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Assessing the social life cycle impacts of the Spanish electricity mix: A decadal analysis

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ABSTRACT

Power generation systems are crucial to national energy transitions, such as Spain's, which stands as a notable example. However, this profound transformation could have multifaceted implications, leading to unintended consequences on society. The present work is the first to understand the social impacts of the Spanish power sector and their technology supply chains using the social life cycle sssessment methodology. The functional unit is 1 kWh of electricity produced by the technologies in the Spanish electricity mix. A cradle-to-gate approach is taken using a supply chain protocol to complete the system boundaries. The social life cycle inventory, comprising data on national suppliers, working hours and social flows, was integrated into the PSILCA database to derive the social profile of each power technology and, consequently, to obtain a comprehensive view of the Spanish power sector. The results reveal that social impact associated with the Spanish electricity mix has increased or remained stable from 2010 to 2022. Analysis of four indicators (child labour, contribution of the sector to the economic development, frequency of forced labour and women in the sectoral labour force) reveals significant differences, highlighting three main social hotspots: i) solar PV panel production in East and Southeast Asia, particularly China, ii) natural gas extraction and refining in North Africa, concentrated in Algeria, for natural gas combined cycle and cogeneration plants, and iii) construction and operation of hydropower and nuclear plants in Spain. This study demonstrates that current strategies for Spain's power sector transition may not guarantee a favourable social performance, emphasizing the need for balanced environmental and social considerations in energy policy making, aligned with the Sustainable Development Goals.

1. Introduction

In recent years, the global emphasis on sustainability has been intensified, driven by the accelerated effects of climate change, including ecosystem degradation, increased natural disasters, and social inequality. The United Nations' Sustainable Development Goals (SDGs), set out in the 2030 Agenda, have also promoted sustainability, urging nations to pursue a sustainable future trough environmental protection, economic growth and social well-being (General Assembly UN, 2015; UNEP/Life Cycle Initiative, 2020). This increased awareness has catalysed nations around the world to transition towards sustainable, net-zero economies requiring global mobilisation with a substantial increase in investments and national sustainability-focused plans (Kern et al., 2019; Tsalis et al., 2020). The Organisation for Economic Co-operation and Development (OECD) estimates that to have more than a 50 % chance of limiting global surface temperature increase to under 2 °C, global investments exceeding €500 billion annually over this decade are needed (OECD, 2017).

Numerous regions and countries are actively implementing measures and objectives to make their economies sustainable and net-zero by 2050 (Liobikienė and Butkus, 2017; Brown et al., 2018; Kern et al., 2019). The European Union has well received this transition, as evidenced by its commitment to the European Green Deal, approved in 2020 (European Commission, 2019, 2022, 2023). Specifically, it sets three goals for the European Union: (i) achieving net-zero greenhouse gas emissions (GHG) by 2050, (ii) decoupling economic growth from resource use, and (iii) leaving no one behind. While the pact encompasses various sectors, a key focus is transitioning to net-zero national energy sectors (Ringel and Knodt, 2018; Dupont et al., 2020). Within the European countries, Spain stands as a notable example where specific policies and strategies are being effectively introduced (Espinosa et al., 2021), namely, the 2021 Climate Change and Energy Transition Law

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(Ministerio de Transición Ecológica, 2021) and two essential planning instruments, the National Integrated Energy and Climate Plan (PNIEC) and the Decarbonization Strategy for the Spanish Economy by 2050 (Ministerio de Transición Ecológica, 2020). The objectives of the law and plans encompass ensuring Spain's compliance with the Paris Agreement, promoting economic decarbonisation and a circular economy, along facilitating climate change mitigation and adaptation. Regarding the electricity mix, the initial goal of achieving at least 74 % renewable generation by 2030 has been updated to 81 % in the 2023–2030 PNIEC draft (Ministerio de Transición Ecológica, 2023).

However, the implementation of structural changes aimed at reducing GHG emissions from the Spanish power sector may have profound and multifaceted implications (EU Platform on Sustainable Finance, 2022a, 2022b). Amid the frenzy of debates about the environmental and economic ramifications, shifting the focus to the equally critical social dimension is necessary, ensuring that no stratum of society bears the brunt of this transformative process (Simas et al., 2014; Fortier et al., 2019). Integrating the social dimension into energy planning is a complex task, but it is an indispensable challenge, as recognised by international institutions (European Commission, 2019; UNEP/Life Cycle Initiative, 2020). Neglecting such dimension in energy transition efforts can lead to adverse and unintended social consequences, which has the potential to undermine the overarching objectives of a sustainable power sector (Tsalis et al., 2020; Sachs et al., 2022).

In the last decade, environmental life cycle assessment (LCA) has gained relevance to assess the environmental impacts caused by the transition to renewable power systems (Hertwich et al., 2015; Pehl et al., 2017; Kiss et al., 2020). Advances in this field have allowed to evaluate environmental issues such as the contribution to climate change or the use of resources of the Spain's power sector transition (García-Gusano et al., 2016; Martín-Gamboa et al., 2019; Iribarren et al., 2020). However, despite the paramount importance of this topic, there is still a notable dearth of comprehensive studies on the social implications, including a supply-chain perspective, of current transitions in national power sectors. This is particularly important assuming the increasing offshoring of energy markets and their complex value chains.

Under these circumstances, social life cycle assessment (S-LCA) emerges as a crucial and well-regarded method within the realm of sustainability science as well as a key approach for both the public and private sectors (UNEP, 2020). S-LCA is a technique that comprehensively addresses the possible positive and negative impacts throughout the entire value chain and life cycle of products and/or systems (UNEP, 2020). In recent years, the results of S-LCA are increasing their relevance to support policy decisions and business strategies (Ramos Huarachi et al., 2020). Therefore, its use is considered convenient and justified for understanding the social repercussions of the current transformation of the Spanish power sector. In this way, the general objective of this article is to present, for the first time, a comprehensive evaluation of the social impacts inherent to the Spanish electricity mix and their power technologies involved, following a supply chain perspective, during the last twelve years. Moreover, at present, the number of power generation systems evaluated through the S-LCA methodology is still low in the literature (Mancini et al., 2023; Martín-Gamboa and Iribarren, 2023). Thus, another contribution of this article to the current state-of-the-art is to provide a broad representation of the social implications of such systems. This portfolio of results will allow identifying not only the social impacts of electricity production but also those associated with the energy systems' supply chains.

The present article is structured into several distinct sections. Section 2 details the methodology, comprising: i) description of the Spanish electricity mix and the technologies involved (Section 2.1) as well as ii) description of the S-LCA framework (Section 2.2) and its application to power technologies in terms of goal and scope (Section 2.2.1), data collection for social life cycle inventory (S-LCI) Analysis (Section 2.2.2) and social life cycle impact assessment (S-LCIA) (Section 2.2.3). Section 3 (results and discussion), encompassing social impacts and hotspots of power technologies (Section 3.1), as well as past evolved results of the Spanish electricity mix over the last decade (Section 3.2). Lastly, Section 4, the conclusions, encapsulates main findings, emphasises their implications, and delineates directions for future research and policy implementation.

2. Material and methods

The present article aims to respond to the following research question: what are the specific social implications of the current transition of the Spanish power sector? To reach this, the general objective of this work is the S-LCA application to evaluate the social impacts of the power technologies involved in the Spanish electricity mix and their supply chains over more than a decade (from 2010 to 2022). This objective aligns with the recommendations established by the United Nations Development Programme, the International Labour Organization and the European Green Deal ("leave no one behind"). Specific objectives of the present study include: i) to estimate the social life-cycle impacts and identify the main hotspots related to the power generation technologies and their supply chains, ii) to verify if current proposed measures for the transition of the Spanish power sector are both mitigating potential social risks and contributing to positive social impacts, and iii) to provide useful scientific-based recommendations that can guide Spanish energy policy and decision-making processes, ensuring a socially equitable transition.

2.1. Evolution of the Spanish power sector across the last decade

In Spain, the evolution of the power sector has been marked by several factors. First of all, it is important to analyse the variation in electricity consumption. In general, a downward trend can be observed with a reduction of 10 % of the total national demand over the last twelve years (from 255 TWh in 2010 to 235 TWh in 2022) (REE, 2024). Several reasons mark this trend in consumption habits, such as the intermediate economic recovery experienced from 2014 to 2018, the global pandemic and the beginning of political tensions due to the conflict in Ukraine (Pablo-Romero et al., 2023). These recent events have denoted a change in the country's productive structure, with a subsequent decrease in the energy demand of the industrial sectors and their contribution to the Gross Domestic Product (GDP). Finally, another variable that stands out is the notable increase in self-consumption, accounting for 7154 MW of solar self-consumption systems installed across Spain so far (REE, 2024).

Energy planning has also significantly shaped the Spanish power sector over time. Before the studied period, policy-making strategies were initially focused on nuclear, affected by a nuclear moratorium in the 1980s, coal thermal, and hydropower. In this line, coal and nuclear power accounting for 60 % to 70 % of total output during the 1990s and beginning of the 2000s (REE, 2024). Simultaneously, the Spanish regulation of renewable energies began in the 1980s. Several initiatives were passed to encourage renewable energy production, highlighting the establishment of the special regime under Law 40/1994, the 1999 Renewable Energy Promotion Plan (PFER) and the National Action Plan for Renewable Energy in Spain (PANER) for the period 2011–2020 (Ministerio de Industria, Comercio y Turismo, 2010). The latter translated the Directive 2009/28/EC, including the target of achieving 20 % renewable energy consumption by 2020, although its effective implementation was hindered by the effects of the 2008 economic crisis. Particularly, law 15/2012 introduced new taxes for the electricity sector, and Royal Decree-Law 1/2012 suspended economic incentives for new renewable energy plants. At present, the National Integrated Energy and Climate Plan (PNIEC) and the Decarbonization Strategy for the Spanish Economy by 2050 (Ministerio de Transición Ecológica, 2020), are boosting again the transition to renewable energy sources and the search for a mix balance between energy security, sustainability, and competitiveness.

Fig. 1 illustrates how the contributions of each power technology have evolved between the years 2010 and 2022, reflecting the past and present trends in the Spanish power sector landscape. The reduction in the coal thermal power contribution is noteworthy, especially in the last year of analysis (3 % of contribution to the electricity mix). The gradually decreasing of electricity production from coal is due in part to stricter emissions regulations and the rising costs associated with this power technology. Additionally, Spain has sought to diversify its energy matrix to reduce dependence on a single source, in contrast to the 1990s and 2000s decades. Nuclear power has consistently contributed to the mix (around 22 %), despite ongoing debates about its future due to public opinion. It is also worth noting the unique situation of hydropower, whose deployment was carried out before the study period. At present, there is limited scope to expand its capacity due to natural resource constraints (Vliet et al., 2016). Furthermore, the escalating incidence of droughts in Spain is causing a decline in its contribution to the mix, with a share of 7 % in the year 2022.

The evolution of the natural gas combined cycle (NGCC) power in Spain has been significant in the last decade. Since the installation of the first plant, generation has increased within the Spanish electricity mix until the end of 2012 when the national installed capacity reached 24,948 MW (REE, 2024). From that point forward, the generation capacity of these plants has remained constant up to the present day in contrast to their production which has suffered substantial variations. For instance, in 2010, NGCC contribution to the mix was 10 % (Fig. 1) while in 2022, it became one of the main sources of electricity generation in Spain, accounting for nearly 23 % (REE, 2024). This shift can be attributed to their flexibility and their comparatively lower GHG emissions relative to other fossil fuel technologies (Martín-Gamboa et al., 2018).

During the study period, cogeneration in Spain has experienced contribution percentages around 10 %. This technology has been supported by the government in its drive towards reducing GHG emissions and improving energy efficiency, being a power and heat source for numerous industrial complexes (REE, 2024). With respect to the renewable power technologies, a steady and robust increase of their contribution to the mix has been experienced in the last decade, as shown in Fig. 1, being particularly notable in the case of wind - onshore and solar photovoltaic (PV) power generation. In the first case, this advancement has been facilitated by the presence of regions with significant wind energy potential, the implementation of renewable energy plans and a robust wind energy sector in Spain (Frade et al., 2018; Macedo et al., 2022). At present, wind power has an installed capacity around 30 GW. This figure represents a quarter of the total national installed capacity, remaining as the technology with the highest participation in the installed power structure and the main source of renewable generation in Spain (REE, 2024). In the case of solar PV, it recently emerges as the technology with the greatest growth facilitated by the easing of regulations on self-consumption generation (Shirazi and Shirazi, 2012). At present, solar PV has an installed capacity of 19,785 MW, accounting for 16.6 % of the total national installed capacity (REE, 2024).

2.1.1. *Technical specifications of power generation technologies*

In this section, further information in terms of the technical specifications for the power generation technologies within the Spanish electricity mix is provided. This ensures that the results of the study are representative to the general situation of the power sector in Spain. Table 1 gathers the complete list of technologies considered in this study and four key parameters namely, capacity factor, efficiency, averaged installed capacity, and averaged annual output, which are essential for a comprehensive understanding of the power sector. The power generation technologies considered are those that existed during the evaluated period in the Spanish energy mix, excluding those with a contribution of less than 1 %. Values in this table were collected from national (REE, 2024; Ministerio de Transición Ecológica, 2024) and international

Table 1
Technical characteristics of the power generation technologies involved in the Spanish electricity mix.

Power generation technology	Capacity factor	Efficiency (%)	Averaged installed capacity (MW)	Averaged annual production (GWh)
Coal thermal	0.80	45.00	1,500.00	10,512.00
Natural gas combined cycle (NGCC)	0.80	58.00	800.00	5606.40
Cogeneration	0.75	57.00	20.00	131.40
Nuclear	0.95	37.00	1,000.00	8,322.00
Hydropower - dam	0.25	80.00	350.00	766.50
Hydropower – run-of-river (RoR)	0.30	80.00	4.00	10.51
Wind - onshore	0.30	35.00	2.00	5.26
Solar photovoltaics (PV)	0.21	15.00	5.00	9.20
Solar thermal without storage	0.38	36.00	50.00	166.44
Waste-to-energy plant	0.80	27.00	20.00	140.16
Biomass plant	0.70	34.00	50.00	306.60

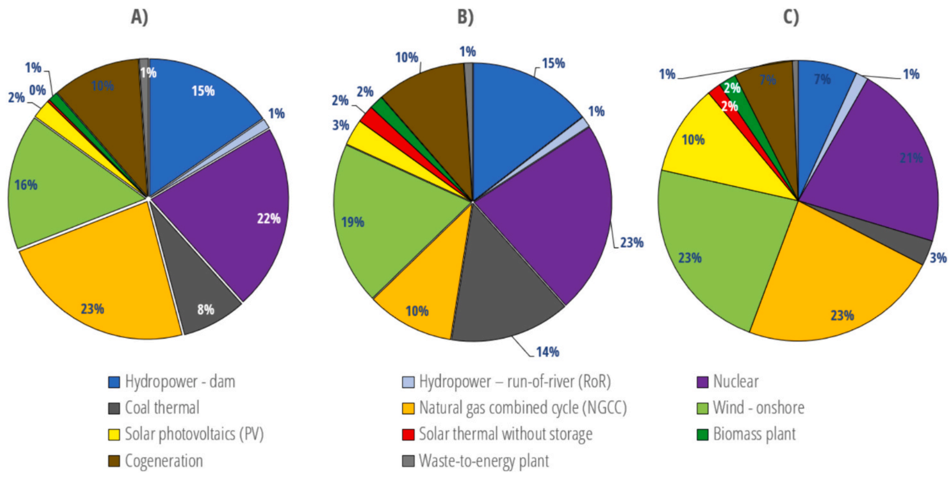

Fig. 1. Power generation structure in Spain for the years a) 2010, b) 2016 and c) 2022.

statistics (OECD, 2024). First, the capacity factor is a critical measure interpreted as the percentage of time in which the plant operates at its maximum capacity. A higher factor indicates more efficient use of installed capacity, however, a low-capacity factor can indicate availability issues, such as frequent maintenance or unplanned downtime (Joskow, 2011). In this aspect, the technologies with the highest ratio within the Spanish electricity mix are coal thermal, NGCC, cogeneration, nuclear as well as waste-to-energy and biomass plants. It is important to bear in mind that three of these technologies, namely NGCC, cogeneration and nuclear, represented around half of power generation over the period evaluated.

Secondly, efficiency is a critical measure of a plant's ability to transform primary energy inputs (such as solar, wind, coal, etc.) into usable electricity. This parameter is closely related to the capacity factor. Although a power technology may have high efficiency, its ability to operate constantly significantly influences its annual production. Looking at the data in Table 1, it can be highlighted that technologies vary significantly in terms of efficiency. For instance, hydropower has remarkably high efficiencies, whereas waste-to-energy plants and, notably, solar PV register much lower values. In the case of the former technology, its high efficiency does not offset its low capacity factor, leading to an increasingly less significant participation of hydropower in the electricity mix.

Installed capacity refers to the maximum amount of electricity that plants can physically produce. The power technologies with the highest average capacity per plant in Spain include coal thermal, NGCC, nuclear and hydro dam. These types of plants typically operate on a large scale, requiring significant capacity investment. This contrasts somewhat with the total installed capacity data, which shows a strong presence of wind and solar PV technologies in recent years of the evaluated period, representing 24 % and 20 % of the total, respectively (REE, 2024). This pattern suggests a clear commitment to renewable sources, although it is important to note that coal-fired plants still constitute a 3 % of the installed capacity in Spain. Annual electricity production, measured in GWh, represents the total amount of energy generated by each type of power plant over a year. While solar PV plants have a relatively minor power output per plant, this technology has emerged as significant contributor, accounting for more than 10 % of the Spanish power generation structure in the last years. In contrast, hydroelectric plants, with an exceptional efficiency of 90 %, have moderate production levels due to their capacity factor. Natural gas plants, noted for their solid performance, have a notable relatively output, contributing more than 40,000 GWh annually which highlights their importance in the current energy mix.

2.2. S-LCA framework

The S-LCA methodology, based on the updated Guidelines for S-LCA of products (UNEP, 2020), offer researchers and practitioners a practical and widely recognised framework for assessing both positive and negative social and socio-economic impacts of products throughout their life cycle. This methodology comprises four interconnected phases, as illustrated in Fig. 2, based on the ISO 14040 standard (ISO, 2006). The "goal & scope definition" phase of the S-LCA involves setting the objectives of the study, the functional unit (FU), and the system boundaries. Completing these boundaries remains a challenge, especially in the background system, given the system boundaries shall be representative of the product system, involving product-specific processes within them and their associated regions or, at least, countries. However, this challenge is alleviated in this study by incorporating a supply chain definition protocol, a procedure proposed by Martín-Gamboa et al. (2020). This protocol helps practitioners to define supply chains for S-LCA studies and integrates the use of both trade and LCI databases, taking into account statistical data from recent years to ensure the acquisition of reliable information on international trade of commodities as well as the suitable identification of potential suppliers.

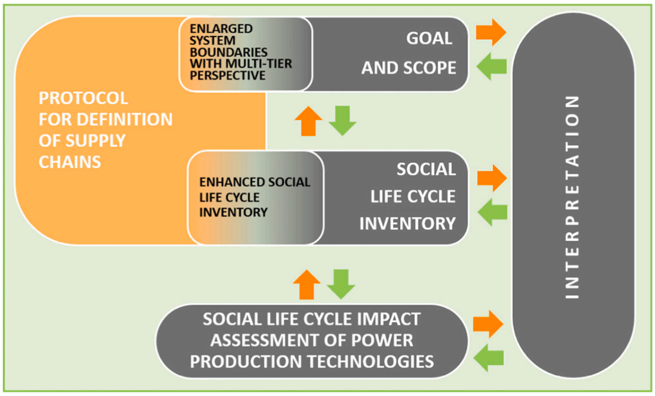

Fig. 2. S-LCA framework for the present study with integrated supply chain definition protocol.

Proceeding to the S-LCI analysis, it is centered on data collection for unit processes within predefined boundaries, using geographical information and an activity variable per FU (UNEP, 2020). Given the site-dependent nature of social impacts, it is essential to use regional/sector-specific or, at least, country-specific data in S-LCA (Iribarren et al., 2023). However, acquiring such information may be challenging for S-LCA practitioners, particularly for upstream processes. The application of the protocol addresses this challenge by identifying the countries of origin for the unit processes involved in the value chain. The S-LCIA phase involves the evaluation of potential social impacts associated with the product system under study (UNEP, 2020). Activity variables are translated into social impacts through an impact assessment method, with a choice between two main approaches: the reference scale approach (type I) and the impact pathway approach (type II). This study adopts the reference scale approach, a method currently recognised as the most feasible and readily applicable. For instance, the ORIENTING and SH2E projects, initiatives aimed at developing a robust and operational methodology for life cycle sustainability assessment, endorse the use of the first type of impact assessment approaches (Hackenhaar et al., 2024; Martín-Gamboa et al., 2024). Further information regarding reference scale approaches can be found in the Supplementary Material (Section S3.1). Finally, the interpretation phase involves a comprehensive review and in-depth discussion of the results. The goal here is to draw meaningful conclusions and provide informed recommendations for decision-making.

2.2.1. Goal and scope

The goal of this S-LCA study is to comprehensively evaluate the potential social impacts associated with each of the power technologies involved within the Spanish electricity sector and their supply chains, providing the evolved profile of the sector across the last twelve years (i.e., from 2010 to 2022). The FU of the study is defined as 1 kWh of electricity produced in Spain. This study adopts a cradle-to-gate approach, covering the following stages: extraction and processing of raw materials, manufacturing of capital goods (i.e. infrastructure and equipment), assembly and/or construction, as well as operation and maintenance of power plants. The distribution of electricity and the end-of-life (Eol) stage of the power technologies are not included within the system boundaries of the value chains. The exclusion of the latter is due to the uncertainties linked to EoL modelling of power technologies, particularly the renewable ones, and the limited data available in social databases. Fig. 3 illustrates the representative system boundaries for the power technologies under examination.

Current guidelines for conducting S-LCA for energy systems (UNEP, 2020; Iribarren et al., 2023) stipulate that system boundaries must accurately represent the system under evaluation, incorporating product-specific processes. Power technologies usually involve complex value chains with a considerable number of unit process across various

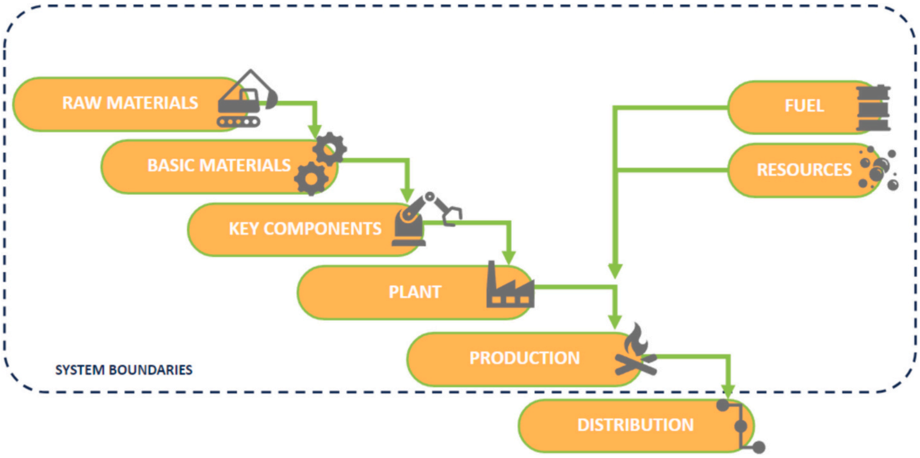

Fig. 3. Simplified system boundaries for the power generation technologies under evaluation.

"tiers" (Wu et al., 2017). Therefore, it is crucial to use procedures that fully define the system boundaries, with special emphasis on background processes. The protocol applied in this study combines life-cycle inventory (LCI) data regarding the flows of components, materials, and energy within unit processes, alongside determining the country where the evaluated product is obtained considering historical import-export balances. It is important to note that "historical" term should be understood as the use of past statistical data that allowing to appropriately select the countries of origin according to the installation dates of the power plants. To discard less relevant unit processes within the chosen value chains, the protocol applies an economic cut-off criterion based on techno-economic assessments. According to Iribarren et al. (2023), it is a common practice to apply a cut-off criterion in the selection of product-specific processes for inclusion in the S-LCA of energy systems. In this regard, the recommendation suggests that, at least, all processes contributing economically by more than 5 % to the final economic output value should be incorporated following a product-specific approach. If this is not the case, it is advised that practitioners transparently state and justify the rationale behind their cut-off choice.

Finally, the "Social Impacts Weighting method" provided by the PSILCA database (Loubert et al., 2023) is adopted for the social impact assessment while the selection of impact categories followed a two-step indicator prioritisation strategy based on data quality and materiality assessment. The first step consists of a pre-selection of the whole sample of indicators available in the PSILCA database. This involved the analysis of the characteristics of these indicators using PSILCA documentation (Loubert et al., 2023) and consultation with experts in the field for the following factors: technical and completeness conformity, geographic and temporal coverage, and the reliability of the source(s). Section S1 of the Supplementary Material includes further details on the data quality procedure and presents the list of 19 indicators that have been preselected according to this assessment.

In the second step of the prioritisation, the materiality assessment, two surveys were conducted online to identify and prioritise the issues most significant to stakeholders, including representatives from companies, policy, academia, and civil society. The first assessment (A) focused on indicators related to the worker category and included a sample size of 155 individuals from Spain. The distribution among the surveyed groups was 38 %, 21 %, 18 %, and 23 %, respectively. Section S2.1 of the Supplementary Material provides further details about the sample characteristics (Figs. S1–S3). The second assessment (B) covered indicators associated with stakeholders' local communities, society, and value chain actors, involving a sample size of 57 individuals. In this case, the distribution among companies, policy, academia and civil society was 12 %, 9 %, 20 %, and 59 %, respectively. Section S2.2 of the Supplementary Material further elaborates on the characteristics of the second sample (Figs. S4–S6). In both surveys, the age distribution shows a significant number of participants in the 20–30 age range, indicating a substantial concentration of individuals within this demographic. This particular age distribution could potentially influence the survey's results and conclusions, as the viewpoints and opinions of this age group could significantly impact the analysis. The questionnaire designs for materiality assessments A and B can be found in Sections S2.3 and S2.4 of the Supplementary Material, respectively, while the results from those questionnaires are available in Section S2.5 (Figs. S7 and S8) and S2.6 (Figs. S9–S11). Based on the results obtained from the two-step indicator prioritisation strategy, Table 2 contains the final list of stakeholders and indicators used for the assessment, aligning with the S-LCA database utilised in this study (refer to Section 2.2.2 for more details).

2.2.2. *Social life cycle inventory*

S-LCI for each power technology requires data on the activity variable, potential suppliers, and social flows. Since the system boundaries of these technologies have a product perspective and according to the S-LCA guidelines (UNEP, 2020), an activity variable has been used to represent the share of a given activity linked to each unit process within the product system. The activity variable chosen is 'working hours' which, for foreground processes, was estimated from information on the required staff and working time of the process being evaluated. A greater number of worker hours to a unit process implies a larger share of the process within the life cycle, thereby increasing its contribution to the overall impact indicator results of the product system. Worker hours data were obtained from different sources specified in Supplementary Material. Information for the inventory of background processes was retrieved from global databases and techno-economic studies (refer to Supplementary Information of S-LCIs). An economic cut-off criterion was implemented at the unit process level to disregard flows that contribute less than 0.5 % to the total cost. The selection of this criterion ensuring all relevant processes from extraction of raw materials (e.g., coal, natural gas, nuclear or biomass) to the final electricity production

Table 2
Preselected sample of social indicators according to a two-step indicator prioritisation approach.

Stakeholder	Indicator
Worker	Child in employment, total Frequency of forced labour Women in the sectoral labour force
Local community	Level of industrial water use (related to total withdrawal) International migrant stock
Society	Contribution of the sector to economic development Health expenditure, total
Value chain actors	Social responsibility along the supply chain

are included. These economic flows are subsequently linked to working hours specific to each country and/or sector using the PSILCA database.

Potential suppliers were identified based on trade statistics for the years corresponding to the installation dates of the power plants. Trade information was retrieved from the UN Comtrade database (UN Comtrade database, 2024), the largest repository of international trade data with approximately 40 billion data records from 170 countries/regions since 1962. Export and import data extracted from the UN Comtrade database are systematically managed through an automated process in Python code following the steps of the supply chain protocol (Martín-Gamboa et al., 2020). Final results from the applied protocol, including the identified unit processes within the supply chains and their locations, along with the remaining input and output S-LCI information and data sources are detailed in the Supplementary Material. For materials and components not included in the selected trade database, market share analysis was employed to identify potential suppliers' regions (GWEC, 2021; IEA, 2022).

The final stage in the S-LCI analysis involved defining reference scales for different levels of social performance or social risk. Given the challenge of obtaining direct information for the definition of such scales, they were retrieved from the PSILCA database. This method offers social indicator flows for 189 countries and 14,838 country-specific sectors and commodities, drawing on data from international statistical agencies such as the World Bank, the International Labour Organization (ILO), World Health Organization, United Nations, and various private or governmental databases (Loubert et al., 2023). It should be noted that version 2 of the PSILCA database and method was used in this study to provide a retrospective perspective of the social flows according to the average year of installation of each type of power plant, as determined from the Spanish registry of electrical energy production facilities (MITECO, 2024).

2.2.3. Social life cycle impact assessment and interpretation

The overall social impacts of the power generation technologies in the Spanish electricity mix were calculated by aggregating the social risks/opportunities of all involved processes along the identified value chains. Social risks/opportunities result from combining the economic flows, working hours and characterisation factors. This was carried out through inventory data implementation into the OpenLCA software (GreenDelta, 2024) and the use of the Social Impact Weighting Method. The unit to report the results of social impacts are reported in medium risk hours (mrh) per FU. These units represent the number of worker hours along the supply chain that are potentially characterised by a certain level of social risk. It is important to note that the risk hours associated with different indicators should not be compared or combined (Martin and Herlaar, 2021; Valente et al., 2019). For the sake of clarity, a high impact score may indicate either a labour-intensive process or a power technology system with high social risks (i.e. more negative performance), or a combination of both factors. The only exception is the *contribution of the sector to economic development* indicator, which is a positive impact indicator, so, higher values are more desirable. Finally, the interpretation allows to check and discuss in depth the results. This includes comparing the performance of different power generation technologies, understanding the implications of the social hotspots identified, comparing different scenarios and suggesting potential areas for improvement (see Sections 3.1 and 3.2). The interpretation phase ensures a basis for conclusions, recommendations, and decision-making in accordance with the goal and scope definition.

3. Results and discussion

3.1. Social life cycle impact assessment of power technologies involved in the Spanish electricity mix

Addressing the research question of this study requires a first thorough evaluation and interpretation of the social impacts associated with each of the power technologies involved in the Spanish electricity mix. In this sense, Table 3 shows the social impact results for the technologies described in the Section 2.1.1. To facilitate the discussion this section considers four selected indicators from Table 2: *child labour* (*total*), *contribution of the sector to economic development*, *frequency of forced labour*, and *women in the sectoral labour force*. A color-coded guide is included to help readers easily classified the relatively social performance of power technologies for each indicator. The impact results for the complete set of indicators of Table 2 can be found in the Supplementary Material (Section S3.2 of the Supplementary Material - Table S2). It is important to note that the values presented in Table 3 do not represent actual social impacts, but rather the potential for such impacts. For instance, when examining the child labour indicator for wind power systems, the interpretation should be as follows: for a typical plant (representing the main characteristics of Spanish wind energy facilities), there is a statistical probability of approximately $1.89 \cdot 10^{-6}$ h of child labour risk per FU occurring across the countries encompassing its value chain.

About the analysis of the results presented in Table 3, it is important to highlight that these must be evaluated indicator by indicator. For a precise interpretation of the *child labour* results, it is crucial to understand its definition. This rationale applies to the other indicators as well. *Child labour* definition is as follows: "Children in employment refer to children involved in economic activity for at least one hour in the reference week of the survey […] The data here have been recalculated to present statistics for children ages 7–14." (World Bank, 2024). A significant variability is observed in the social impact results across the different power technologies. For instance, while wind and nuclear power show very low values, solar PV, NGCC and cogeneration show relatively high impacts. It is important to highlight that hydropower dam and RoR show zero impact on *child labour*. This indicates that these technologies involve unit processes located in national sectors with null risk (assigned to a zero value in PSILCA), which is a positive aspect for eradicating child labour.

This observed variability deserves further analysis in terms of social hotspots. In the case of solar PV, its high impact value is mainly associated with the geographical concentration of part of its supply chain in the East and Southeast Asia, predominantly China. These regions presented higher child labour risk levels in the majority of sectors involved at the date of plants installation. Particularly, the process with the greatest potential risk corresponds to the polycrystalline silicon production, which is used in solar wafer manufacturing (Crawford and Murphy, 2023). In the case of NGCC and cogeneration, the risks stem from to the extraction and refining of fossil fuels in North Africa, particularly in Algeria. The zero impact of hydropower dam and RoR can be attributed to the geographical concentration of their value chain in Spain, the country under study.

The indicator *contribution of the sector to economic development* evaluates the extent to which sectors contribute to country's economic development, quantified as their monetary contribution to the national GDP. Thus, the overall social impact results for this category represent the net effect of each technology on the economic development of the countries involved in their respective value chains, which can be translated in the creation of jobs or specific investment in education and training. Values in the Table 3 indicates that solar PV has a significant positive impact in this category, suggesting a notable contribution to the economic development of the countries involved across the value chain, particularly those located in the East and Southeast Asia (i.e. China). Similarly, nuclear and hydropower dam also has a positive impact, although of a smaller magnitude, specially concentrated on the construction and operation of power plants in Spain. In contrast, wind onshore shows the relative lower contribution among the technologies. This highlights the importance of incorporating positive impacts in the evaluation of energy systems, which is a current challenge in the S-LCA methodology (Di Cesare et al., 2018), enabling a balanced interpretation of social aspects.

Table 3
Heat map of S-LCIA results per FU for the power technologies involved in the Spanish electricity mix. Shaded cells denote a relatively more favourable [green] or unfavourable [red] performance of the power technology under a specific indicator.

Power Generation Technology	Child labour, total (CL med risk hours)	Contribution to economic development (CE med risk hours)	Frequency of forced labour (FL med risk hours)	Women in the sectoral labour force (W med risk hours)
Coal thermal	$3.53\cdot10^{-6}$	$-1.17\cdot10^{-3}$	$4.49\cdot10^{-6}$	$5.49\cdot10^{-4}$
Natural gas combined cycle (NGCC)	$1.12\cdot10^{-2}$	$-1.84\cdot10^{-3}$	$1.13\cdot10^{-4}$	$1.56\cdot10^{-2}$
Cogeneration	$2.48\cdot10^{-3}$	$-2.23\cdot10^{-3}$	$3.98\cdot10^{-5}$	$5.23\cdot10^{-2}$
Nuclear	$3.63\cdot10^{-5}$	$-1.62\cdot10^{-2}$	$2.47\cdot10^{-5}$	$3.37\cdot10^{-2}$
Hydropower - dam	0.00	$-1.63\cdot10^{-2}$	$2.81\cdot10^{-5}$	$6.10\cdot10^{-2}$
Hydropower – run-of-river (RoR)	0.00	$-6.74\cdot10^{-3}$	$1.08\cdot10^{-5}$	$1.79\cdot10^{-2}$
Wind - onshore	$1.89\cdot10^{-6}$	$-4.73\cdot10^{-4}$	$2.46\cdot10^{-6}$	$6.90\cdot10^{-4}$
Solar photovoltaics (PV)	$3.24\cdot10^{-2}$	$-3.39\cdot10^{-2}$	$4.65\cdot10^{-5}$	$5.32\cdot10^{-3}$
Solar thermal without storage	$2.72\cdot10^{-4}$	$-3.93\cdot10^{-3}$	$2.43\cdot10^{-5}$	$2.75\cdot10^{-2}$
Waste-to-energy plant	$1.16\cdot10^{-5}$	$-1.41\cdot10^{-3}$	$1.11\cdot10^{-5}$	$5.42\cdot10^{-3}$
Biomass plant	$2.19\cdot10^{-3}$	$-1.99\cdot10^{-3}$	$8.32\cdot10^{-5}$	$1.38\cdot10^{-2}$

The *frequency of forced labour* indicator is defined as “all work or service which is exacted from any person under the menace of any penalty and for which the said person has not offered himself voluntarily” (ILO, 2024). The results of this indicator show that the social impact of technologies varies. NGCC technology has the highest impact, followed by biomass plants and solar PV. Conversely, the lowest impacts are associated with power technologies such as wind onshore and coal thermal. Most of the potential impact within the value chains of biomass and NGCC is due to the significantly higher risk levels associated with the extraction and refining of fossil fuels at the date of plants installation in Spain. These processes are primarily located in the regions of North Africa, Eastern Europe, and Western Asia. In the case of solar PV, the process that generates the greatest potential risk is related to the production of polycrystalline silicon in East and Southeast Asia, particularly China. The solar PV panel supply chain notably contributes to both child labour and forced labour risks, as well as to the positive impact. This highlights the necessity of such activities for the socio-economic development of regions as long as transparency and comprehensive monitoring of social and labour conditions across the entire power technology value chain is ensured, with the ultimate goal of respecting human rights (Crawford and Murphy, 2023).

The final social aspect to evaluate is the *women in the sectoral labour force* indicator, which serves as a measure of structural discrimination against women. “Structural discrimination refers to rules, norms, routines, patterns of attitudes and behaviour in institutions and other social structures that represent obstacles for groups or individuals in achieving the same rights and opportunities available to the majority of the population.” (Najcevska, 2010). There are significant differences in women’s participation in the sectoral workforce, depending on the power technology being evaluated. For instance, hydropower dam and cogeneration power plants show a higher potential risk of excluding women across the value chain compared to other technologies. Within the hydropower dam value chain, geographically concentrated in Spain, the activity that generates the greatest risk is construction, where the presence of women is scarce. It is important to note that this analysis is retrospective, considering risk values at the time of the plant’s construction, which persist today. The situation with cogeneration plants is similar to that of hydropower, as the high values obtained in this indicator stem from the same root cause. These findings highlight the need for policies and practices that promote diversity and gender equality in the workplace, which can, in turn, contribute to the social dimension of sustainable development in the power sector.

Overall, these results invite reflection on how labour and social conditions can be improved in power technologies and their supply chains, with the aim of transitioning towards a more ethical and socially sustainable energy systems. Furthermore, these results emphasize the importance of considering both environmental and social aspects when evaluating power technologies. The choice of a particular technology should not only comply with environmental performance standards but also align with socially fair and responsible deployment.

3.2. Social life cycle impact assessment of the Spanish electricity mix

Beyond the individual social evaluation of power technologies, it is of utmost importance to analyse the cumulative impacts of the Spanish electricity mix, taking into account the contribution of each technology. A technology with a higher potential impact does not necessarily have a significant effect on the electricity mix as a whole. This is also dependent on the proportionate contribution of each technology to the mix over time. This analysis will allow us to answer the research question of the present study: understanding the social implications of the current transition of the Spanish power sector. In this sense, the present section reflects the evolution of the social performance of the Spanish electricity mix in the selected impact categories over more than a decade (2010–2022). The S-LCIA results were obtained by multiplying the impacts per kWh (i.e. FU) of the power technologies by their relative participation in the mix generation structure during each year of the evaluated period. The evolved profiles for the remaining indicators of Table 2 can be found in the Supplementary Information (Section S3.2 - Figs. S12–S15).

Fig. 4, which illustrates the evolution of the *child labour* indicator, reveals a significant increase, especially in recent years. This is primarily

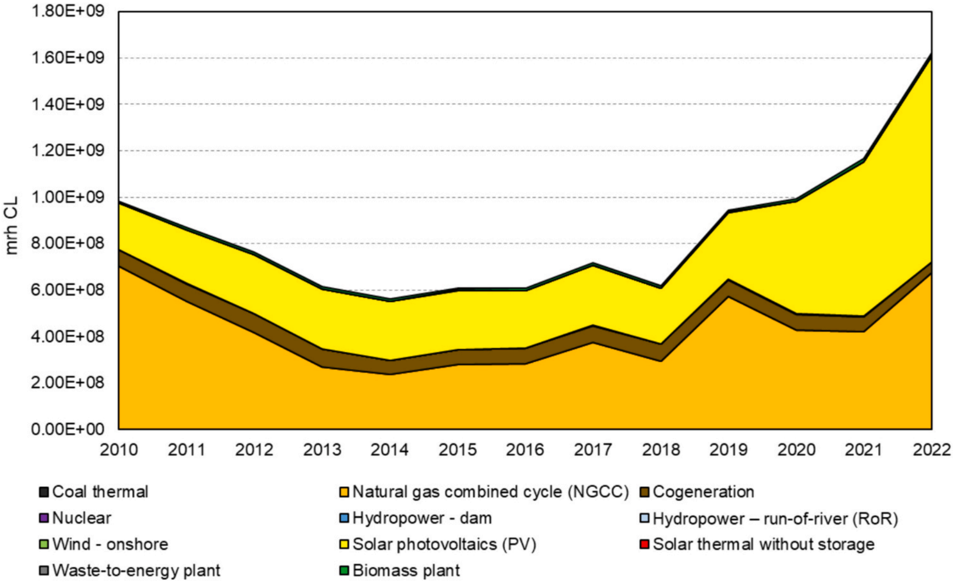

Fig. 4. Evolution of child labour impact of the Spanish electricity mix over the period evaluated (2010–2022).

attributed to the growth of solar PV in the electricity mix. The valleys observed in the intervening years correspond to a decrease in power generation through NGCC. This trend is similarly explained as in the previous section, due to the location of a significant part of the supply chain of these technologies in regions with notable potential levels of child labour risk at the date of plants installation. Specifically, this includes the supply chain of solar PV panels in East and Southeast Asia, predominantly in China, as well as the extraction and refining phase of fossil fuels in North Africa and mainly in Algeria (NGCC).

Fig. 5 depicts the evolving profile of the *contribution of the sector to economic development* indicator for the period under analysis. A stable performance with a progressive increase (around 30 %) in the last years is observed, mainly related to the higher solar PV contribution within the Spanish electricity mix. As discussed in the previous section, this is the most significant technology contributing positively to the national economies involved in its supply chain. This fact, along with the rapid growth of solar PV energy in the Spanish power sector, provides a unique opportunity to provide socioeconomic development through a clean energy source across the regions involved in its supply chain, as long as a zero social risk is guaranteed.

Despite the growing trend of solar PV, the most significant contributions to this indicator are given by nuclear and hydropower - dam, accounting for more than 70 % in most of the analysed period. This contribution is driven by the construction and operation activities of these plants in Spain, representing the construction and energy sector more than 7 % of the country's GDP during the analysed period. These results reflect the methodological need to incorporate a greater number of positive social aspects in S-LCA in order to enable a balanced interpretation of results for informed decision-making.

Fig. 6 shows the evolution of *frequency of forced labour* for the Spanish electricity mix over the last decade. This indicator demonstrates that, despite the individual social performance of each technology, its

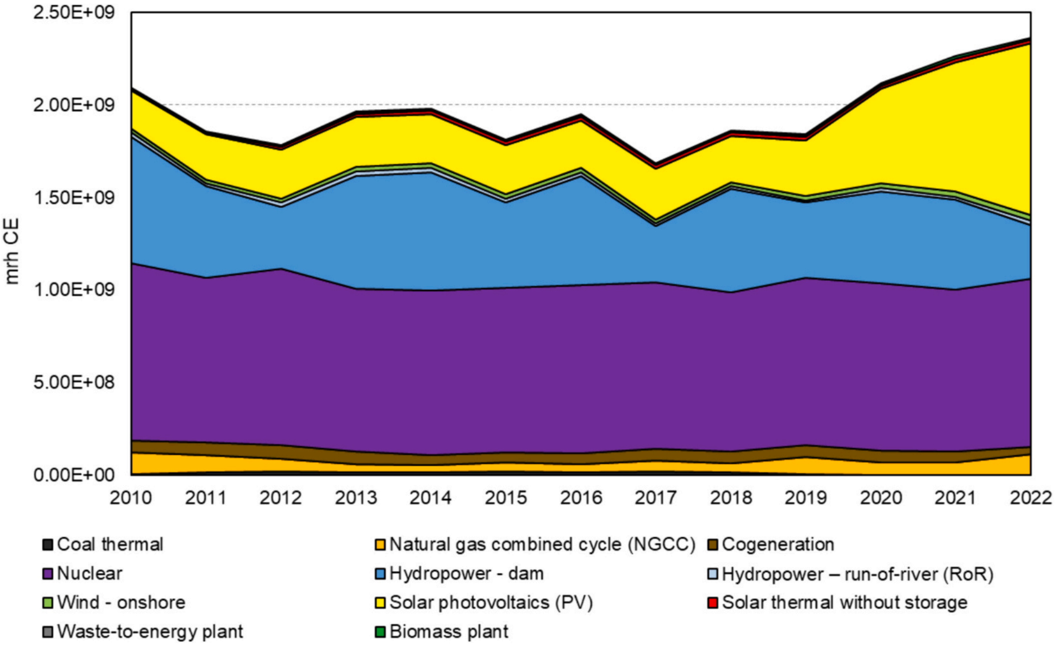

Fig. 5. Evolution of contribution of the sector to economic development impact of the Spanish electricity mix over the period evaluated (2010–2022).

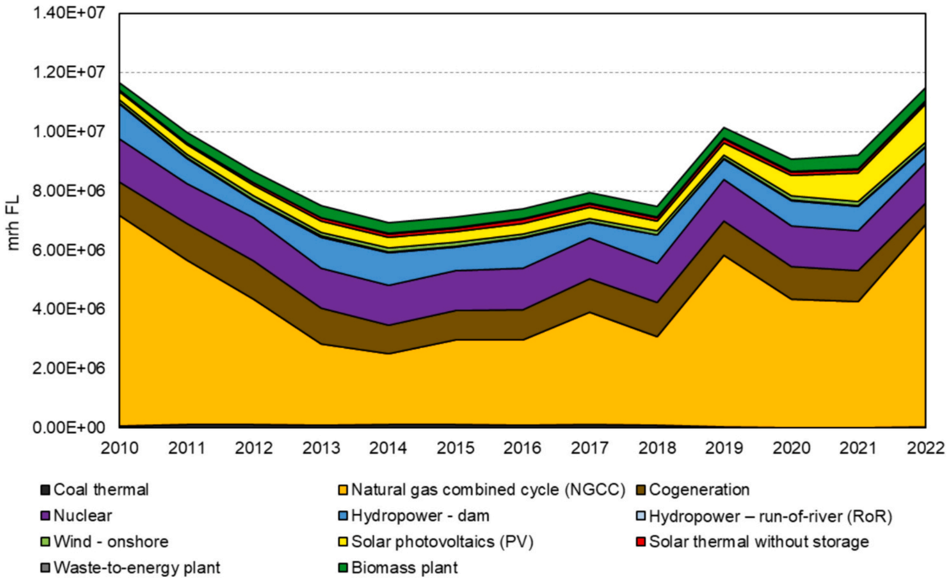

Fig. 6. Evolution of frequency of forced labour impact of the Spanish electricity mix over the period evaluated (2010–2022).

contribution to the electricity mix over time is key to determining the overall social impact of the power sector. In this case, although NGCC and biomass technologies have the highest impact values per FU, their different participation within the production mix over the last decade leads to very disparate evolved impact results. In this sense, the average contribution of NGCC technology to the potential risk of *frequency of forced labour* during the evaluated period is around 40 % compared to 3 % for biomass. As mentioned, this potential risk is mainly located in the extraction and refining of fossil fuels in North Africa. Seeking alternative natural gas suppliers with lower associated risk levels could be a short-term solution to minimise the potential impact of this technology. However, considering the nature of these impacts, it is crucial to aim for zero-risk targets in the medium-to-long term through monitoring and ensuring the respect of human and working conditions in the current countries involved in this stage of the value chain.

Finally, Fig. 7 shows the evolution of the *women in the sectoral labour force* indicator. The impact result, which remains relatively constant, is strongly influenced by the general trends of cogeneration, nuclear and hydropower technologies within the Spanish electricity mix, especially the variations of the latter. Particularly, these three technologies have the most significant impact per kWh on this indicator. This evolving profile is closely linked to the situation of women in the workforce of the energy and construction sectors during the evaluated period. According to official statistics, the presence of women in the Spanish energy sector in 2020 was 29.4 %, marking an approximate annual increase of 2 % since 2010 when it was 23.8 % (AEMENER, 2022). However, in the case of operator positions, the share is lower (19.3 %) and has even decreased over the decade evaluated, compared to the rest of the professional categories. Additionally, national reports reveal a significant gender gap in engineering areas, particularly those related to the supply of electricity, gas or steam (AEMENER, 2022). In the construction sector, which has traditionally been dominated by men, the scenario mirrors that of the energy sector. Over the past decade, women have constituted approximately 10 % of the workforce in Spain (INE, 2023). Given these trends, it is clear that there is a pressing need for additional policy instruments that encourage the participation of women in the energy and

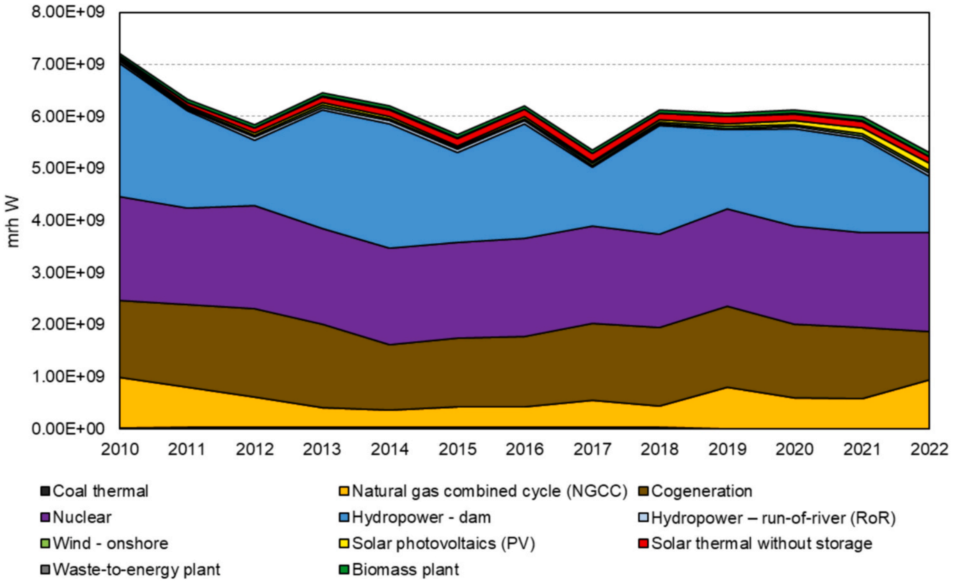

Fig. 7. Evolution of women in the sectoral labour force impact of the Spanish electricity mix over the last decade.

construction sectors. Such policies could help address the gender imbalance in these critical sectors, fostering diversity and inclusivity (CARE, 2022). This could not only enhance the sectors' resilience and innovation but also contribute to a more equitable and socially sustainable energy transition.

Overall, the S-LCIA results presented in this section provide a clear vision of how key social aspects have evolved within the Spanish electricity mix sector during the last twelve years (i.e. 2010–2022). It is crucial to recognise that, according to these findings, informed-decision making should be based on a combined interpretation of social indicators from both individual technologies and the electricity mix. In this sense, a higher risk associated with a particular technology does not necessarily translate into a significant effect on the electricity mix as a whole. Upon analysing the previously evolving profiles of the Spanish electricity mix, it becomes clear that the trajectory of social impacts over the years is either rising or stabilizing. This trend persists despite a reduction in electricity production and its associated GHG emissions during the same period. Solar PV deserves special attention due to its significant power production growth in recent years is translating into relevant potential impacts in the most of social indicators. This observation aligns with the objective of the study and reveals that the current strategies for transitioning Spain's power sector do not adequately consider the social repercussions of deploying power technologies and their supply chains, nor do they establish social targets to mitigate these effects. Consequently, current efforts to achieve sustainable power systems are falling short, as the social dimension is becoming increasingly decoupled from the economic and environmental aspects under a production perspective.

It is important to highlight that the updated S-LCA guidelines emphasize the importance of defining value chains in the assessment from primary (company-specific) data, and while the protocol used in this study provides a systematic approach, it relies on representative value chains modeled from average trade and life-cycle inventory data. This limitation extends to the use of S-LCA databases, such as PSILCA, which facilitate inventory generation and impact assessment, but employ data with low granularity (e.g., available only at the country level or with poor sectorial disaggregation) in certain social indicators. Additionally, complex social aspects requiring detailed data or positive impacts of power technologies, like reduced energy poverty, are also not captured. Potential future developments could address these aspects, providing a thorough assessment of social impacts.

Therefore, it is essential to incorporate social aspects in energy policy design and to evaluate these effects when making large-scale decisions. Since this study confirms that the current integration of renewable systems does not mitigate social impacts, the need for comprehensive social evaluations in national plans aimed at achieving 100 % renewable energy systems is especially crucial. The strategies should align with those established by international institutions. For instance, the European Platform for Sustainable Finance has proposed a social taxonomy that aims to provide a classification system to determine the social sustainability of an economic activity (EU Platform on Sustainable Finance, 2022a). Following this rationale, designing energy policy based on quantitative social criteria, in addition to economic and environmental ones, would enable the direction of capital flows towards entities, activities, and systems that respect human rights. This approach would support investments that improve living conditions, particularly for the most disadvantaged.

4. Conclusions

The present article provides an exhaustive S-LCA of the Spanish electricity mix, delving into the main social impacts and hotspots of the power technologies and their supply chains involved as well as, shedding light on their respective contributions and potential risks within the generation structure. When examining the trajectory of the last twelve years (2010–2022), it observes that the social impact associated with the Spanish electricity mix have increased or remained stable. Within value chain hotspot, three points stand out for their special contribution: i) the production of solar PV panels in East and Southeast Asia, predominantly China (solar PV plants), ii) the extraction and refining of natural gas in North Africa, particularly in Algeria (NGCC and cogeneration plants), and iii) the construction and operation of hydropower and nuclear plants in Spain. These results contrast with the widely spread assumption that the progressive integration of renewable technologies alone guarantees an improvement in the social performance of the Spanish electricity mix and, therefore, highlights the urgent need to implement a social impact perspective across the entire power technology value chain in any energy plan design or modification.

The present work also lays a solid and well-informed foundation for policy makers, researchers, and industry stakeholders, interested in considering the broader social implications of their decisions. Any transition in the energy landscape must be meticulously planned and conscientiously executed to ensure fairness for all segments of society. In this sense, the results can serve as a call to action for researchers and energy planners worldwide to prioritise and integrate social aspects into their respective national planning frameworks. In addition, due to the use of social life cycle indicators, the recommendations derived from this work will not only have an impact on national energy strategies but also on the management strategies of energy system supply chains, a geopolitical and logistical aspect that is receiving increasing attention.

Finally, the present research also defines key directions for future work. Firstly, it implicitly calls for an S-LCA of potential energy technologies planned for integration into the Spanish electricity mix to anticipate and mitigate their potential social impacts. Secondly, it advocates for an exploration of the evolution of social impacts within the electricity mix, forecasting trends and challenges in the long term (e.g. until 2050). Finally, future research should propose an evaluation and prioritisation of alternative scenarios to provide decision-makers with valuable information that facilitates sustainability-focused decision-making.

CRediT authorship contribution statement

Luisa Berridy-Segade: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **María del Prado Díaz de Mera Sánchez:** Writing – review & editing, Formal analysis, Data curation. **Miguel Ángel Reyes-Belmonte:** Writing – review & editing, Formal analysis, Data curation. **Mario Martín-Gamboa:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.06.030.

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