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A social sustainability assessment of a newly developed solar thermal energy system for industrial integration

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ABSTRACT

The deployment of solar thermal energy (STE) systems plays a critical role in decarbonising industrial heat demand; however, their sustainability performance includes not only technical efficiency and environmental impacts but also social considerations across the supply chain. This study presents a comprehensive social sustainability assessment of a newly developed STE system focusing on the manufacturing stages of its main components: SunDial concentrator, a phase change material (PCM) thermal storage tank, and a control unit. Social risks were quantified using a database driven risk hour (RH) approach, across different impact categories. including health and safety (H&S), fair payment, excessive working time, gender equality and policy compliance. The data were collected using Social Hotspot Database (SHDB) software, which simulated social risk levels based on material quantities and countries of origin of system components.

The results revealed that social risks are strongly dependent on country of origin and economic sector, rather than material quantity alone. The SunDial component manufactured in Spain demonstrated moderate H&S and gender inequality risks within the steel sector, while comparable components produced in Germany showed consistently low social risk levels. Similarly, manufacturing of PCM tank subcomponents in the Polish non-ferrous metals sector showed increased H&S risks, largely driven by high policy non-compliance and exposure to metal dust, while chemical production in the Netherlands showed substantially lower social risks due to stricter regulatory implementation.

The findings highlight the importance of geographically and sector specific social assessments when sourcing components for renewable energy systems. Incorporating social sustainability metrics at early stages of design can guide responsible supply chain decisions, improving the overall sustainability performance and social acceptability of industrial STE technologies.

1. Introduction

Social Life Cycle Assessment (SLCA) provides structural framework for evaluation of social impact along product life cycles and is formally grounded in the UNEP/SETAC Guidelines (2009; updated 2021) [1]. The guidelines adopt a stakeholder based approach that identify five primary stakeholder groups relevant to social impact analysis: workers, local communities, society, consumers and value chain actors. These stakeholders are linked to impact cathegories such as fair salary, working hours, health and safety (H&S), forced and child labour, equal opportunities, social security and community engagement [1,2]. The practical implementation of SLCA depends on selecting indicators that are stakeholder-relevant and methodologically feasible across global supply chains.

Current SLCA methodology is shaped by two dominant approaches.

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Nomenclature

Acronyms

ASTEP	Application of Solar Thermal Energy to Processes
HR	High Risk
H&S	Health and Safety
LH	Low Risk
MR	Medium Risk
PCM	Phase Change Material
PI	Principal Investigator
RH	Risk Hours
SHDB	Social Hotspots Database
SHIP	Solar Heat for Industrial Processes
SLCA	Social Life Cycle Assessment
SP	Social Performance
STE	Solar Thermal Energy

First, primary data approaches such as surveys, interviews, audits, Human resourses records that have been used to assess workers' conditions, local community impacts, and company-level practices in engineering systems [3,4]. While these methods offer high empirical validity, they are limited by resource intensity, narrow geographical coverage, and challenges in upstream data collection [3]. Second, the database-driven approaches, most notably the Social Hotspot Database (SHDB) combine country × sector risk data from international sources such as the ILO, WHO, UNDP, and the World Bank [4]. These methods allow researchers to map potential social risks in the complex supply chains and operate at aggregated sectoral scales that may obscure firm-level conditions [5]. Consequently, the use of SHDB benefits from triangulation with region-specific evidence to validate risk patterns and interpret root causes. Given these methodological characteristics, SHDB-based SLCA is particularly suitable for analysing emerging renewable-energy technologies whose material inputs span multiple geographical regions. This includes new generations of Solar Thermal Energy (STE) systems developed under the EU's Solar Heat for Industrial Processes (SHIP) strategy, which supports the transition towards a 55% reduction in greenhouse gas emissions by 2030 [1]. SHIP highlights the need to supply industrial thermal demands between 200 and 400 °C, and highlights the need for environmental, economic, and social assessments throughout the STE life cycle. Recent developments of SLCA offer the methodological tools needed to build such social scenarios and assess the social performance of STE technologies.

A growing number of studies have applied SLCA in industrial contexts. Corona & Miguel [6] used an SLCA to asses a real Concentrating Solar Power (CSP) technology across supply chain activities such as R&D, procurement of materials, and installation. By organising the results around sustainability sub-questions and presenting them at multiple scales, their study supports informed decision-making by stakeholders such as policymakers and investors. Zafar et. al [7] identified that employees and value chain actors are the main stakegholders for such systems, noting that they are affected by their pay, working hours, and health & safety (H&S) conditions while value chain actors are material suppliers and end users.

Building on these stakeholder definitions, recent SLCA applications in STE systems have used Human Reseourses records, surveys, and audits to evaluate social issues such as fair payment, excessive working hours, on-site accident rates, and PPE use [3,5,6].

To assess the social impact across these stakeholder groups, recent advancements of SLCA have focused on developing more robust and reliable data collection methods for assessing STE systems and other technical applications. For example, Corona & Miguel [6] applied SLCA to a CSP plant by examining Human Resource records to assess employee related issues such as fair payment and excessive working hours as well as Health and Safety (H&S) indicators including accident rates and Personal Protective Equipment (PPE) usage. Similarly, Terrapon-Pfaff et. al [8] studied how employees benefit from engineering STE power plants by assessing working conditions, qualifications, and job creation and also surveyed the Local Community stakeholder group to evaluate the broader social impact of STE deployements. Surveys and audits remain widely used tools in social impact assessments. Gu & Chi [9] surveyed 892 participants on job satisfaction and identified a need for improved training while Subramanian and Yung [10] used audits to assess the compliance with wage legislations in a computer manufacturing and found a high risk of non-compliance in factories producing the metallic desktop casing.

In addition, as highlighted by Norris & Norris [5], numerous authors have extended SLCA with examining social impact in geographical areas of their supply chains by assessing social risk levels using Social Hotspot Database (SHDB) software. Corona & Miguel [6] applied this approach in their SLCA and identified high levels of social risks related to H&S issues in metal producing industries in China and African countries. Similar findings were reported by Pucciarelli et al. [11] and Costa et al. [12], who used SHDB to evaluate the production of microbial keyboard covers and pulp production in Portugal and Spain, respectively. Costa et al. [12] specifically found a high risk of injuries and fatalities in pulp mills across these regions. Collectively, these studies demonstrated that the value of SHDB in SLCA demonstrating its effectiveness in identifying critical H&S related risks in specific regions and economic sectors where supply chain activities are outsourced abroad.

Futher social risk in other employee-related categories was also identified through the application of the SHDB software. Aridi & Yehya [13], for instance, assessed the manufacturing of Phase Change Material (PCM) storage units and found substantial risks related to fair payment and labour rights during the manufacturing of the metal components, particularly in South Africa and China. Similarly, Koese et al. [14] reported high levels of risk in fair salary indicators in their SLCA of lithium-ion battery energy storage units. More importantly, they identified a high risk of non-compliance with employment legislation along their supply chain, which explains why such high risks in these category occur. These risks were consistently higher in manufacturing activities based in China compared with those in Germany. Other important employee-related issues frequently highlighted in the literature include excessive working time, low representation of women in the workforce, and the presence of child labour [5,6].

However, several knowledge gaps persist. Pollok et. al [15] and Kühnen & Hahn [3] emphasised that many SLCA case provide insufficient interpretation of the root causes underlying social risks. For the STE systems, this include limited analyses of factors influencing issues such as employee H&S, fair payment, and excessive working hours. Dantas & Soares [16] further highlighted the absence of the limited number of SLCA studies specifically to solar thermal technologies and discussion on how social issues affect employees in STE supply chains.

Zafar et al. [7] also emphasised the need to apply social sustainability assessments for emerging STE technologies. While numerous studies have evaluated these technologies from environmental and economic perspectives, the social dimension has remained largely overlooked. For instance, Suresh & Rao [17], analysed evacuated tube collectors operating at 100–150 °C that have been applied to textiles, pulp and paper, dairy, leather, and automobile industries in India reporting environmental benefits of up to 9.1 Mt of annual CO_2 reductions. Kumar et al. [18] evaluated low-temperature flat plate collector systems (<100 °C) for the textile industry and identified energy cost savings of around 10%. Likewise,Fuentes et al. [19] found that evacuated tube collectors in Chilean dairy applications operated at temperures of 120 °C supplying approximately 15% of annual thermal demand while achieving an equivalent reduction in CO_2 emissions. Although these studies provide strong evidence for the environmental and economic benefits of STE technologies, they do not consider how their adoption influences workers such as impacts on job characteristics,

health and safety requirements, workload changes, training demands, or long-term employment stability.

A newly developed modular STE system called Application of Solar Thermal Energy to Industrial Processes (ASTEP), which is the main focus of this study, represents major technological advance over earlier STE solutions. It has been developed under the European Union's SHIP strategy as documented [20], It integrates Multi-Axis Rotary Fresnel Solar Collectors, a Phase Change Material (PCM) Thermal Storage Tank, and an advanced Electronic Systems Control Unit. This combination enables higher operational temperatures, improved thermal stability, and greater adaptability to fluctuating industrial energy demands. The system is currently being prototyped for two end-users: a dairy production facility in Greece (MAND) and a steel tube manufacturer in Romania (AMTP). Performance evaluations proved that ASTEP can deliver more than 120 MWh of thermal energy annually, achieving CO_2 emission reductions and energy consumption of approximately 20%, financial savings of up to €25,000 in energy costs and €18,000 in carbon tax relief [21,22], These reductions are translated into financial savings of approximately €25,000 in energy costs and €18,000 in carbon tax relief [23,24]. Due to these strong environmental and economic advantages, it attracted growing interest from diverse industrial actors including aerospace, automotive, metals, and food and beverage industries, demonstrating its high potential for widespread industrial deployment [25]. However, the main characteristics that make ASTEP highly attractive to industry is because its operational efficiency and suitability to be integrated into energy- intensive production lines, also amplify the urgency of assessing its social implications. While environmental and economic aspects have been thoroughly examined, the social dimension remains unexamined. This represents a significant gap particularly as the development of high- temperature solar thermal technologies can compromise health and safety, inequities in working conditions, unfair payment practices, or reduced job satisfaction.

Building on previous work, this study aims to analyse and critically evaluate the social risk generated during the production phases of a recently developed STE technology, ASTEP, with the objective of improving managerial decision-making and resource allocation.

The research question include: (i) What are the main social risks associated with development of the STE solar thermal energy

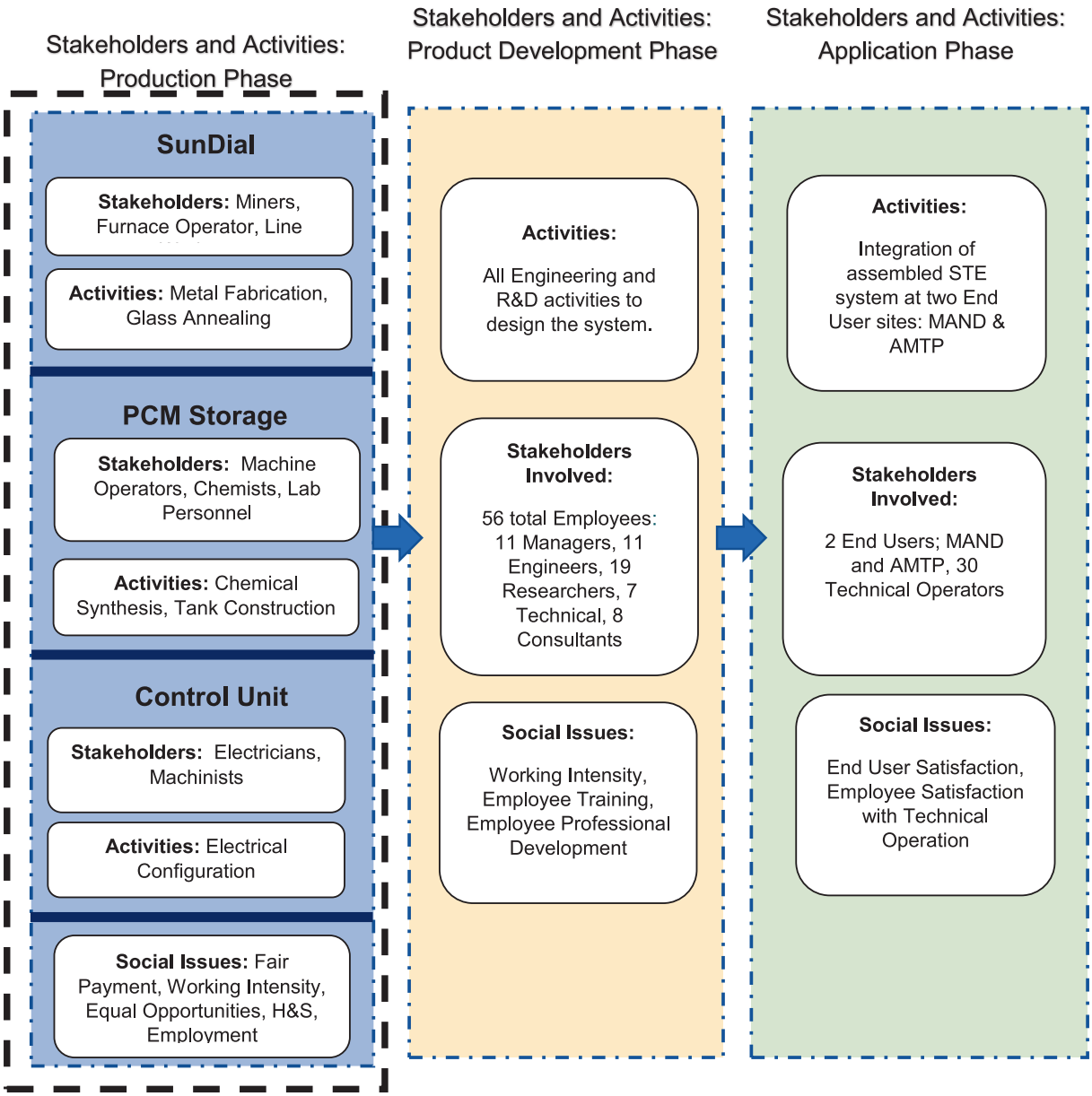

Fig. 1. Boundary Conditions of Social Sustainability Assessment.

technology, particularly in relation to employee health and safety and working conditions; (ii) How do these social risks vary across the geographical regions and industrial sectors as identified through SHDB analysis and (iii) how the integration of SLCA and SHDB improve managerial decision- making for ASTEP and support socially responsible deployment of next generation STE technologies**?**

The novelty of this study lies in two main contributions (i) It advances a limited body of SLCA research applied to STE technologies by providing a detailed critically evaluated social performance of high-tempreture STE systemand (ii) It introduces a more comprehensive methodological approach than previously seen in any comparable studies combining SHDB results with region- specific evidence to verify social risks and identify their root causes. This approach directly responds to recent calls for more transparent, interpretative, and policy-relevant applications of SLCA within thermal and energy engineering research [16; 26].

2. Methods

2.1. Defining the case study boundary conditions

The social assessment of ASTEP system was conducted within clearly defined boundary conditions, presented in Fig. 1.These boundaries include all social stakeholders, processes and business activities involved in the life cycle of the ASTEP system. The boundary conditions are applicable for both of the STE systems developed the two inductrial users MAND (Greece) and AMTP (Romania). The subset of boundary conditions specifically addressed in this study are the downstream phases, which is highlighted in the dashed box, on the left hand side of the Fig. 1. The analysis focuses explicitly on the workers stakeholder group, consistent with the capabilities and data structure of the Social Hotspots Database (SHDB) (SHDB, version 4.1 software integrated within SimaPro 9.5 (Pre-Sustainability, Amersfoort, the Netherlands). Although the broader ASTEP project addresses additional stakeholder groups, these are outside the scope of the SHDB Database analysis presented in this study and are no longer implied in figures or text. This approach is consistent with the methodological guidance of the SHDB manual by Norris and Norris [5], which restricts the assessment of social issues to employee-related impacts only.

The Social Hotspots assess the social risks associated with the ASTEP solar thermal system supply chain using four main stages: (i) collection of material and cost data for ASTEP components, (ii) harmonisation of economic data and currency conversion, (iii) mapping of materials to SHDB, country and sector codes, and (iv) calculation of risk hours per USD of material input (Fig. 1).

2.2. Data collection

The SHDB was used to model social risks associated with materials and manufacturing processes of ASTEP components. SHDB is an input – output (IO) based SLCA database aligned with UNEP/SETAC and Life Cycle Initiative guidelines, linking economic sectors with country-level social risk indicators through the GTAP database. Three primary inputs were used and processed in conjunction with the SHDB workflow (Fig. 2) processes as adapted from Norris & Norris [5]. The first input comprised of the material quantities and types used for the underlying subcomponents of the three main components of the two ASTEP systems: a) SunDial, b) PCM Thermal Storage Tank, and c) Control Unit (Fig. 2). The material quantities were provided separately for the two ASTEP developers and included: material types, quantities (kg), total procurement costs, and countries of origin for each subcomponent. Data were collected separately for the two ASTEP systems (MAND and AMTP), accounting for minor differences in component configuration and material quantities. The second input identified the relevant economic sector for producing each material, determined by relating the material type with its country of origin. The third input was the

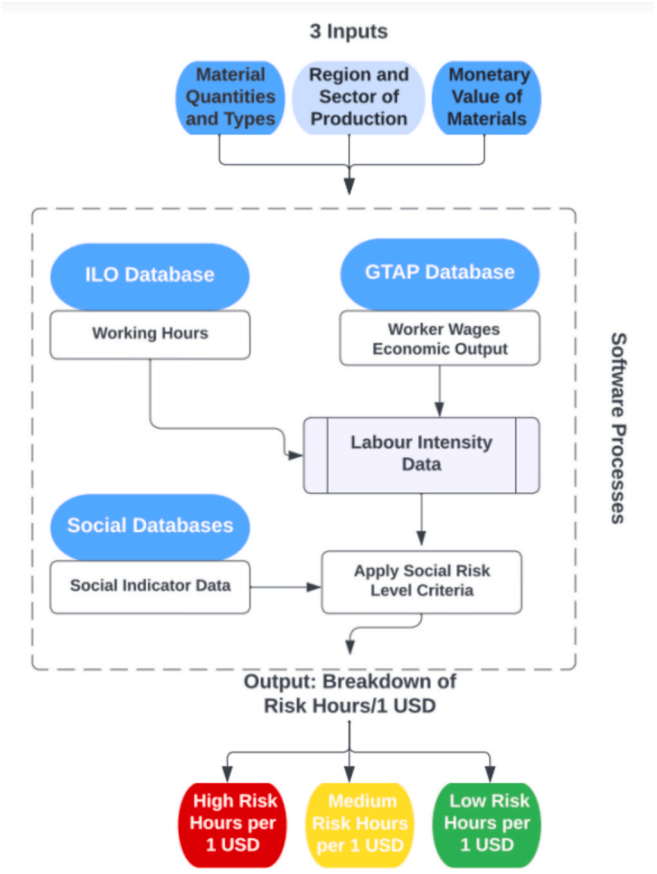

Fig. 2. Map of SHDB Input-Output Model.

monetary value of each material, expressed in United States Dollars which is the standard currency used by SHDB [5], derived from the market value. Section 2.3 elaborates on the three inputs and describes the origin of all material data.

Table 1 presents the material data used in the SHDB simulations provided by the developers, including material quantities, procurement values and the country of origin for each subcomponent.

2.3. Mapping of the components

The mappng of the ASTEP materials to the SHDB was carried out in three steps. First, each subcomponent was classified according to its primary material type such as. steel, aluminium or chemicals compounds. Second, the country of origin for each material was identified based on supplier documentation provided by the technology developer. Finally, each material and country combination was assigned to the corresponding GTAP/ SHDP economic sector such as irin and steel, non–ferrous metals or chemical products. These assignments followed the standard sectoral harmonisation and methodological guidance provided in SHDB v4.1 documentaion [4]. Where materials could plausibly fall under multiple industrial sectors, the primary processing route identified by the technology developers was adopted to reduce classification ambiguity. To ensure compatibility with SHDB, the original supplier prices in EUR were converted to USD using 2019 reference conditions. This harmonisation step ensured consistency between foreground monetary inputs and the background economic and labour data embedded within SHDB.

The data of three main components of ASTEP and their subcomponents, the material types for each subcomponent and their country of origin, the economic sector, material quantities, conversion rate and value are presented in Table 1.

Table 1
Material Input Data of all Components for both STE Systems.

Main Component	Subcomponent	Material Type	Country	Economic Sector	Price (original currency) of Supplier [€]	Material Quantities (kg)	Step 1: Deflation to 2019 (GDP Deflator Applied)	Value (USD) using 2019 EUR–USD exchange rate (ECB annual avg: 1 EUR = 1.13 USD)	Notes
SunDial	Concentrator	Steel	Spain	Iron & Steel	776 940	1940	761 920	$860 (AMTP)/ $1040 (MAND)	Two end users configurations
	Rotating Platform	Steel	Spain	Iron & Steel	1194	2500	1159	$1310	Spain sourcing
PCM Tank	Steel Tank	Steel	Spain	Iron & Steel	950	2000	920	$1040	Final value used in simulation
	Thermal Storage Material	Chemicals	Netherlands	Chemical Products	1364	2200	1325	$1497	Value corresponds to Netherlands sourcing
	Shell Inserts	Aluminium	Poland	Non-Ferrous Metals	968	2928	931	$1052	Value cooresponds to Poland sourcing
Control Unit	Unit Board	Steel	Germany	Iron & Steel	122	255	120	$136	Germany sourcing

The first component of ASTEP system is SunDial solar concentrator consists of two steel subcomponents: the concentrator and rotating platform. The both concentrators were manufactured using steel sourced from Spain and mapped to *the Iron and Steel sector,* The concentrator requires 1640 kg of steal with a value of $860 for the AMTP instalation and 1940 kg steel with a value of $1040 for the MAND instalation. The rotating platform uses 2500 kg Spanish steel from the same economic sector, with acorresponding value of $1310.

The second major ASTEP compronent, the PCM thermal storage tank, comprises from three subcomponent: steel tank, thermal storage material andt shell inserts. The first subcomponent of steel tank is manufactured using steel sourced from Spain and assigned to *the iron and steel sector*, with a total quantity of 2000 kg and a corresponding value of $1040. The second subcomponent, thermal storage material, is composed of chemicals sourced from the Netherlands, and produced by the chemical products sector, accounting for 2200 kg and a value of $1497. These chemicals were selected specifically for latent heat storage applications. Accordingly, the reported material quantities and associated costs reflect only the monetary values supplied by the ASTEP developers at the time the latent storage materials were procured. The third subcomponents, the shell inserts, is made form aluminium that is purchased from Poland and manufactured by the non-ferrous metals sector, with a material quantity of 2928 kg and a value of $1052.

The final ASTEP component, the Control Unit, comprises a single subcomponent, the unit board, which is produced using steel sourced from Germany and assigned to *the iron and steel sector*.

The market prices of steel, cement, aluminium and glass were sourced from the published data [26,27] and were used to validate the supplier-reported procurement costs. To address variability in material prices and the associated background data, a ± 5% uncertainty range was applied to the calculated risk hours, in line with the approach proposed by Norris and Norris [5]. In SHDB-based assessments, this uncertainty margin is regarded as standard practice for capturing short-term variability in material cost inputs.

2.4. Currency conversion and price assumption

All monetary values used in SLCA were expressed in United States Dollars (USD), as required by SHDB. Raw procurement prices provided by suppliers were converted to USD using annual average exchange rates for 2019, obtained from the European Central Bank (ECB), corresponding to 1 EUR = 1.13 USD. Market prices for steel, aluminium, chemicals, cement, and glass were derived from internationally recognised commodity price references [26,27] to ensure internal coherence of the analysis. The raw USD values introduced into the SHDB model for each material and subcomponent are reported in Table 1 and were entered directly as monetary flows associated with their respective country–sector combinations.

2.5. Selection of social impact categories and indicators

Once the material and economic inputs were defined, the SHDB framework was used to contextualise these inputs within internationally recognised labour and social statistics. Sector-level wage and economic output data were drawn from the the Global Trade Analysis Project (GTAP) as presented in Fig. 2 while corresponding labour hour information was sourced from the International Labour Organization (ILO) [4]. This combination creates labour intensity data as monetary output per working hour, and the software relates this intensity data with sets of quantitative social data, including mean wages, working hours, and H&S accident rates as provided by national statistics for a geographical

Table 2
SHDB Social Impact Categories and Indicators.

Social Impact Category	Social Impact Indicators
Employee Fair Payment	Risk of Low Occupational Wage
Excessive Working Hours	Risk of Overtime Work Risk to Compliance of Labour Law
Equal Opportunities for Employees	Risk of Low Female Representation in the Workforce Risk of Compliance with Anti-Discrimination Policies
Employee H&S	Risk of Non-Fatal Work-Related Injuries Risk of Fatal Work-Related Injuries Risk of Diseases DALYs Risk to Compliance of H&S Policy
Community Engagement	Risk of Unemployment

location [6]. This social data is extracted from certain social impact categories presented in Column 1 of Table 2, which represent key social issues affecting the associated employee stakeholder group. These social impact categories were measured by impact indicators presented in Column 2 of Table 2, which were adapted from the software manual provided by Norris et al. [4].

For this study, four impact categories relating to employees and one relating to local communities were used for analyses (Table 2). The first impact category, employee fair payment, measures the risk that the average wage (AW) for a given employee is below the living wage as regulated by the regional location of that economic sector. The living wage for an economic sector is represented in the software by the Non-Poverty Guideline (NPL) established in each country [4]. The next impact category consists of the risk that employees are working excessively, measured by the risk that a given employee is made to work overtime. Complimenting this social indicator is another indicator relating to how well labour laws particularly relating to working hours are enforced and implemented within a given economic sector. Following this, another social category to be analysed is the risk of gender inequality among the employee pool within a given economic sector. This is represented by how low the representation of female employees in the workforce is in an economic sector. To complement this indicator, the risk that non-compliance to Anti-Discrimination policies which enforce gender equality in an economic sector is measured to aid the critical evaluation of its complementary indicator.

The next impact category, Employee H&S, includes the measurement of risk that specific hazards associated with the working environment have on the health of the employees. This risk to the H&S on the Employee stakeholder group during the manufacturing of all subcomponents in Table 1 is represented by three indicators in the right Column of Table 2: non-fatal and fatal injuries and the risk of disease-related Disability-Adjusted Life Years (DALYs) that an employee may experience working in a given economic sector. The non-fatal and fatal injury indicators are measured per 100,000 workers for a given economic sector. Disability-Adjusted Life Years (DALYs) is an indicator which represents one year lost by an individual due to disease [4]. The fourth indicator is the risk of non-compliance to H&S policy within a given economic sector and will be used to complement the risk levels observed by the three other indicators within the H&S social impact category for critical evaluation. For the H&S impact category, all risk levels for each of the four indicators will be averaged out with equal weightings to give the overall risk in this impact category in the results. The last indicator in Table 2 measures the risk of unemployment generated by the economic sector to highlight the social risk to job creation as the result of producing within that economic sector.

2.5.1. Conversion of monetary flow to risks hours

The SHDB software was used to convert the material input data from Table 1 into imposing social impact. The total working hours per USD were calculated using the Equation (1):

$$\text{Working Hours per USD} = \frac{\text{Total Sector Labour Hours}}{\text{Total Sector Economic Output (USD)}} \quad (1)$$

where:

- Total Sector Labour Hours represents the cumulative number of hours worked by all employees in a given material sector
- Total Sector Economic Output (USD) corresponds to the total monetary value of goods produced by that sector over the same period, expressed in US dollars.

The calculated working hours are then distributed into the three risk levels; a) High Risk, b) Medium Risk, and c) Low Risk for each social impact indicator, based on indicator-specific thresholds embedded within SHDB. The resulting metrics are known as Risk Hours (RH), and represent the portion of working hours associated with social conditions under each social impact category (Table 2). The allocation of the total number of the working hours to risk levels is governed by indicator-specific thresholds embedded within SHDB, which are described in Table 3. For example, the risk level for excessive working hours depends on the percentage of employees in an economic sector in geographical location that work more than 60 h per week [4]. According to ILOSTAT data [28], the *Non-Ferrous Metals Sectors* in Poland report shares exceeding 15%, corresponding to a high-risk classification, while the Iron and Steel Sector in Spain typically reports values in the range of 11%, corresponding to medium risk. In contrast, and *the Chemicals Sector* Netherlands generally report shares below 9%, resulting in low-risk classifications under the criteria defined in Table 3. The risk level for low occupational wage is represented by the percentage of employees that are being paid below the living wage, i.e (National povetry line) NPL> (Average wage) AW. With further reference to the interaction between economic sector and geographical context, the Non-Ferrous Metals sector in Poland reports that the national non-poverty line (NPL) exceeds the average wage (AW) by approximately 30–40%, according to ILOSTAT data [29]. This places the sector within the high-risk category (NPL > AW by 25–50%) as defined in Table 3. By comparison, the Iron and Steel sector in Spain shows wage differentials of around 10–15%, corresponding to a medium-risk classification (NPL > AW by < 25%). In contrast, the Chemical Products sector in the Netherlands consistently reports average wages above the non-poverty line (AW > NPL), which aligns with a low-risk classification under the criteria outlined in Table 3. The Health and safety risks (H&S) are assessed using sectoral rates of fatal and non-fatal injuries, disease-related Disability-Adjusted Life Years (DALY) per 100,000 employees in that sector and the level of compliance with occupational safety policies. According to ILOSTAT occupational injury statistics [30], the Non-Ferrous Metals sector in Poland reports fatal work-related injury rates of approximately 6–7 per 100,000 workers and non-fatal injury rates exceeding 600 per 100,000 workers. These figures place the sector in the high-risk category for both indicators under the criteria defined in Table 3. By comparison, the Iron and Steel sector in Spain generally records fatal injury rates of 2–4 per 100,000 workers and non-fatal injury rates of around 300–400 per 100,000 workers, corresponding to a medium-risk classification. In contrast, the Chemical Products sector in the Netherlands reports fatal injury rates below 1 per 100,000 workers and non-fatal injury rates below 80 per 100,000 workers, which aligns with a low-risk classification according to Table 3. The criteria used to define the risk level of policy compliance-based indicators from Table 2, which follows a similar procedure presented in Table 3 [4]. In this case, instead of using quantified amounts measured by a social indicator, the software uses

Table 3
Risk Conversion Criteria.

Social Impact Indicator	Risk Level		
	High	Medium	Low
	Conversion Criteria Based on Measured Amount of Social Indicator		
Risk of Overtime Work	> 15% and < 20% work > 49 h/week	> 10% and < 15% work > 49 h/week	< 9% work > 49 h/week
Risk of Low Occupational Wage	NPL > AW by 25–50%	NPL > AW by < 25%	NPL < AW
Risk of Fatal Work-Related Injuries per 100,000 Workers	>5	>1	1
Risk of Non-Fatal Work-Related Injuries per 100,000 Workers	>500	>100	< 100
Risk of Average Diseases DALYs	> 50,000	> 40,000	< 40,000
Female Representation in the Workforce	10–20%	20–33%	>33%
Risk of Unemployment	10–15%	5–10%	<5%

qualitative descriptors of the level of policy compliance by firms within an economic sector, which is directly related to risk level. The complete set of conversion criteria applied in this study is presented in Table 3.

The output demonstrated the variation of risk levels recorded across an entire specified economic sector in its corresponding geographical location for each social indicator label in Column 2 of Table 2, associated with producing 1 USD worth of each material type from Table 1. The simulation is replicated for each of the three main components listed in Fig. 2. High-risk components were identified and prioritised for analysis, where the results for the subcomponents were displayed for the high risk component to pin down the exact area of high risk. Separate simulations were performed for both ASTEP systems at MAND and AMTP. Only components with different material quantities were simulated separately for the MAND and AMTP sites, and only significant differences between the social risks generated by the systems being implemented at each of the two sites were highlighted.

2.6. Weighting assumptions and aggregation

For impact categories represented by multiple indicators (e.g. Employee H&S), equal weighting was applied when aggregating indicator-level risks into a single category score. This assumption was adopted for three reasons:(i) SHDB does not provide scientifically validated weighting factors for individual sub-indicators; (ii) equal weighting avoids introducing subjective prioritisation in the absence of consensus-based weights; and (iii) this approach is consistent with previous SHDB-based SLCA studies of energy and manufacturing systems [4]. The implications of this assumption are explicitly acknowledged and discussed in the Results and Discussion sections. No thresholds or default parameters beyond those embedded in SHDB v4.1 were modified.

2.7. Simulation strategy

Separate SHDB simulations were performed for the ASTEP systems installed at MAND and AMTP. Only components with differing material quantities between the two installations were modelled separately. Results were first analysed at the component level to identify high-risk components, followed by subcomponent-level analysis to identify the primary sources of social risk.

3. Results and discussion

Fig. 3 shows the total amount of Risk Hours (RH) per USD of material associated with production of ASTEP's main components listed in Table 1 with a 5% uncertainty as represented by the error bars. As defined in the methodology, RH represents the expected exposure time to social risk per unit of economic output, integrating sector-specific labour intensity with geographically differentiated social risk indicators.

It can be seen that the overall risks associated with H&S social impact category, under the H&S Risks indicator was observed to be the greatest with 0.09 RH, which reflects the labour-intensive nature of upstream manufacturing activities and the elevated risk conversion factors associated with specific economic sectors and countries of origin. The PCM storage tank accounts the largest share of H&S risk contributing 0.051 RH, equating to 57% of the total H &S risk. A breakdown of this component and geography reveals that 0.038 RH originates from the production of aluminium inserts in Poland while 0.013 RH is attributable to the PCM chemicals produced in the Netherlands. This outcome directly reflects the methodological assumption that social risk is strongly dependent on both sectoral characteristics and geographical context, as encoded in the risk conversion matrices applied during the life cycle social assessment. In contrast, the SunDial produced in Spain generated a substantially lower H&S risk at 0.017 RH while the Control Unit produced in Germany generated even less risk at 0.014 RH (Fig. 3). To further elucidate these findings, Table 4 summarises the relative contributions of the ASTEP components to the overall social risk across each social impact category, expressed as percentage risk shares and benchmarked against one another within a ± 5% uncertainty range. These results are additionally illustrated in Fig. 4, where the ± 5% uncertainty is shown through the associated error bars.

As seen in Fig. 4, gender inequality risks are relatively evenly distributed between the SunDial and Control Unit components, each accounting for 35.6% of the total risk, while the PCM Storage Tank contributes a slightly smaller share at 28.9%. In contrast, Health and Safety (H&S) risks are strongly dominated by the PCM Storage Tank, which represents 62.2% of the total risk, clearly identifying it as the primary hotspot within this category. The SunDial and Control Unit contribute markedly smaller and comparable shares of 20.7% and 17.1%, respectively.

A comparable trend is observed for excessive working time, where the Control Unit is the largest contributor, accounting for 43.8% of the total risk, followed by the PCM Storage Tank at 31.3%, with the SunDial contributing the lowest share at 25.0%. Mean wage-related risks are

Table 4
Relative Risk Shares of Social Impact Categories for Each ASTEP Component with ± 5% Uncertainty Ranges.

Social Impact Category	SunDial (%)	PCM Storage Tank (%)	Control Unit (%)
Gender Inequality	35.6 ± 1.8	28.9 ± 1.4	35.6 ± 1.8
Health & Safety (H&S) Risks	20.7 ± 1.0	62.2 ± 3.1	17.1 ± 0.9
Excessive Working Time	25.0 ± 1.3	31.3 ± 1.6	43.8 ± 2.2
Mean Wage	17.6 ± 0.9	20.6 ± 1.0	61.8 ± 3.1
Local Employment	28.6 ± 1.4	54.5 ± 2.7	± 0.8

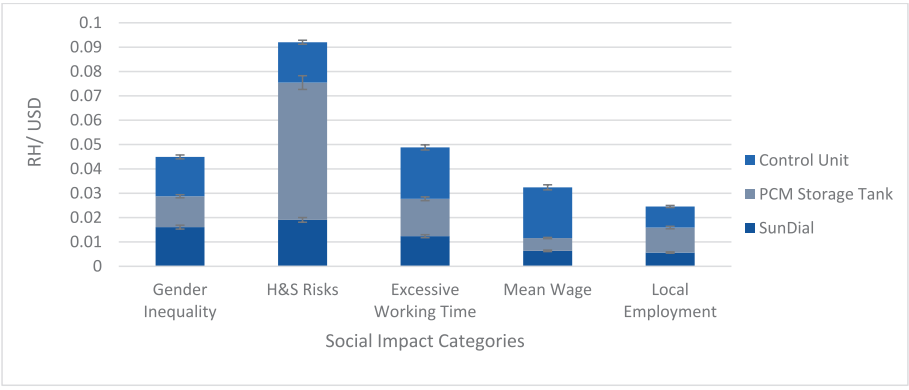

Fig. 3. Risk Distribution for each ASTEP Component.

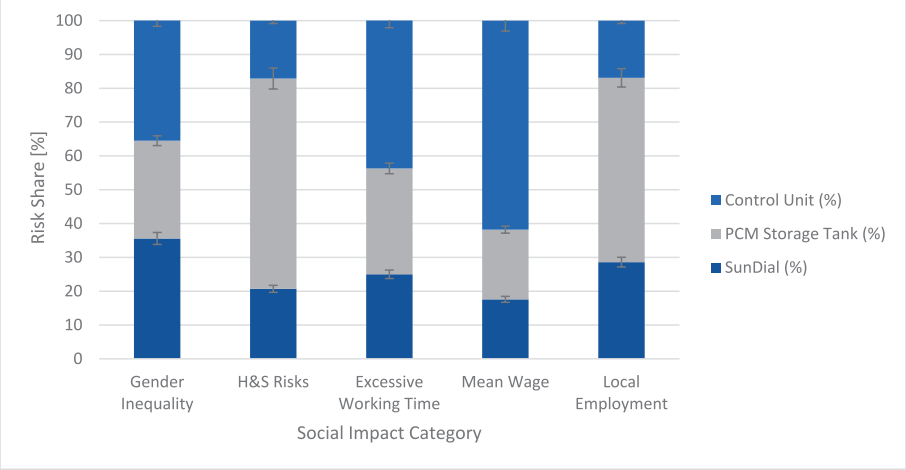

Fig. 4. Relative Risk Shares of Social Impact Categories Across ASTEP Components.

likewise largely driven by the Control Unit, which accounts for 61.8% of the total risk, compared with 20.6% for the PCM Storage Tank and 17.6% for the SunDial. In contrast, risks associated with local employment are predominantly attributed to the PCM Storage Tank, which contributes 54.5% of the total risk, while the SunDial and Control Unit account for 28.6% and 16.9%, respectively.

These findings are consistent with lower risk conversion factors assigned to the relevant industrial sectors in these countries, reflecting stronger regulatory frameworks and enforcement mechanisms. The concentration of social risk within the PCM Storage Tank is consistent with previous studies on thermal energy storage systems. Corona & Miguel [6] analysed a similar CSP plant in Spain, who found that nearly 40% of high social risk under the '*Toxic and Hazards*' indicator was generated during the extraction and manufacturing stages of the PCM tank production. Their study also found that nearly 25% of the risk to overall Health and Safety was generated by their PCM tank, forming the second largest portion of all five of their components in this social category. Nartowska et. al [31] provided detailed analysis of the production stages of PCM tanks used in STE systems, identifying chemical, metal dust exposure and poor use of Personal Protection Equiptment (PPE) as the primary sources of the occupational risk. Similar conclusionswere drawn by Rahimpour et al. [32] who assessed the social impact on employees involved in the production of STE's materials and reported high H&S risk in the production of the PCM despite strong employment generation. Otieno & Loosen [33] further corroborated these findings, demonstrating that the highest H&S risk attributed to CSP technology is associated with the heat transfer fluid chemicals used between the collectors and the PCM storage tank. Their assessment demonstrated increased injury incident rates due to chemical leakages and unsafe handling practices during laboratory and manufacturing operations. Additionally, Aridi & Yehya [13] indetified significant risk of injuries and fatalities related to the production of chemicals needed for thermal energy storage, ephesising supply-chain-level vulnerabilities associated with PCM materials. Collectively, these studies substantiate the high H&S risk levels observed for the PCM storage tank component in the present assessment.

Given the pronounced social risk concentration observed in the PCM tank's production, the country and sector specific origin of PCM tank production are examined in greater detaiil in Section 3.1.

3.1. *Social risks during the manufacturing of the thermal PCM storage tank*

Fig. 5 presents the total social risk hours (RH) associated with PCM

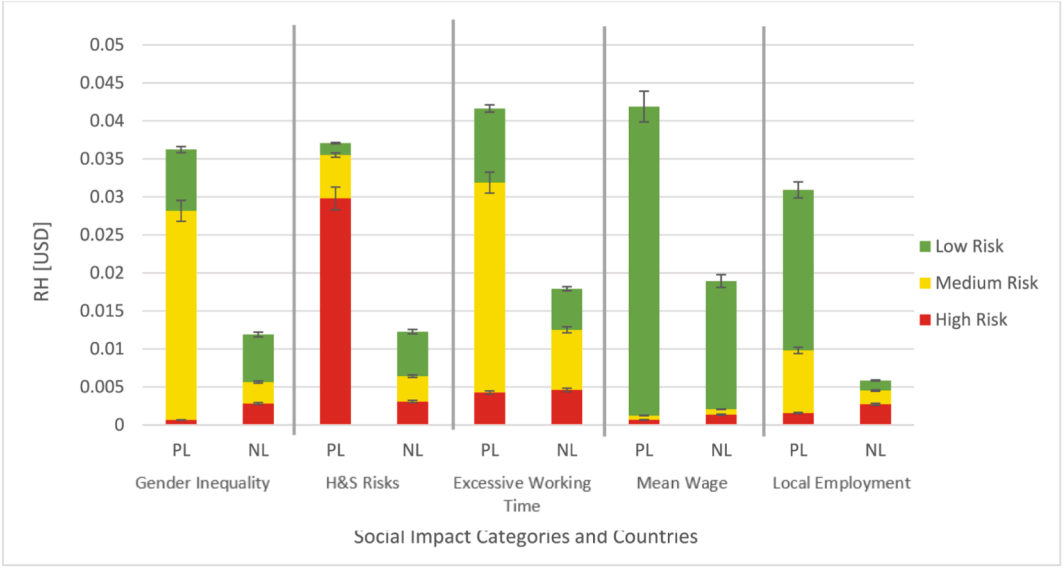

Fig. 5. Social Risk Levels for PCM Storage Tank (PL and NL).

Storage split into High Risk (HR), Medium Risk (MR), and Low Risk (LR) categories comparing production in Poland (PL) and the Netherlands (NL), with a 5% uncertainty as represented by the error bars. In line with the methodology, the results were presented as RH per USD of materials allowing direct comparison between countries and sectors while controlling the difference in economic output.

Fig. 5 compares the PCM storage tank's social risk hours per USD across five impact for two PCM storage tank subcomponents: aluminium insert produced in Poland within the Non-Ferrous Metals sector and PCM chemical produced in the Netherlands in the Chemical Products sector.The H&S category shows the highest overall risk in Poland amounting 0.038 RH, with the majority of this risk concentrated in the high-risk range of 0.029 RH. This finding supports the results in section 3.0, confirming that the PCM Storage Tank is dominant contributor to the increased H&S risk observed at the system level in Fig. 3. Excessive Working Times also present a medium to high risk for the Polish non-ferrous metals sector, with 0.045 RH. On the other hand, Mean Wage indicator shows the lowest risk level, of 0.04, suggesting minimal expousure to unfair payment practices for employees in this sector. The inclreased H&S risks observed for the Polish subcomponent are coconsistent with the findings of Dziubanek et al. [34], who revealed persistent H&S issues in the non-ferrous metals sector in Poland, affecting factory employees and the wider community. These observations are further supported by Grzegorz et al. [35] who linked increased H&S risks in the Polish metals sector to persistent soil and dust contamination with heavy metals such as lead, cadmium, arsenic, and zinc.

In contrast Fig. 5, indicates that the Netherlands has notably lower risk levels of PCM chemical subcomponet.The H&S for the Chemical Products sector is approximately 0.012RH with the distribution inclining towards the medium and low risk categories.Similarly the Excessive Working Time indicator shows a lower at 0.019 RH for the chemical sector.The results are consistent with findings by Zwetsloot et. al [36], who conducted repeated H&S assessments of nineteen companies in the chemical sector in the Netherlands between 2012 and 2018. Their results showed strong adherence to H&S procedures, supported by systematic accident monitoring procedures, effective communication and comprehensive training programmes led by management and supervisory teams.

Further examination into the observed cross- country and cross-sectors differences is presented in Fig. 6, which demonstrates the risk levels of policy non-compliance with three social policy during the producting of the PCM storage tank.

It can be seen in Fig. 6, the risk of non-compliance to H&S policy is substantially higher in Polish Non-Ferrous Metals sector, totaling about 0.039 RH and dominated by high risk values of 0.03 HR. This finding is corroborated by Pałęga & Knapiński [37], who identified insunffisient enforcement of PPE protocols and frequent non-compliance with H&S legislation as major contributors to workplace accidents in this industry. They further stressed the need for stricter regulatory enforcement of H&S regulations to ensure the proper provision and use of personal protective equipment (PPE) by employees.

On the other hand, the Chemical Products sector in the Netherlands exhibited substantionally lower policy non-compliance risk at approximately 0.009 RH, with a low to medium risk distribution. This results are verified by Schenk & Antonsson [38] who demonstrated strong compliance with Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) framework with the chemical sector. Their findings, based on Swedish case studies, are transferable to the Netherlands due to the harmonised implementation of REACH across EU member states.

Taken together, the evidence from Figs. 5 and 6, and the supporting literature, it indicates that the Polish non-ferrous metals sector contributes extremely to social risk levels within the H&S impact category when compared to the chemical sector in the Netherlands. This difference is primarily driven in regulatory compliance and sector specific expousure to hazardous working conditions. The results clearly demonstrate that geograohical origin and the economic sector PCM storage tank subcomponents exert a great influence on the level of social risk generated by the assessment.

Finaly, the moderate excessive working time risk (0.027 MR) and low mean wage risk (0.04 LR) observed in Fig. 5 are consistent with the relatively low labour non-compliance risk shown in Fig. 6 (0.016 MR). This suggests that, despite elevated H&S risks, Poland generally mentains strong adherence with EU regulations governing wages and working hours. This inetrpretation is supported by Obolewicz [39], who reported effective enforcement mechanisms preventing excessive working hours and underpayment in Poland, as well as by Surdykowska and Pisarczyk [40] who found strong adherence to labour legislation across EU member states, including both Poland and the Netherlands. These finings help explain similarities and differences between social risk levels identified in ASTEP's assessment and those reported by Corona & Miguel [6] and Aridi and Yehya [13]. While previous studies highlighted high H&S and fair payment risks associated with outsourcing PCM production to regions in Africa and Asia, the ASTEP

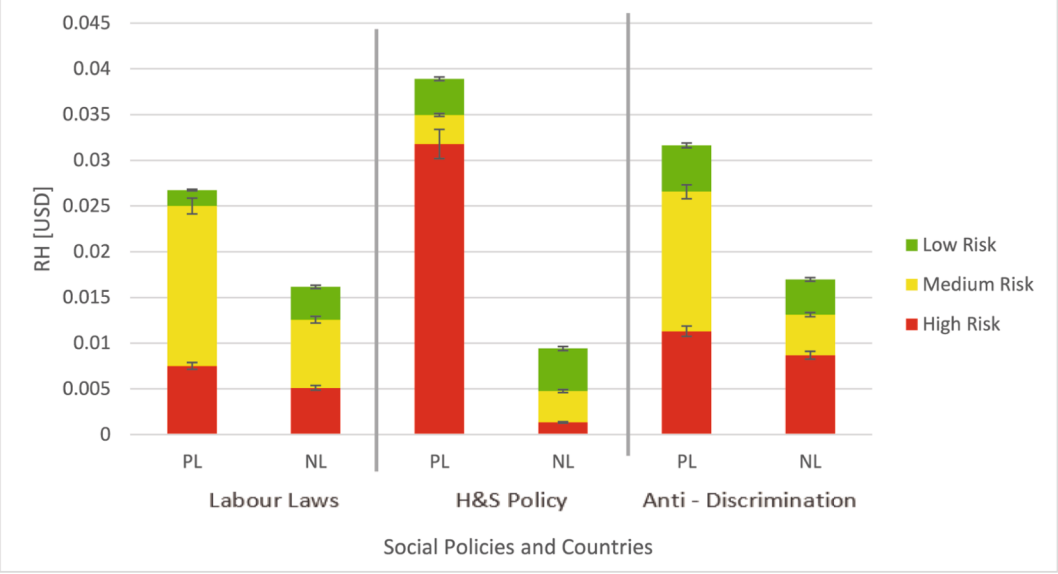

Fig. 6. Risk to Policy Compliance for PCM Storage Tank (PL and NL).

system sources its PCM storage tank components from EU sectors characterised by elevated H&S risk but comparatively low risks related to wages and working hours.

3.2. Social risks during the manufacturing of the SunDial

Fig. 7 presents the social risks associated with the SunDial component, with a 5% uncertainty as represented by the error bars, which represents the second-large contribution to the overall system social risk. The SuDial is produced solely in Spain and results are reported separately for the configurations implemented at the AMTP and the MAND end- user sites.

As shown in Fig. 7 the difference in social risks levels between the two end- user confogurations are marginal, despite the higher steel quantities used for the SunDial Concentrator at the MAND site. This finding reflects the methodological normalisation of results per USD of material input, confirming that material quantity alone is not the dominant driver of social risk. Instead, the geographical location and the characteristics of the industrial sector in which production occurs play a more significant role in determining risk intensity.The most prominent social risk associated with the SunDial arises within the H&S category for the Spanish steel sector. The total H&S risk amounts to approximately 0.015 RH, comprising both medium- and high-risk contributions (0.015 MR and 0.005 HR). This elevated risk level is primarily associated with non-compliance with H&S policies within the steel sector in Spain. These findings are consistent with the work of Torrecilla-García et al. [41], who reported persistently high accident rates and insufficient preventive practices in Spainish metal sector, particularly in steel processing operations. Similarly, Bargues et al. [42] identified significantly elevated cancer risks among steel foundry workers in Spain due to prolonged exposure to industrial fumes and inadequate ventilation systems. In contrast, labour-related indicators such as Excessive Working Times and Mean Wage exhibited very low risk levels for the Spanish steel sector. This reflects strong adherence to labour regulations, in line with the findings of Surdykowska & Pisarczyk [40], who demonstrated robust complience with EU labour laws governing wages and working hours across economic sectors in member states, including Spain.

Another noteworthy result from Fig. 7 conserns the risk that Gender Equality, defined as the risk associated with an imbalanced male-to-female workforce ratio relative to national benchmarks [4]. This indicator shows a relatively high risk level, with a combined medium- and high-risk contribution of 0.012. This observation was in agreement with the findings of Tolettini & Maria [43], who reported significant gender imbalances in Spainish industrial workplaces, particularly within management positions with female representation being lower. These conclusions are further supported by Mínguez-Vera and Martin [44] who revealed that women remain disproportionately underrepresented in senior leadership roles, particularly in traditionally male-dominated sectors like steel. Simillar patterns were also reported by Corona & Miguel [6], who also found great imbalances in the gender ratio from their site assessment of a CPS project in Spain. Additional context for the elevated gender inequality risk is provided in Fig. 8, with a 5% uncertainty as represented by the error bars, which presents the risk of non-compliance with anti-discrimination policies in the Spanish steel sector.

Fig. 8 indicates relatively high risk hours associated with anti-discrimination policy non-compliance. This indicator reflects the degree to which firms engage with gender equality and anti-discrimination policies within a particular sector, and observed moderately to high-risk levels in the Spanish steel sector show non-compliance. These findings is supported by a large scale survey study conducted by Engerst Yedra et al. [45], who identified resistance among Spanish firms to adopting gender equality policies and promoting women's participation in the workplace. Collado & Vázquez-Cupeiro [46] further emphesised that gender equality policies in metallic industries in Spain require stronger enforsment, noting that women are often excluded from leadership and decision-making roles. Company level evidence reported Corona & Miguel [6] similarly documented highly unequal gender imbalances among employees and management positions in Spanish CSP related projects.

3.3. Social risks during the manufacturing of the control unit

The Control Unit produced in Germany, demonstrated lowest overall risk among ASTEP's components, as shown in Fig. 9, with a 5% uncertainty as represented by the error bars. The highest oserved risk is associated with Excessive Working Time, at 0.02 RH, which remains substantially lower than the corresponding risk as compared to for the PCM storage tank (0.043 RH).

The lower level of risk seen in Fig. 9 can be largely explained by the geographical locations of production in Germany. Zimmer et al. [47] reported consistently low overall social risks attributed to the German steel sector, which aligns with the findings of the ASTEP assessment. A more detailed explanation provided by Beske et. al [48] who employed extensive surveys and rigorous audit procedures to demonstrate the effective enforcement of H&S and labour regulations across the German steel and related automotive sectors. Their analyses of 53 companies showed that the majority of the companies implemented comprehensive H&S management system, which led to a steady reduction in workplace

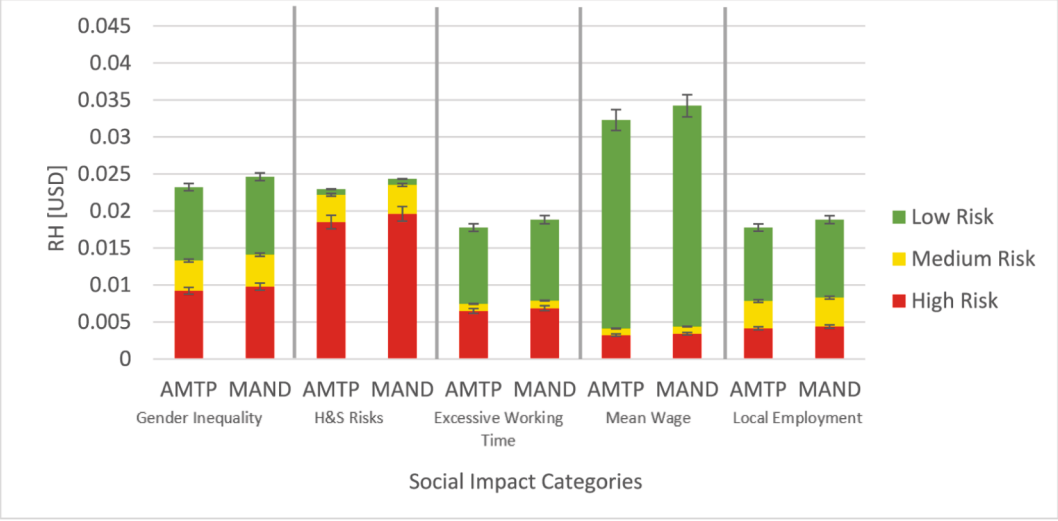

Fig. 7. Social Risk Levels for Sun Dial (AMTP and MAND).

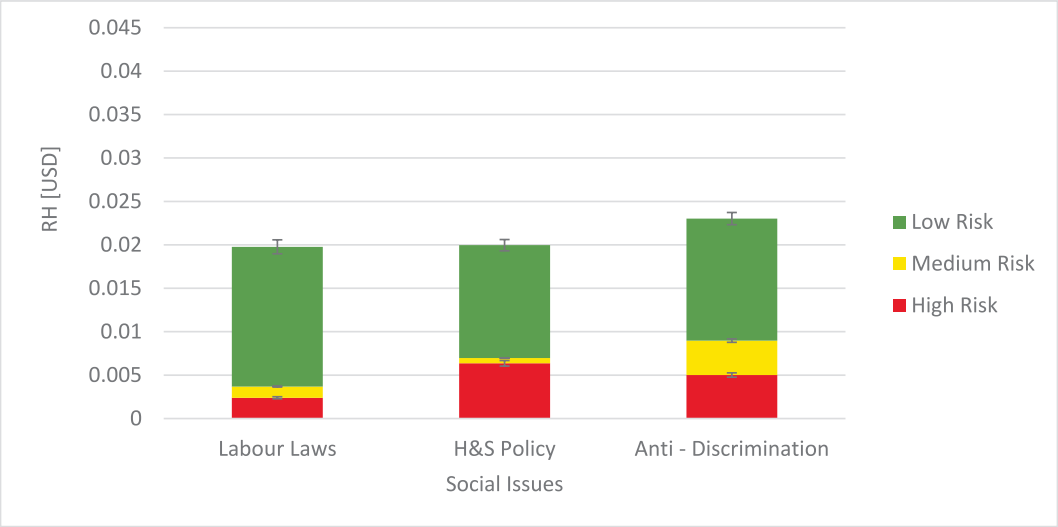

Fig. 8. Risk to Policy Compliance in Steel Sector for Spain.

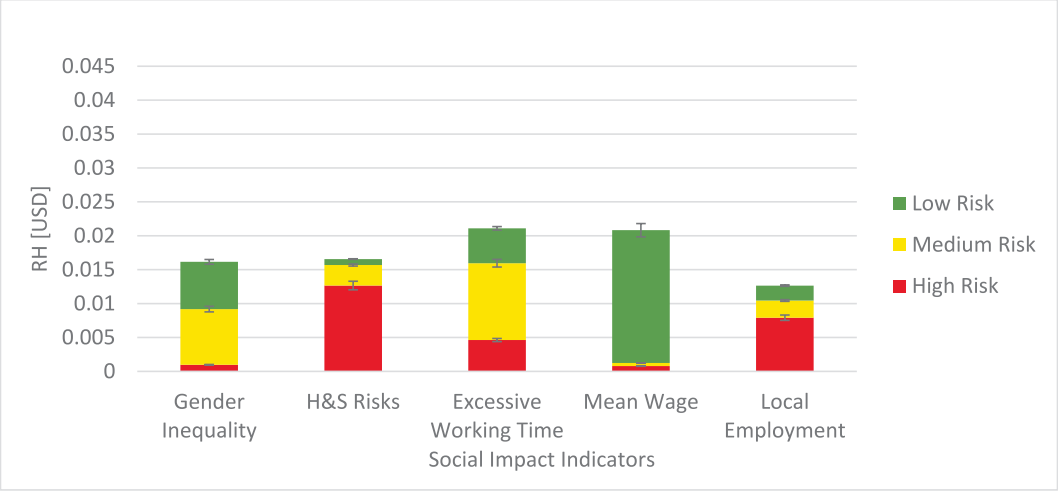

Fig. 9. Social Risk Levels for Steel Sector in Germany.

accidents and injuries over time, as well as reduced costs associated with lost working time and compensation claims.

4. Conclusion

This study applied SLCA famework, based on the SHDB to evaluate social risks associated with the downstream manufacturing stages of the ASTEP solar thermal energy system that consist of PCM storage tank, SunDial and control units. By expressing social impacts as risk hours (RH) per USD of material input, the assessment allowed consistent comparison across components, economic sectors, and geographical locations while accounting for differences in economic output. The results demonstrated that the PCM thermal storage tank is the dominant contributor to overall social risk within the ASTEP system, particularly within the H&S impact category, primarily associated with aluminium insert production in the Polish non-ferrous metals sector (0.038 RH) and, to a lesser extent, with chemical production in the Netherlands (0.013 RH). These risks are linked to sector specific exposure to hazardous working conditions and varying levels of regulatory enforcement, as corroborated by relevant literature. In contrast, labour-related indicators such as Mean Wage and Excessive Working Time generally exhibited low risk levels (0.04 RH and 0.027 RH, respectively) across the countries, reflecting strong compliance with EU labour regulations.

The SunDial component, manufactured in the Spanish steel sector, represented the second highest contributor to social risk of 0.015 RH. While H&S risks were moderate, they were consistently driven by policy non-compliance within the steel sector rather than by material quantity or end-user configuration. Gender inequality emerged as a notable social risk of 0.012 RH for this component, highlighting persistent structural imbalances within traditionally male-dominated industrial sectors. Conversely, the Control Unit, produced in Germany, exhibited consistently low social risks of 0.02 RH across all indicators, reflecting the strong implementation of labour and H&S regulations within the German industrial context.

The findings underscore the importance of geographical location and economic sector as main determinants of social risk intensity, outweighing the influence of material quantities alone. The study further demonstrates the value of SHDB-based SLCA as a screening tool for identifying social risk hotspots in energy system supply chains, thereby supporting more socially informed design, sourcing, and procurement decisions.

Future work should seek to extend the assessment beyond the employee stakeholder group, integrate temporal price variability and site-specific data, and complement database-driven results with long-

term empirical monitoring. Such developments would enhance the robustness of social sustainability assessments and support the wider deployment of socially responsible solar thermal energy technologies.

5. Assumptions and limitations

Several assumptions underpin the social sustainability assessment conducted in this study. First, it is assumed that the social impacts experienced by workers during the downstream manufacturing stages of the ASTEP system components are adequately represented by country and sector level social risk data embedded within SHDB. Accordingly, the geographical location of production and the associated economic sector are treated as proxies for site-specific working conditions, regulatory enforcement, and social performance. Second, the conversion of monetary flows into working hours and subsequently into RH assumes that sectoral averages for labour intensity, wages, and social indicators derived from GTAP, ILO, and national statistical sources are representative of the actual manufacturing processes supplying the ASTEP components. This implies homogeneous conditions within each country–sector combination, despite potential variability between individual firms. Third, it is assumed that the qualitative and quantitative social indicators embedded in SHDB, including those related to Health and Safety, labour conditions, gender equality, and policy compliance, capture the most relevant social risks for the employee stakeholder group within the context of solar thermal energy system manufacturing. Equal weighting was applied to sub-indicators within each impact category, assuming comparable relevance in the absence of sector-specific weighting schemes. Fourth, monetary values introduced into the model are assumed to reasonably represent typical procurement prices for the reference year used in the analysis. Although commodity prices may fluctuate, the use of annual average values is assumed to be sufficient for screening-level comparison of social risks across components and locations. Finally, the study assumes that the selected downstream manufacturing boundary adequately captures the most socially relevant stages of the ASTEP system supply chain for the purpose of this assessment. Upstream raw material extraction and downstream operation and end-of-life phases were not considered.

Additionally, two limitations were also identified which influenced the methods used in this study and the generation of results. 1) The SHDB software used has limitations with regard to the number of social impact categories and social risk data that could be analysed for the study. 2) The social data and impact categories concerning the Value Chain Actor stakeholder group were found to be limited for the purposes of drawing accurate conclusions and thus were entirely omitted for this study. Additionally, the software can only access limited secondary data provided by statistical databases and government reports that were incorporated into the GTAP and ILO models.

6. Recommended future works

The present study provides a screening-level social sustainability assessment of the ASTEP solar thermal energy system; however, several avenues for future research are identified to improve the robustness, applicability, and impact of the findings. First, future work should aim to complement database-driven social life cycle assessment with primary data collection that include sitespecific audits, worker surveys, and structured interviews within manufacturing facilities supplying the system components. This would allow validation of SHDB-derived risk indicators and allow a more accurate representation of occupational H&S practices, labour conditions, and policy compliance at the firm level. Second, the scope of the analysis could be extended beyond the employee stakeholder group to include additional stakeholders, such as local communities, value chain actors, and consumers. Involving those actors would support a more comprehensive social sustainability evaluation.Third, future studies should address the temporal dynamics of economic and social variables, particularly price volatility of raw materials and components, involving labour regulations, and changes in industrial safety performance. Integrating more dynamic analyses would improve the reliability of social risk estimations over different investment horizons. Fourth, there is a need to strengthen the integration between technical performance and social sustainability metrics. Future work should combine experimental and long-term operational data that include system efficiency, durability, and maintenance requirements with social impact indicators. Finally, the results of this study highlight the importance of geographical differentiation of social risks. Future research could further refine regional classification by incorporating sub national data or region specific risk modifiers, particularly for countries with strong inter national variability in labour practices and regulatory enforcement.

CRediT authorship contribution statement

Imaad Zafar & Valentina Stojceska were involved in writing and review while **Antonio J. Rovira de Antonio; Ruben Abbas; Juan Pedro Solano Fernandez; Krzysztof Naplocha; Jose Munoz Camara; Peter Kew, Krzysztof Naplocha & Savvas Tassou** in providing data.

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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Data availability

Data will be made available on request.

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