of recommendations to decision- and policy-makers for the management of social supply chain risk within the energy sector.

2. Materials and methods

2.1. Case study and methodological framework

S-LCA is a methodology to comprehensively evaluate potential social impacts along the life cycle of products and services, thus supporting decision-making processes for the improvement of organisations' performance and social well-being [20]. Within the developments aimed at improving the methodological robustness of product S-LCA [22], a novel procedure for enhanced definition of system boundaries and subsequent construction of thorough social life-cycle inventories (S-LCIs) has recently been proposed [21]. This novel approach jointly uses conventional LCI and trade databases to carefully identify representative supply-chain paths according to the expected countries of origin for the unit processes involved in the product system under evaluation. In the present article, following the case study of Portuguese bioelectricity in Ref. [21], the enhanced S-LCA methodological framework is enriched with (i) a novel approach to the definition of alternative supply chain strategies, and (ii) MCDA tools to prioritise strategies that minimise the potential social risks across the bioelectricity supply chain. The choice of this case study is supported by the important bioeconomy potential of Portugal, largely based on the vast availability of by-products and residues from its agri-food and forestry sectors and its high-profile research facilities on bio-based products and materials [23]. In fact, Portuguese decision-makers are especially interested in promoting a robust energy sector with a predominant role of bio-based systems [24], as reflected in regulatory texts such as the Decree-Law 64/2017 on biomass plants (amended by Decree-Law 120/2019).

Fig. 1 shows the boundaries of the bioelectricity system originally defined in da Costa et al. [25] and subsequently expanded in Martín-Gamboa et al. [21]. The first life-cycle stage corresponds to the "eucalypt forest management" block. This stage includes the forestry operations needed to obtain the biomass feedstock, i.e. the eucalypt residue: site preparation, eucalypt planting, stands tending, logging, and establishment of the infrastructure (road and firebreak building). Fertilisers, fuels, lubricants and capital goods were the main input flows considered in this block.

The second life-cycle stage corresponds to the "feedstock collection, processing and transportation" block, involving operations to process the eucalypt residue into chips suitable to be used as input material in the energy conversion process. The main operational inputs of this stage are diesel and lubricants, while capital goods refer to forestry machinery (forwarder, tractor, truck, and chipping terminal).

The final life-cycle stage corresponds to the "energy conversion" block. In this case study, energy conversion to obtain electricity takes place in a grate furnace system, which is a common power generation technology in Portugal [25]. The functional unit (FU) of the system was defined as 1 kWh of bioelectricity produced [21]. Besides the biomass chips, the main operational inputs include natural gas, sand, and water. Additionally, this stage involves the main capital goods of the biomass power plant (silo, boiler, and turbine).

Fig. 1 also shows the identification of the items within the bioelectricity system which involve the supply chains with major contributions to the social risks analysed according to the original S-LCA study [21]. The crude oil supplied to Portugal by Russia, Azerbaijan, Saudi Arabia and Kazakhstan would dominate the social risk within the bioelectricity supply chain in terms of health expenditure, frequency of force labour, and women in the sectoral labour force. The nitrogen (N)-based fertiliser and ammonia supplied by Algeria and the Portuguese bioelectricity plant itself would

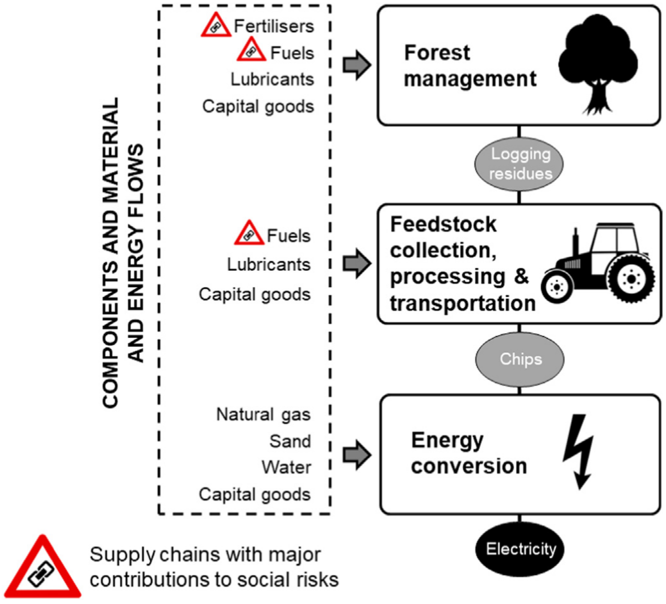

Fig. 1. Boundaries of the bioelectricity system.

contribute most to the unfavourable social performance in terms of child labour and gender wage gap, respectively.

Fig. 2 shows the methodological framework proposed in the path towards an enhanced social sustainability performance of the bioelectricity system, though applicable to any other system. In this framework, data acquisition is repeatedly required to carry out the S-LCA of the original energy system as well as to define supply chain strategies and evaluate their potential for minimising social risks under the new system configurations. In this regard, LCI and trade data are the basis to identify the boundaries of the original and alternative energy systems [21], while socio-economic data (in terms of economic flows and working hours) are necessary to build the S-LCI of each system. The first S-LCA application allows the identification of social hotspots along the supply chain of the energy system under the original strategy (i.e., the original system). It should be noted that the comprehensive definition of system boundaries through the supply-chain definition protocol suggested in Ref. [21] provides a multi-tier perspective, involving different stages from raw material extraction to the provision of the energy product. Thus, the social life-cycle profile of the energy system can reveal opaque social aspects by reaching commonly unexplored tiers [2,7]. Further details on the S-LCA component can be found in Section 2.2.

After the identification of the original system's social hotspots, alternative strategies should be conceived to minimise social risks. The present article proposes a novel approach to the formulation of alternative supply chain strategies to potentially mitigate social risks. Taking into account that social impacts are closely linked to the countries where the unit processes within the energy system's supply chain are located [26,27], the proposed approach bases the definition of alternative supply chain strategies on the identification of exporting countries alternative to those that penalise the original system's social performance. The steps and criteria used for the search for potential alternative countries, as well as the list of strategies proposed to mitigate the social risks of the bioelectricity system, are detailed in Section 2.3. Each of the alternative strategies means a new supply chain configuration of the energy system that should be re-evaluated through S-LCA.

Depending on the set of strategies, a straightforward selection of the most appropriate one to minimise social risks can be challenging. Hence, the final component of the proposed framework refers to the use of MCDA tools. MCDA consists of a process that evaluates alternatives by compiling a set of criteria and stakeholders' preferences and using them to build a preference model that allows the prioritisation of alternatives. Within the proposed methodological framework, the selection of the MCDA tool is at the discretion of the analyst, who should take into account the features of the specific case study (including the total number of strategies). The MCDA component of the present case study is addressed in Section 2.4.

2.2. S-LCA component

Fig. 3 shows the four interrelated phases of the S-LCA methodology, on the analogy of the standard structure of environmental LCA [20]. In the first phase (goal and scope definition), it is required to clearly define the purpose of the study and the FU, as well as to describe the product system and its boundaries (unit processes included in the analysis). With the aim of contributing to the methodological robustness of this crucial step, Martín-Gamboa et al. [21] proposed a general protocol for the identification of representative countries of origin of the unit processes involved in a product system. The application of this protocol leads to identify the countries of origin of the system's component flows and material and energy flows through the joint use of LCI and trade databases. This protocol has already been successfully tested in the original bioelectricity system under study, resulting in the identification of more than 400 processes within seven tiers of the supply chain [21].

The second phase of the S-LCA methodology refers to S-LCI preparation, compiling (social) data for the unit processes included in the system boundaries. In this second phase, activity variables measure the activity of the processes that constitute the product system under evaluation [26,28]. In line with the study of the original bioelectricity system [21], the present article uses working hours per FU to express the activity variables.

The third phase of the S-LCA methodology is social life cycle impact assessment (S-LCIA). In this phase, activity variables are converted into social risks across the supply chain of the product system. There are two general approaches for S-LCIA methods: the

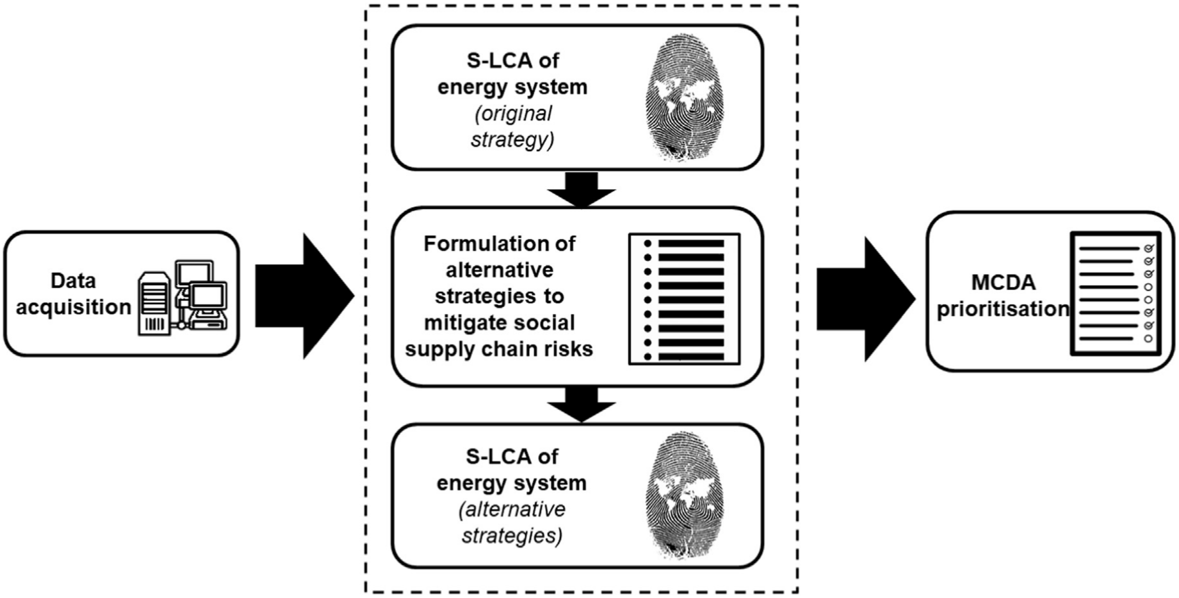

Fig. 2. Framework for the mitigation of social supply chain risks in energy systems.

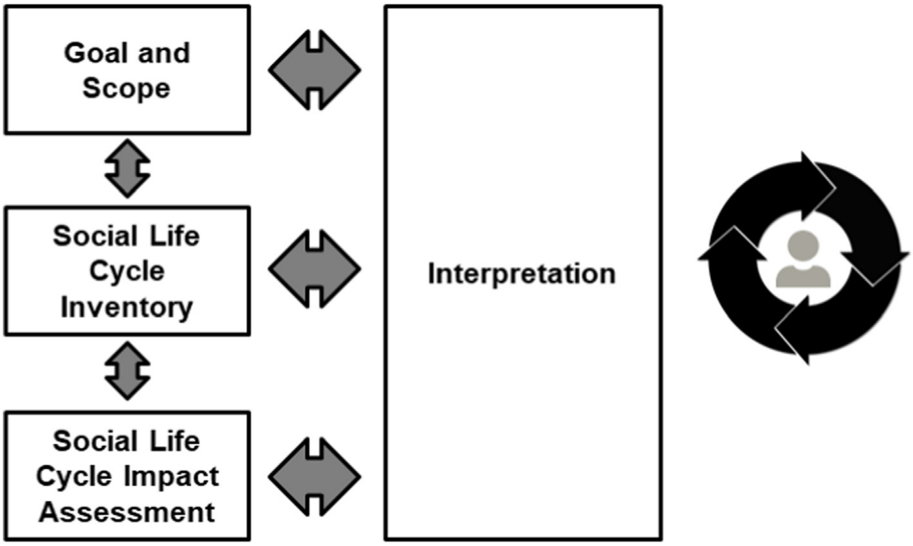

Fig. 3. S-LCA phases.

reference scale approach (Type I), and the impact pathway approach (Type II) [20,29–31]. In line with the original study of the bioelectricity system [21], the quantification procedure detailed in Valente et al. [26] was followed in this S-LCA study, and PSILCA was used not only as a database but also as the characterisation method [32]. Hence, the study is framed in the first type of S-LCIA methods. The following social life-cycle indicators were evaluated: total child labour, frequency of forced labour, gender wage gap, women in the sectoral labour force, health expenditure, and contribution to economic development. The selected set of social indicators widely addresses the social dimension, taking into account aspects from three of the four pillars of this dimension: labour conditions, human rights, and society. Additionally, the considered indicators highly contribute to addressing 8 of the 17 Sustainable Development Goals (SDGs), especially SDG 3 on "good health and well-being", SDG 5 on "gender equality", SDG 8 on "decent work and economic growth", and SDG 10 on "reduced inequalities" [33]. Hence, this choice of indicators strengthens the relevance of measuring the potential social impacts of a given set of alternative strategies for decision-making processes effectively aligned with official objectives of the international community (e.g., abolition of forced labour) [34]. The final S-LCA phase is interpretation, where the social results are discussed and conclusions and recommendations are provided to support decision-making.

2.3. *Approach to the definition of alternative supply chain strategies*

Given the supply chain perspective, the social performance of partners may highly influence the social risks of a product system (and thus of purchasing organisations) [35]. The influence of partners is often critical beyond the first and second tiers of the supply chain, which tend to be located in emerging economies with lax legislation in terms of social equity [7]. Hence, partner selection has become a vital aspect to enhance the social performance of (energy) product systems [36]. However, approaches and criteria for the selection of socially suitable partners have received insufficient attention in the literature [35].

To bridge this research gap, a two-stage approach to partner selection was herein developed, understanding "partner" as a selected exporting country of a commodity required by the system. The first stage deals with the identification of alternative partners with a historical commitment with the purchasing partners for the socially critical components and material/energy flows. Based on average trade flows for the last ten years (in economic or mass units), any partner with an individual import share ≥2% or contributing to reach 90% of cumulative import share was initially deemed a potential partner. The use of trade databases such as the UN Comtrade database [37] is recommended to retrieve this type of information.

The second stage of the approach consists of a final screening of the potential partners by means of two criteria: political stability index, and assumable demand. The former measures perceptions of the likelihood that the relevant government will be destabilised or overthrown by unconstitutional or violent means [38]. The latter refers to the partner's capability to assume an extra demand for the relevant component or material/energy flow taking into account the ratio of the corresponding total imports of the relevant purchasing partner (importing country) to the corresponding total exports of the potential partner (exporting country). In this case, the use of trade databases such as the UN Comtrade database is again recommended [37]. Partners capable of both increasing political stability with respect to the reference choice (original strategy) and assuming the demand would finally qualify as potential alternatives to the original country for the definition of alternative supply chain strategies.

Table 1 presents the resultant set of strategies for the specific case study of bioelectricity. The alternative strategies included in Table 1 (labelled as St1-15) were focused on the social hotspots of the original system:

- Oil extraction. The strategies oriented to mitigate social risks of the oil extraction supply chain were based on alternative exporting countries (Angola, Norway, and Brazil) in combination with new shares of the original exporting countries (Russia, Azerbaijan, Saudi Arabia, and Kazakhstan).
- Fertiliser production. The strategies in this area were proposed at the level of the fertiliser itself (first-tier strategy) and at the level of fertiliser-related material (second-tier strategy):
    - The first-tier strategies oriented to mitigate social risks of the N-based fertiliser supply chain were based on alternative exporting countries (the Netherlands, Belgium, Croatia, and Russia), avoiding Egypt and Algeria as original exporting

Table 1
Strategies considered in the bioelectricity supply chain.

Description	Strategy code	New mix of suppliers[a]
Supply chains presented in the original case study [21]	St0	–
Strategies oriented to mitigate the social risk of the oil extraction supply chain	St1	30% AGO; 20% BRA; 15% NOR; 14% RUS; 9% AZE; 6% SAU; 6% KAZ
	St2	35% AGO; 15% BRA; 15% NOR; 14% RUS; 9% AZE; 6% SAU; 6% KAZ
	St3	40% AGO; 15% BRA; 15% NOR; 12% RUS; 7% AZE; 5.5% SAU; 5.5% KAZ
Strategies oriented to mitigate the social risk of the N-based fertiliser supply chain	St4	45% NLD; 35% BEL; 20% DEU
	St5	45% NLD; 35% BEL; 20% HRV
	St6	45% NLD; 35% BEL; 20% RUS
Strategies oriented to mitigate the social risk of the superphosphate fertiliser supply chain (phosphate rock)	St7	100% MAR
	St8	70% MAR; 30% SEN
Strategies oriented to mitigate the social risk of the superphosphate fertiliser supply chain (phosphoric acid)	St9	100% BEL
	St10	60% BEL; 40% MAR
Strategies oriented to mitigate the social risk of the ternary fertiliser supply chain (ammonium nitrate)	St11	58% TTO; 27% LTU; 15% NLD
	St12	58% TTO; 22% LTU; 15% NLD; 5% POL
	St13	58% TTO; 20% LTU; 15% NLD; 7% ROU
Strategies oriented to mitigate the social risk of the ternary fertiliser supply chain (diammonium phosphate)	St14	80% LTU; 20% MAR
	St15	60% LTU; 40% MAR

[a] AGO: Angola; BRA: Brazil; NOR: Norway; RUS: Russia; AZE: Azerbaijan; SAU: Saudi Arabia; KAZ: Kazakhstan; NLD: the Netherlands; BEL: Belgium; DEU: Germany; HRV: Croatia; MAR: Morocco; SEN: Senegal; TTO: Trinidad and Tobago; LTU: Lithuania; POL: Poland; ROU: Romania.

countries and reducing or eliminating the original share of Germany.

- A set of second-tier strategies considers alternative supply paths for superphosphate components (phosphate rock and phosphoric acid) originally imported only from Israel. In this regard, Morocco and Senegal were considered as alternative exporting countries for phosphate rock, and Belgium and Morocco for phosphoric acid.
- Another set of second-tier strategies considers alternative supply paths for ammonium nitrate from Egypt (as the only original exporting country identified as a social hotspot, unlike Trinidad and Tobago) and diammonium phosphate from Morocco (as the only original exporting country). In this respect, Lithuania, the Netherlands, Poland and Romania were considered as alternative exporting countries for ammonium nitrate, and Lithuania for diammonium phosphate.

2.4. MCDA component

According to the case study under evaluation and the number of strategies in Table 1, two MCDA tools were selected to provide ranking indices that support the prioritisation of supply chain strategies according to the system's social life-cycle profile: the weighted sum method (WSM) and Data Envelopment Analysis (DEA).

The WSM is one of the most commonly used MCDA tools due to its simplicity [39]. It uses simple arithmetic formulae taking into account specific weights for each social life-cycle indicator to obtain a single overall value for each alternative. The WSM follows the principle of aggregating the performances under each of the criteria according to an additive aggregation function (Eq. (1)):

$$S(a_i) = w_1 \cdot v_1(a_i) + \ldots + w_n \cdot v_n(a_i) = \sum_{j=1}^{j=n} w_j \cdot v_j(a_i) \tag{1}$$

where a_i stands for the i-th system strategy, n is the number of social life-cycle indicators, w_j denotes the weight of the j-th indicator, $v_j(a_i)$ is the normalised value of the j-th indicator for the i-th system strategy, and $S(a_i)$ indicates the overall social performance value —used as a ranking index— of the i-th system strategy. Although the social risks are expressed in the same units (medium risk hours, mrh), the values aggregated in Eq. (1) should be normalised to make the scales comparable. Eq. (2) represents the common normalisation approach applied in this study:

$$v_j(a_i) = \frac{\left|I_j(worst_j) - I_j(a_i)\right|}{\left|I_j(worst_j) - I_j(best_j)\right|} \tag{2}$$

where $I_j(a_i)$ stands for the value of the j-th indicator for the i-th system strategy, $I_j(worst_j)$ denotes the worst value of the j-th indicator within the set of system strategies, and $I_j(best_j)$ indicates the best value of the j-th indicator within the set of system strategies. According to Eq. (2), the normalised values of each indicator range between 0 (for the worst strategy under that indicator) to 1 (for the best strategy under that indicator).

Regarding the second MCDA tool applied for the prioritisation of strategies, DEA is a linear programming methodology that empirically measures the relative efficiency of multiple resembling entities or decision-making units (DMUs) [40]. To that end, DEA optimisation models are formulated according to a set of specific technical features such as metrics (e.g., non-radial model), orientation (e.g., input and output-oriented model), and display of the production possibility set (e.g., constant returns to scale). In this study, the DMU corresponds to each bioelectricity system strategy and was defined by five negative social impacts as the inputs (total child labour, frequency of forced labour, gender wage gap, women in the sectoral labour force, and health expenditure) and one positive social impact as the output (contribution to economic development as an absolute value) [41]. A non-oriented slacks-based measure (SBM) of super-efficiency model with constant returns to scale [42] was used to calculate the super-efficiency score of each system strategy (Φ_j). This type of model allows identifying the best strategies among a set of multiple DMUs with a relatively high number of entities previously labelled as efficient according to the conventional SBM model (i.e., SBM-efficient entities) [43]. The DEA super-efficiency model was formulated as follows:

$$\Phi = \text{Min}\left(\frac{\frac{1}{M}\sum_{k=1}^{M}\frac{\bar{x}_k}{x_{k0}}}{\frac{1}{S}\sum_{r=1}^{S}\frac{\bar{y}_r}{y_{r0}}}\right) \tag{3}$$

subject to

$$\bar{x} \geq \sum_{j=1,\neq 0}^{N} \lambda_j x_j \tag{4}$$

$$\bar{y} \leq \sum_{j=1,\neq 0}^{N} \lambda_j y_j \tag{5}$$

$$\bar{x} \geq x_0 \text{ and } \bar{y} \leq y_0 \tag{6}$$

$$\bar{y} \geq 0, \lambda \geq 0 \tag{7}$$

where N: number of system strategies; j: index on the system strategy; M: number of negative social indicators; S: number of positive social indicators; k: index on the negative social indicator; r: index on the positive social indicator; 0: index of the SBM-efficient system strategy under assessment; x_j: values of the negative social indicators associated with the system strategy j; y_j: values of the positive social indicators associated with the system strategy j; x_{k0}: value of the negative social indicator k associated with the SBM-efficient system strategy under assessment; y_{r0}: value of the positive social indicator r associated with the SBM-efficient system strategy under assessment; λ_j: coefficients of linear combination associated with the strategy j; and Φ: super-efficiency score of the SBM-efficient system strategy under assessment. The scores lead to discriminate between comparatively efficient ($\Phi \geq 1$) and inefficient ($\Phi < 1$) system strategies.

3. Results and discussion

3.1. S-LCA of supply chain strategies

The strategies in Table 1 involve a straightforward modification of the original S-LCI model of bioelectricity [21]. The S-LCIA results of each of the bioelectricity system strategies were calculated through the implementation of the S-LCIs in the software openLCA [44] and the subsequent use of the PSILCA method [32]. Table 2 presents the social life-cycle profile of each system strategy. It should be noted that the negative (i.e., favourable) values found for the indicator “contribution to economic development” indicate the desirable nature of this impact indicator.

According to the results in Table 2, the implementation of strategies oriented to mitigate social risks of the oil extraction supply chain (St1-3) would lead to the greatest differences in the social performance of the bioelectricity system with respect to the original system (St0). In this sense, implementing this type of strategy could reduce social risks by > 30% in terms of frequency of forced labour, gender wage gap and health expenditure, and by > 7% in terms of women in the sectoral labour force. However, it could penalise the social life-cycle profile of bioelectricity under other indicators, especially child labour (>five-time increase) and −to a lesser extent− contribution to economic development (13% average deterioration). The inclusion of Angola considerably increases the risk of child labour, while the selection of Brazil and Norway allows improving 4 out of 6 indicators (with a particularly unfavourable effect on the contribution to economic development).

Concerning the strategies oriented to minimise social risks of fertiliser supply chains (St4-15), those focused on N-based fertiliser production (St4-6) would generally involve the highest percentages of social risk mitigation with respect to the original system (St0), except for gender wage gap (14% average increase) and contribution to economic development (negligible variation). The inclusion of the Netherlands and Belgium (countries with decent work conditions and social benefits according to the International Labour Organization [45]) as suppliers of the N-based fertiliser to the detriment of Egypt and Algeria was found to be behind this general improvement in the social life-cycle performance of the bioelectricity system.

The strategies oriented to mitigate social risks of the ternary fertiliser supply chain by considering Lithuania as a supplier of diammonium phosphate (St14-15) would also have a significant effect on the social profile of the bioelectricity system. This set of strategies was found to be associated with the highest social benefit in terms of contribution to economic development (4% average improvement with respect to the original system) while also improving the health expenditure indicator (11% average reduction). Nevertheless, St14 and St15 could penalise the social performance of the bioelectricity system under other indicators such as gender wage gap and forced labour.

The implementation of the remaining supply chain strategies (St7-13) was found to involve a negligible effect on the social performance of the bioelectricity system with respect to the original one (St0). Overall, even though the strategies oriented to mitigate social risks of the oil and N-based fertiliser supply chains emerge as potential trade-off solutions, the variability observed in social results hampers a straightforward identification of the most suitable supply chain strategies to enhance the social life-cycle performance of the bioelectricity system. Therefore, MCDA tools were additionally used to support the prioritisation of the strategies under study (Section 3.2).

3.2. MCDA prioritisation

After characterising the social life-cycle performance of the bioelectricity system strategies, the WSM model was used to estimate ranking scores and subsequently prioritise the proposed strategies. The data presented in Table 2 constitute the inputs (total child labour, frequency of forced labour, gender wage gap, women in the sectoral labour force, and health expenditure) and the output (contribution to economic development in absolute values) of a matrix which was implemented in an own-developed Excel spreadsheet to compute the ranking scores. Fig. 4 shows the prioritisation of system strategies according to the WSM results. St1, St3 and St2 (i.e., the strategies oriented to mitigate social risks of oil extraction) arose as the three best strategies. These system strategies present similar WSM scores (>0.65) and could be deemed as appropriate short- and medium-term strategies to achieve an enhanced social life-cycle performance of the bioelectricity system. The strategies based on mitigating social risks of the N-based fertiliser were ranked fourth, fifth and sixth (St6, St5 and St4, respectively). The remaining strategies present scores <0.4, only slightly better than that of the original system (St0).

In order to check the sensitivity of the ranking to analysts' and decision-makers’ preferences, Table 3 reports the modification of the default WSM ranking (Fig. 4) when using DEA as an alternative MCDA tool and when considering output prioritisation. Regarding DEA application, a matrix with the same inputs and the same output as the WSM matrix was implemented in a non-oriented slacks-based measure of super-efficiency model with constant returns to scale, which was solved using the software DEA-Solver Pro to compute the efficiency score of each system strategy [46]. Regarding the consideration of decision-makers’ preferences,

Table 2
Social life-cycle profile of each system strategy (values in mrh per kWh).

Strategy code	Child labour	Gender wage gap	Health expenditure	Frequency of forced labour	Women in the sectoral labour force	Contribution to economic development
St0	$3.19 \cdot 10^{-3}$	$1.38 \cdot 10^{-2}$	$5.00 \cdot 10^{-2}$	$1.87 \cdot 10^{-4}$	$2.62 \cdot 10^{-2}$	$-2.29 \cdot 10^{-3}$
St1	$2.03 \cdot 10^{-2}$	$9.65 \cdot 10^{-3}$	$3.03 \cdot 10^{-2}$	$1.25 \cdot 10^{-4}$	$2.43 \cdot 10^{-2}$	$-2.00 \cdot 10^{-3}$
St2	$2.32 \cdot 10^{-2}$	$9.64 \cdot 10^{-3}$	$3.06 \cdot 10^{-2}$	$1.28 \cdot 10^{-4}$	$2.43 \cdot 10^{-2}$	$-1.99 \cdot 10^{-3}$
St3	$2.61 \cdot 10^{-2}$	$9.38 \cdot 10^{-3}$	$2.89 \cdot 10^{-2}$	$1.25 \cdot 10^{-4}$	$2.42 \cdot 10^{-2}$	$-1.97 \cdot 10^{-3}$
St4	$1.35 \cdot 10^{-3}$	$1.57 \cdot 10^{-2}$	$4.84 \cdot 10^{-2}$	$1.64 \cdot 10^{-4}$	$2.56 \cdot 10^{-2}$	$-2.27 \cdot 10^{-3}$
St5	$1.35 \cdot 10^{-3}$	$1.59 \cdot 10^{-2}$	$4.85 \cdot 10^{-2}$	$1.65 \cdot 10^{-4}$	$2.55 \cdot 10^{-2}$	$-2.29 \cdot 10^{-3}$
St6	$1.44 \cdot 10^{-3}$	$1.56 \cdot 10^{-2}$	$4.96 \cdot 10^{-2}$	$1.73 \cdot 10^{-4}$	$2.55 \cdot 10^{-2}$	$-2.35 \cdot 10^{-3}$
St7	$3.19 \cdot 10^{-3}$	$1.35 \cdot 10^{-2}$	$5.04 \cdot 10^{-2}$	$1.87 \cdot 10^{-4}$	$2.62 \cdot 10^{-2}$	$-2.29 \cdot 10^{-3}$
St8	$3.27 \cdot 10^{-3}$	$1.35 \cdot 10^{-2}$	$5.04 \cdot 10^{-2}$	$1.87 \cdot 10^{-4}$	$2.62 \cdot 10^{-2}$	$-2.29 \cdot 10^{-3}$
St9	$3.19 \cdot 10\text{-}^{3}$	$1.35 \cdot 10^{-2}$	$5.00 \cdot 10^{-2}$	$1.87 \cdot 10^{-4}$	$2.60 \cdot 10^{-2}$	$-2.28 \cdot 10^{-3}$
St10	$3.19 \cdot 10^{-3}$	$1.35 \cdot 10^{-2}$	$5.19 \cdot 10^{-2}$	$1.89 \cdot 10^{-4}$	$2.60 \cdot 10^{-2}$	$-2.29 \cdot 10^{-3}$
St11	$3.19 \cdot 10^{-3}$	$1.39 \cdot 10^{-2}$	$5.00 \cdot 10^{-2}$	$1.88 \cdot 10^{-4}$	$2.61 \cdot 10^{-2}$	$-2.30 \cdot 10^{-3}$
St12	$3.19 \cdot 10^{-3}$	$1.39 \cdot 10^{-2}$	$5.00 \cdot 10^{-2}$	$1.88 \cdot 10^{-4}$	$2.61 \cdot 10^{-2}$	$-2.30 \cdot 10^{-3}$
St13	$3.19 \cdot 10^{-3}$	$1.39 \cdot 10^{-2}$	$5.00 \cdot 10^{-2}$	$1.88 \cdot 10^{-4}$	$2.61 \cdot 10^{-2}$	$-2.30 \cdot 10^{-3}$
St14	$3.19 \cdot 10^{-3}$	$1.53 \cdot 10^{-2}$	$4.36 \cdot 10^{-2}$	$1.96 \cdot 10^{-4}$	$2.62 \cdot 10^{-2}$	$-2.38 \cdot 10^{-3}$
St15	$3.19 \cdot 10^{-3}$	$1.49 \cdot 10^{-2}$	$4.52 \cdot 10^{-2}$	$1.94 \cdot 10^{-4}$	$2.62 \cdot 10^{-2}$	$-2.36 \cdot 10^{-3}$

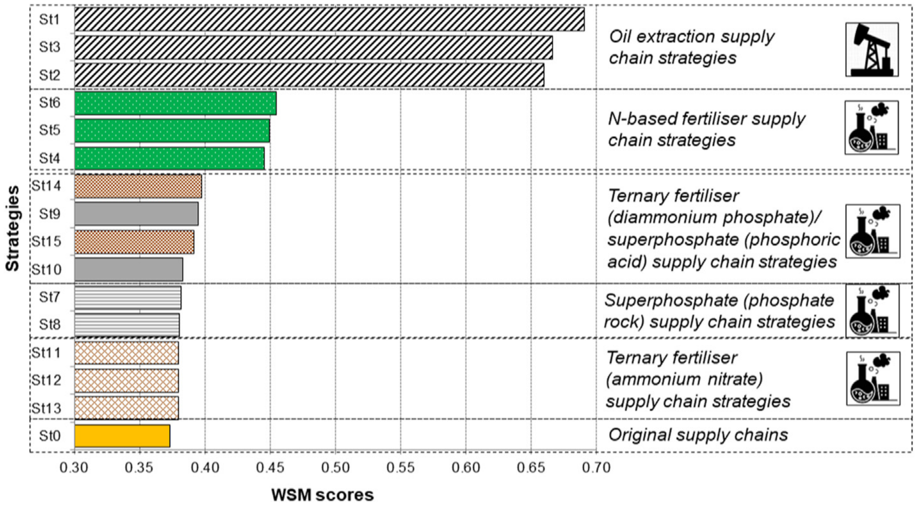

Fig. 4. WSM scores and ranking of the set of strategies.

Table 3
Modification of the default WSM ranking due to (i) DEA application and (ii) WSM output prioritisation.

Default ranking (Fig. 4)	Strategy code	DEA ranking[a]	WSM output prioritisation[a]
1	St1	=	↓ 13
2	St3	↓ 2	↓ 14
3	St2	↓ 13	↓ 11
4	St6	↑ 2	↑ 3
5	St5	=	↑ 1
6	St4	↓ 4	↑ 1
7	St14	↑ 4	↑ 5
8	St9	↓ 3	↓ 4
9	St15	=	↑ 6
10	St10	↑ 3	↑ 1
11	St7	↑ 5	↑ 1
12	St8	↑ 4	↑ 1
13	St11	↓ 2	↑ 5
14	St12	=	↑ 7
15	St13	↑ 2	↑ 9
16	St0	↑ 4	↑ 3

[a] Numbers in this column correspond to the number of places up or down relative to the default ranking.

Table 3 also illustrates the effect of incorporating a weighting vector (0.5 to the whole set of inputs and 0.5 to the output) that prioritises the output (contribution to economic development) in the WSM analysis. In both cases (DEA use and WSM output prioritisation), significant variations were found in the ranking with respect to the default one (WSM with equal weights). This was especially noticeable when incorporating output prioritisation into the analysis, which led to penalise oil-based strategies while promoting strategies focused on the N-based fertiliser and diammonium phosphate supply chains.

Despite their usefulness, the application of MCDA tools and weighting approaches in this study should be understood as illustrative. Given the high variability found in the rankings, the direct involvement of decision-makers in this type of study is highly recommended when it comes to providing reliable choices on the indicators to be selected and prioritised [47]. Otherwise, a separate evaluation of each indicator is recommended in order to subsequently discuss trade-off solutions under social aspects. In this regard, a greater consensus on the most appropriate indicators depending on the case study is needed among S-LCA analysts. Moreover, a cautious selection of the MCDA tool is required, e.g. taking into account the specific case study and the number of strategies.

3.3. *Final remarks*

The implementation of structural changes aimed at reducing greenhouse gas emissions in the energy sector must be accompanied by actions in social sustainability that highly contribute to the achievement of SDGs [34]. To that end, a drastic increase in the flow of capital towards social investment is crucial. Some international organisations such as the European Commission have already begun to plan the mechanisms to direct public and private investment to socially-sustainable activities, e.g., through a social taxonomy [34]. With the aim of attracting investment and contributing to the transition towards a sustainable energy sector, stakeholders need tools that define, quantify and benchmark actions to mitigate social risks. Regardless of the specific case study addressed in this work, the framework illustrated in this article has the potential to fulfil this general need by combining three approaches, namely, S-LCA, MCDA, and —in particular— a novel approach to the definition of alternative supply chain strategies.

The general approach to defining alternative supply chain strategies developed in this study represents a step forward to systematically set actions that could mitigate the social life-cycle impacts of energy systems, thereby further enhancing the combination of S-LCA and MCDA (e.g., DEA) tools [48]. This is in line with the acknowledged importance of considering changes in the location of supply chains to mitigate negative social impacts [20]. The proposed two-stage approach facilitates the definition of location changes through new partner selection based on robust criteria that reduce the randomness of the decision-making process by making use of quantitative criteria readily available from official and transparent statistical sources (e.g., World Bank and United Nations databases).

Finally, it should be noted that the overall combined framework is inherently associated with a finite number of alternative supply chain strategies. At the case-study level, the limited number of proposed mitigation actions should be considered as strategies to implement in the short-to-medium term. In the medium-to-long term, strategies to minimise social risks should actually be geared towards effectively improving working conditions and strengthening the defence of human rights in those countries with high social risks. Such long-term strategies require the direct involvement of governments and deep structural changes, which is outside the scope of the study.

4. Conclusions

A framework for the definition, assessment and prioritisation of strategies to mitigate social life-cycle impacts across the supply chain of a product was developed and successfully illustrated through a case study of bioelectricity. Thus, 15 strategies were defined to potentially mitigate social risks across the supply chain of Portuguese bioelectricity. The strategies were focused on the social hotspots of the bioenergy system, i.e. oil extraction and fertiliser production. In particular, the strategies oriented to mitigate social risks of the oil extraction and N-based fertiliser supply chains were identified as trade-off solutions to improve the social life-cycle performance of the original bioelectricity system. This was found to be linked to the inclusion of exporting countries with decent work conditions and social benefits such as Norway, Belgium, and the Netherlands. Regarding the prioritisation of strategies, the use of WSM confirmed the previous finding, but the ranking outcomes were highly sensitive to the use of alternative MCDA tools (e.g., DEA) and weighting approaches.

Overall, the proposed framework paves the way for sound decision-making processes pursuing the thorough identification, assessment and implementation of social improvement strategies at the level of representative product supply chains. Nevertheless, further advancements are required to e.g. effectively involve decision-makers and develop guidelines for the selection of relevant social life-cycle indicators according to the type of energy case study.

CRediT authorship contribution statement

Mario Martín-Gamboa: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization, Writing – review & editing. **Ana Cláudia Dias:** Writing – review & editing. **Diego Iribarren:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

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