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Developing a triple helix approach for CO_2 utilisation assessment†

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Assessment of the sustainability of CO_2 utilisation technologies should encompass economic, environmental and social aspects. Though guidelines for economic and environmental assessment of CO_2 utilisation (CDU) have been presented, a methodology for social assessment of CDU has not. Herewith, social impact assessment for CDU is systematically investigated, a methodological framework derived and examples of application given. Both process and deployment scenarios are found to be key factors in the assessment and the sourcing of raw material is observed to be a hotspot for social impacts within the assessed CDU technologies. This framework contributes a new aspect to the development of holistic sustainability assessment methodologies for CDU by enabling a triple helix to be created between life cycle assessment (LCA), techno-economic assessment (TEA) and social impact assessment (SIA). Therefore, the triple helix approach will enable trade-offs between environmental, economic and social impacts to be explored, ultimately enhancing effective decision making for CDU development and deployment.

Introduction

Sustainability is key to the future of green chemistry and holistic methodologies to assess this are a necessity.[1] Sustainability should be considered as a three-dimensional concept, with the constituent parameters generally defined as the economy, society and the environment. Life cycle assessment (LCA), life cycle costing (LCC) or techno-economic assessment (TEA) and social impact assessment (SIA) or social life cycle assessment (SLCA or S-LCA) are common methodologies used to assess the three dimensions. These concepts can be further considered as a triple helix structure with cross-linkages between parameters. By expanding our thinking to consider the whole life cycle of a product (life cycle thinking) within the facets of environment, social and economic impacts we can seek to reduce resource use, emissions, social and environmental impacts.[2] Of

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these three assessment methods, SIA or S-LCA has historically been the least developed.[3,4]

Within the field of carbon dioxide utilisation, most technology assessments to date focus primarily on assessing the economic and environmental impacts of emerging carbon dioxide utilisation (CDU) technologies and their enabling infrastructure.[5] Increasingly, these studies are moving towards being "integrated" with the intention of investigating trade-offs between environmental benefits and increased financial burdens.[6] This shift into a two-dimensional assessment approach is one which should be encouraged but leaves open the risk that the third societal pillar remains neglected. Therefore, approaches to integrate all three aspects are required to attain truly sustainable CDU technology deployment.[6–8] Guidelines for the economic and environmental assessment of CDU have recently been published to steer practitioners through methodological choices in CDU assessment.[9] However, such guidelines or methodologies do not exist for CDU social assessment, therefore the triple helix cannot easily be completed.

Social impacts should not be confused with social acceptance. Social acceptance is a measure of which an innovation will be accepted or rejected by key actors whereas social impacts measure the consequences of actions on society. Of course, there is an interlinkage between these aspects as social impacts can have an effect on social acceptance. Social acceptance covers the dimensions of socio-political acceptance, community acceptance and market acceptance.[10] Some explorations into the social acceptance of CDU technologies have been investigated,[11–15] though research in this area is still sparse. Generally, CDU technologies are perceived in a positive manner though with some hesitation.

Social impact assessment (SIA) analyses the intended or unintended consequences to humans of new actions. SIA can assist in the development of new chemical technologies, yet such assessment has not been readily applied to CDU. Typically, social impact is considered at a later stage of the development cycle, predominantly in deployment and the full impact may not be realised for many years afterwards. However, leaving such considerations until high technology readiness (TRL) could lead to inadvertent investment in socially unsustainable CDU processes. Therefore, questions are raised as to how SIA can be applied earlier and whether earlier application gives meaningful assessment results? Furthermore, due to the linkages between CDU, renewable energy deployment and industrial symbiosis opportunities, can the indirect impacts (such as using conflict minerals in catalyst synthesis) also be addressed?

Methods of social impact assessment

Social impact assessment is defined by Becker[16] as "the process of identifying the future consequences of current or proposed actions, which are related to individuals, organisations and social macro-systems". Therefore, the focus of social impacts should be on the corporate social responsibility of the activities undertaken by the company which will affect current and future generations.[17] As such, many organisations report social impacts using such mechanisms as the Global Reporting Initiative (GRI)[18] or the UN Sustainable Development Goals (SDGs),[19] however these tend to report on ongoing deployed activities or products rather than emerging technology opportunities. Kühnen *et al.*[20] identified five main frameworks used in social performance measurement research: GRI sustainability reporting, UNEP and SETAC SLCA guidelines,[21] UN SDGs, SAI SA 8000 and ISO 26000. Of these, the most commonly used are the GRI and UNEP & SETAC SLCA guidelines and most researchers, although assessing varying industry sectors and products, tend to use similar SLCA subcategories.

The 'International Principles for Social Impact Assessment'[22] recognises that a definitive definition of guidelines for SIA is complex and that guidelines need to be evolved from core values and principles. All issues that affect people indirectly or directly are relevant in SIA, but guidelines for assessment can enhance practice and are therefore beneficial. To tackle this gap, the UN Environmental Program (UNEP) with the Society of Environmental Toxicology and Chemistry (SETAC) published guidelines for stakeholders for the assessment of social impacts of products in 2009.[23] The guidelines aim to be used as a skeleton approach to enable practitioners to identify key elements which should be considered in a study. The guidelines and methodological sheets[21,24] identify five stakeholder categories: local community, value chain actors, consumers, workers, society. Each of these stakeholder categories is then broken down into subcategories with examples of inventory indicators and data sources to assess the category being given (Fig. 1). The practitioner can then determine appropriate indicators within the subcategories for the scope of their assessment. These guidelines have been widely used and form the basis for many S-LCA studies.[25–29]

The European Commission Joint Research Centre conducted a state of the art review of SLCA, concluding that methodological development and harmonization is still in a preliminary stage when compared to LCA.[30] The JRC highlights the role that S-LCA can play in supporting decision making by identification of hotspots, but also recognises the S-LCA, TEA and LCA can result in conflicting indicators, for example, high wages are seen as positive in S-LCA but have a negative impact in TEA. Issues surrounding data availability, quality and reliability are also highlighted.

Indicators for S-LCA can either be qualitative, semi-quantitative or quantitative in nature.[4,31] Quantitative indicators use statistical sources and can be based on scoring methods. Qualitative indicators can be more exploratory and descriptive in nature and can be used to highlight potential problems. Popovic *et al.*[32] suggested 31 quantitative indicators which can be used to assess supply chains. Particularly focusing on labour practices and human rights the indicators cover

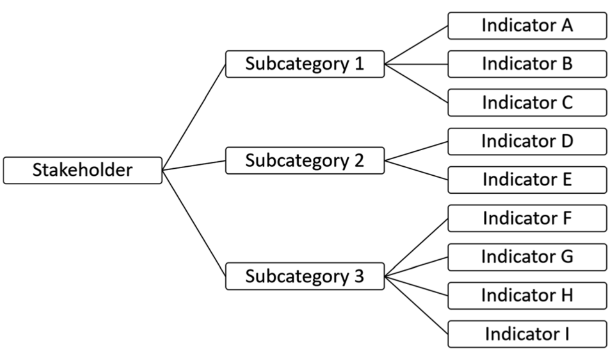

Fig. 1 Structure of UNEP/SETAC guidelines. Adapted from ref. [21].

issues found in company sustainability reports and can be used to monitor the supply chain.

Social impacts for the chemical and process industries are often considered within a broader sustainability assessment incorporating economic, environmental and social aspects. Markeviius *et al.*[33] identified 35 sustainability criteria often found in literature, of which 15 related to social dimensions, 4 to economic and 16 to the environment. 46 experts were asked to rank the criteria for relevance, practicality, reliability and importance and it was found that social criteria ranked lowest in the four attributes. Husgafvel *et al.*[34] created a sustainability index which incorporates both impacts within the supply chain and plant operations, however this is based on deployed technologies and hence depends on organisational data. Haaster *et al.*[35] developed a framework for S-SLCA of novel technologies covering four categories of concern (autonomy; safety, security and tranquility; equality; participation and influence) and 11 mixed qualitative and quantitative indicators to assess these categories. Here the quantitative indicators are aggregated to give a final score (weighted or unweighted), whilst qualitative indicators are used to identify potential concerns. Sector specific sustainability indicators have also been derived (often from frameworks such as GRI or UNEP/SETAC) for example for the mining and minerals sector.[36,37]

Social impact assessment in CO_2 utilisation and emerging technologies

Zimmermann *et al.*[5] highlights the lack of social impact assessment in emerging technologies. The review states that only five social indicators were identified as being employed in social assessment in CDU. Zimmermann found that no CDU studies incorporated assessment of technical, economic, environmental and social impacts, and that CDU social assessment was lacking across all TRLs. Pieri *et al.*[38] reviewed holistic assessment for CDU value chains, in the modelling approaches identified, none employed social impact assessment. Pieri *et al.* concludes that social impact assessment has been ignored and a more holistic approach to assessing sustainability is needed.

The low technology readiness (TRL) of many CDU processes has been identified as an issue for data gathering for social assessment.[39] However, as CDU processes have the potential to provide sustainable solutions in numerous sectors, the low TRL should not inhibit attempts to establish how social impacts could affect CDU deployment. Rafiaani *et al.* highlights that the lack of data can be tackled using experts to identify the most relevant areas to focus social assessment on.[39] Basing the approach upon the UNEP/SETAC guidelines, Rafiaani *et al.* indicates that the main stakeholders for CDU are workers, local community and consumers and therefore only assess in these areas. CDU experts were then asked to rank the importance of the UNEP/SETAC indicators for a stakeholder group. The experts highlighted 'end of life responsibility' and 'transparency' for the consumers, 'fair salary' and 'health and safety' for workers and 'safe and healthy living conditions' for local community as the most important indicators. However, the work did not apply the assessment to any CDU technology to determine if there are significant differences in these areas between the CDU technology and the current technology it would replace. Chauvy *et al.*[40] incorporates some aspects of SIA into the assessment of emerging CDU products by assessing health and safety aspects. In discussing multi-criteria decision analysis (MCDA) approaches for selecting CDU products it was recognised that social aspects were often mixed with environmental criteria but should be assessed separately.[41] Sacramento-Rivero *et al.*[42] considers an approach to sustainability assessment for processes in the conceptual design stage. However, only the aspects of employment and community development are investigated as social impacts and therefore many social considerations are ignored.

Research question

This work focuses on SIA for CDU technologies. Whilst a number of CDU technologies have reached commercial deployment, the vast majority remain under development at varying levels of maturity. Currently, there is little guidance available on the application of SIA for the specific scope of CDU technology development and deployment. To ensure CDU technologies are truly sustainable, herewith the application of SIA to CDU technologies is investigated through the development of a tailored assessment framework. This framework is then applied to a number of CDU technologies and deployment scenarios to illustrate its potential utilisation and highlight any limitations regarding practical implementation and feasibility of the suggested indicators.

This research aims to clarify:

• Which social indicators are key when assessing CDU technologies in a screening-type assessment and should therefore form the baseline of any assessment?

• How should these indicators be assessed – qualitatively or quantitatively?

• How social impacts are distributed between the CDU technology and the deployment scenario?

Methodological development and general principles

Indicator development

The UNEP/SETAC S-SLCA guidelines provide a comprehensive skeleton framework for the development of SIA for products identifying stakeholder groups and key subcategories for the assessment. Therefore, the framework is utilised as a starting point for adaptation to develop SIA for CDU. As discussed, most CDU processes are considered as low maturity or emerging technologies and thus the focus of this work is to develop a SIA framework suitable for assessing technologies at this stage of the development cycle. However, although CDU technologies themselves are classed as emerging, many aspects of their supply chains are fully or highly developed, therefore even with low TRL inventory data for the CDU technology insights into possible social impacts can be obtained or estimated. Given the available data and the uncertainties surrounding both technologies and impact assessments of these at this stage, a 'screening type' assessment was developed – primarily focussing on the identification of potential hotspots, risks and 'red flags' within both the supply chain and the process itself. The developed SIA can be aligned with TEA and LCA studies with a similar scope, adding a third dimension for stakeholders to consider in their process & scenario analysis. Given this intention, the indicators and data used to estimate them remain fuzzy and partially dependent on the practitioner's judgement based on the available data. Sourcing data is a known issue in impact assessment in general, thus the presented framework will focus on utilising open access data where possible to allow for a wider range of decision makers/TEA & LCA practitioners to utilise the framework in their chosen decision analysis.

The UNEP guidelines outline a total of 30 assessment subcategories split between five stakeholder groups, however given the identified scope of this framework many of these were deemed unnecessary for inclusion. Removing subcategories from consideration also allows for a streamlining of data collection and assessment, creating a better fit with the intended utilisation of the framework. In most instances, subcategories were discarded if the UNEP description and assessment aim suggest that the impact is dominated by organizational decisions related to broader corporate behaviour rather than the specific selection of a technology for development or deployment. The indicators used are designed to reflect data availability – users can amend these to fit their data and/or their assessment goals/technologies. This flexibility in the selection and application of indicators is aligned with the principles outlined in the UNEP S-LCA guidelines, where users are encouraged to determine which indicators best suit their assessment needs.

To determine whether a subcategory was needed, a two-dimensional assessment was made considering both:

- Importance of technology choice on the impact subcategory (high or low)
- Importance of indirect relationships on the impact subcategory (high or low)

Scoring each subcategory on both dimensions allows for the determination on how important its inclusion is for the selected scope. A subcategory in which the technology choice has only a low importance is unlikely to require assessment as other organisational behaviours and choices are more likely to be a driving factor. The second dimension of this assessment is more nuanced, but ultimately subcategories dominated by direct relationships rather than indirect ones are less likely to require assessment. Direct relationships are defined here as those that the organization are involved on a 'first party' basis, with indirect being all other subsequent relationships. Through direct relationships an organization can choose suppliers or vendors/customers that can be vetted for the mitigation of risks for negative social impacts associated with technology choices. Indirect relationships however may be more opaque, particularly if the supply chain for an input/output is extensive or complex in its nature. It is here where the organization may have less influence or ability to directly minimize its negative social impact and thus these factors are of more concern for assessment.

Serious efforts have been made to counteract unsustainable practices within supply chains, often with the intention of reducing the risk of utilising products that may impact societies or the environment negatively. Both compulsory (*e.g.* legislative) and voluntary (*e.g.* sustainable trade organisations) systems exist to address identified issues. However, the existence of such systems does not remove the need for assessing the social impact of an operation, even if it is assumed that these systems would be utilised where required. This effort to minimise negative social impacts should be seen as akin to optimising a process to minimize environmental impact or maximize profitability – an action that may be influenced by the results of an assessment but one that is independent of the assessment methodology itself. Furthermore, products that appear to meet voluntary or compulsory standards can still carry risk. As the proposed assessment is of a screening nature and for emerging technologies, the exact source of products and their supply chain will often be unknown. However, this does not negate the importance of including such indicators at this stage to 'flag' potential hotspots through considering already established supply chains. By flagging these hotspots early organisation choice in deployment or alteration of the process during development could mitigate any potential negative impact.

To illustrate this, two examples are explored: palm oil and gold. The Roundtable on Sustainable Palm Oil (RSPO) was created to 'develop and implement global standards for sustainable palm oil' and members include many of the world's biggest palm oil consumers. However, criticism persists both on the RSPO[43] and on the certifying of palm oil as sustainable when produced in areas where heavy deforestation and habitat destruction occurred less than 30 years ago.[44] Arguably more pressing are NGO reports on 'conflict' and 'illegal' palm oil[45,46] that state this palm oil is entering the supply chains of RSPO members. These illicit mills are shown to have significant negative impacts to both the environment and society, infringing the human rights of local communities in the process.

Illicit gold mining in Peru is known to cause significant negative impacts to local communities,[47] driven by criminal exploitation and organized crime. These impacts range from health (a reported 30 tons of mercury is dumped in rivers and lakes in the Amazon region every year, generating dangerously high levels of the material in the watercourse) to social issues such as the trafficking of women and young girls to mining towns to work in brothels. It is reported that in Delta 1, a mining settlement, alone there are approximately 2000 sex workers of which 60% are underage.[47] La Rinconada, another settlement, has an estimated 4500 girls trafficked for sexual exploitation to work in bars frequented by miners. The same report alleges that 35 tons of contraband gold were shipped *via* Lima to the USA and Switzerland between February and October of 2014 alone.

In 2018, Metalor, a Swiss gold refinery, stopped taking gold from the Peruvian Highlands region (including the aforementioned settlement of La Rinconada) that had been certified as 'sustainable' due to concerns of its origins. The company is quoted as stating that whilst they believed that operations were conducted 'in a proper way', they couldn't guarantee that this was the case 'due to the complexity of the supply chain'[48] – the company had processed an estimated 106 tonnes of gold from a Chilean company operating in the region, Minerales del Sur, since 2001 before halting purchases. Metalor customers at the time of the investigation included major technology companies demonstrating how feasible it is for illicit materials to enter the supply chains of companies.

Both of these examples highlight the need to consider in as much granularity as possible the indirect relationships involved in supply chains through SIA. In relation to CDU, awareness of how these issues could impact raw materials such as metal catalysts should be considered. Ultimately these examples illustrate that given the identified scope of this framework there is a need to include a focus on these indirect relationships that are particularly impacted by the choice of technology.

Table 1 shows an abridged version of the framework (showing only two stakeholder categories, the full version can be found in the ESI†) details the subcategories selected from the UNEP/SETAC guidelines identified for inclusion in the SIA framework for CDU. These categories were all determined to be of importance for the assessment scope, utilising the two-dimensional assessment

Table 1 Selected subcategories and their application to CDU social impact assessment (abridged version of full framework found in ESI Table 1)[a]

Stakeholder	UNEP subcategory	Aims of UNEP subcategory assessment	Relevance to identified CDU assessment scope	Suggested indicator(s)	Typical data inputs used for assessing indicator	Suggested external data sources
Local community	Delocalisation & migration	Assess the contribution to delocalization, migration or 'involuntary resettlement' within communities	Changes in land use at scale for economic development can be a driving factor in the creation of displaced persons	Likelihood of forced evictions for technology implementation	Process design calculations, LCI data, geographical data (land use), regional/national data on forced resettlement/ compulsory purchase orders *etc.*	OECD land resources statistics
	Local employment	Assesses how an organization directly or indirectly affects local employment	CDU technologies could bring changes to employment opportunities both directly & indirectly, more so if the supply chain is localised	Operational impact on local employment – direct	Process design calculations, labour estimation calculations, employment & labour statistics	World Bank development indicators (employment), national employment & labour statistics
				Operational impact on local employment – indirect	Employment & labour statistics, IRENA employment statistics, COMTRADE-type data	World Bank development indicators (employment), national employment & labour statistics
	Access to material resources	Assess the extent to which organizations respect/protect/improve community access to material resources & infrastructure	CDU technologies can impact positively & negatively access to resources such as (renewable) electricity, water, land & other products. Additional	Operational impact on local land-use & zoning	Process design calculations, LCI data, geographical data (land use)	OECD land resources statistics
				Changes to local water supply & security	Process design calculations, LCI data,	UN AQUASTAT database, national

Table 1 (*Contd.*)

Stakeholder	UNEP subcategory	Aims of UNEP subcategory assessment	Relevance to identified CDU assessment scope	Suggested indicator(s)	Typical data inputs used for assessing indicator	Suggested external data sources
			strains on areas known to be water/land/energy (renewable & not) constrained may cause problems for communities.		water scarcity data for country/region	reports/statistics (regional perspective)
				Changes to local electricity & energy supply	Process design calculations, LCI data, national electricity/energy statistics (*e.g.*, DUKES)	World Bank WDI & SE4ALL databases, national reports/statistics on electricity & energy consumption/provision
			Operations may also impact access to material produce negatively (consuming limited resources) or positively (increasing domestic security of supply)	Changes to local access to material produce	COMTRADE-type data & national production/market statistics	UN COMTRADE, EU PRODCOM & OECD databases, observatory of economic complexity data
	Safe & healthy living conditions	Assess how organizations impact community safety & health	Potential risks and benefits of CDU plant operation on the communities safety & health should be assessed to determine potential impacts on the local community (considering both regular operation & accident potential)	Impact on air quality & pollution levels	Process design calculations, LCI data	World Bank WDI database
				Utilisation & risks associated with the use of hazardous substances in the operation	Chemical safety data, LCI data, HAZOP studies	COSHH database, ILO international chemicals safety cards database
Workers	Child labour	Assess whether the organization is employing child labour	Choices made in technology development/deployment may have	Potential for utilization of child labour in supply chain	Process design calculations, LCI data, COMTRADE-type data &	UN COMTRADE, EU PRODCOM & OECD databases, observatory

Table 1 (*Contd.*)

Stakeholder	UNEP subcategory	Aims of UNEP subcategory assessment	Relevance to identified CDU assessment scope	Suggested indicator(s)	Typical data inputs used for assessing indicator	Suggested external data sources
		as defined by ILO conventions & to identify the nature of any child labour	unintended consequences regarding child labour utilisation		national production/ market statistics	of economic complexity data
	Forced labour	Assess whether there is the use of forced labour in the organization	Choices made in technology development/ deployment may have unintended consequences regarding forced labour utilisation	Potential for utilization of forced labour in supply chain	Process design calculations, LCI data, COMTRADE-type data & national production/ market statistics	UN COMTRADE, EU PRODCOM & OECD databases, observatory of economic complexity data
	Equal opportunities	Assess whether there is any worker discrimination present in the organization	Choices made in technology development/ deployment may have unintended consequences regarding workplace discrimination	Potential for supporting discriminatory practices in supply chain	Process design calculations, LCI data, COMTRADE-type data & national production/ market statistics	UN COMTRADE, EU PRODCOM & OECD databases, observatory of economic complexity data
	Worker H&S	Assess the rate of workplace incidents and prevention/ management processes	It is widely understood there is a need to assess potential H&S risks in manufacturing	Risk to the H&S of workers associated with operation	ILO data on national workplace accident rate, HAZOP studies, chemical safety data	COSHH database, ILO international chemicals safety cards database, ILO H&S data

[a] The full unabridged version of the framework including all stakeholder categories can be found in the ESI Table 1.

previously mentioned. To provide an example of this assessment consider that the UNEP/SETAC guidelines include in the 'local community' stakeholder group subcategories for 'community engagement', 'cultural heritage' and 'respect of indigenous rights' all of which have been excluded from the CDU SIA framework. In each instance the importance that the technology choice has on the subcategory is low, and the importance of direct relationships is high (all three are characterised by an organisation's direct relationship with the local community and the decision to engage meaningfully with the community and respect its cultural heritage) this is largely dependent on organisational policy and behaviour. Table 1 forms the basis of the derived assessment framework, it provides a brief overview of the UNEP/SETAC subcategory aim and its perceived relevance to the SIA framework for CDU, alongside providing suggested indicators for each subcategory. Indicators for each subcategory are also supplied with typical data inputs that may be used in indicator calculation as the user sees fit and in most cases references to 'external' (*i.e.* not derived from the process) data sources that are generally open access. As discussed, the use of open access data in conjunction with process specific data allows for the broadest application of the framework without the need for costly databases, although in many instances LCI data is seen as beneficial.

Framework for SIA for CDU

SIA for CDU is applied by utilising the standard phases assessment structure as for LCA[49] and which has also been suggested for use in TEA.[9] By using a common assessment structure for LCA, TEA and SIA assessments, practitioners who are carrying out all three types of assessment have the advantage of using a common methodology and can share common inventory data as appropriate. Using a common phase structure also benefits the integration of assessments to create a triple helix for CDU.

For SIA, once assessment indicators have been established, the phases are applied for the analysis:

- Firstly, the goal and scope of the SIA are defined,
- The inventory is then compiled of process and supply-chain data along with identification of data sources for indicators,
- Impacts are assessed in accordance with the chosen indicators,
- Finally, the results are interpreted.

Together with the derivation of indicators these phases constitute a framework for SIA for CDU. The framework can be utilised to assess CDU technologies in a number of ways. Firstly, to compare deployment scenarios, secondly to compare different CDU technologies and thirdly to compare a CDU technology with a reference case or other routes to the same product.

Data collection for the inventory. CDU is not a standalone technology and many processes rely on several common core inputs, namely captured CO_2, low-carbon intensity electricity and green hydrogen to ensure that the environmental impacts are kept to a minimum. Therefore, the data for each of these sub-processes must also be collected for the inventory. In a similar way to LCA to enable fair and equitable comparison to a reference case or between products or scenarios, a functional unit is chosen to determine and model the product system. However, in contrast to LCA the impacts may not always be conveyed by functional unit as a mix of data types (quantitative, semi-quantitative and qualitative) are used. When dealing with qualitative indicators expressing impacts in terms of functional unit can be difficult, however, as the system modelling stems from the function unit, the link is present if not always explicit. When integrating an SIA with a LCA and/or TEA to form holistic assessment utilising the same functional unit for all assessments enhances integration by enabling a common inventory to be used. Some of the data required for the inventory is similar to that of an LCA or TEA, for example mass and energy balances or the estimated number of shift workers/employees needed. Further information on the sources of inputs (*i.e.* geographic location of raw (& manufactured) resource materials for catalysts) and data specific to the organisation is also required for impact categories such as child labour and migration.

Scoring within the framework. A major difference between SIA and LCA and TEA is how each indicator is assessed. In LCA the emissions flows are calculated then multiplied by a characterisation factor for a specific impact category giving a discrete number. In TEA indicators are calculated by adding impacts for example CapEx is calculated by adding together all capital costs throughout the process system. However, for SIA a number of factors must be considered in each indicator therefore, in many cases a discrete numerical indicator based on summation cannot be calculated. This is due to data in the inventory being of mixed type, quantitative, semi-quantitative and qualitative. Therefore, a qualitative scoring methodology which is based on quantitative and semi-quantitative data can be derived to allow the comparison of indicators. The scoring methodology for each indicator and within each example assessment is individual (goal and scope specific) and consists of data from numerous sources. Therefore, although scores for a single indicator can be compared within an assessment, the scores for a specific indicator cannot be compared to those from a separate assessment *i.e.* scores in example 1 below cannot be compared with example 2. Scores that utilise world rankings or comparisons as part of the data calculation method, utilise this data in a relative fashion to the world ranking. It should be noted that the expected relationship between scale and marginal impact is not linear, suggesting that the larger your deployment scale is the higher your scores can be and the more problematic high scores may be in terms of barriers to deployment. Scoring should be applied with a scale with enough granularity to see differences in results to enable hotspot identification therefore, a three-point scale is not recommended, rather five- or nine-point scales. The use of colour through traffic-light systems can aid scoring and enable visual interpretation of results.

Impacts for social assessment can be positive, negative or neutral in nature depending on the specific wording of the indicator with scores given in relation to the specific scenario (or reference scenario, if required). Therefore, care needs to be taken when deriving scoring methods for the framework to ensure consistency in scoring. For example, a decision needs to be taken as to whether a zero score indicates a positive result *i.e.* no social impact or a positive social impact or whether a high score indicates this. For example, in the presented examples below, for the indicator ‘changes to local access to materials produced’, a very high change results in a zero score as this reflects self-sufficiency (a reduction on reliance of imports) as production is increased locally. However, one might expect a very high change to result in a high numerical (score 4 in the examples) scoring rating. Subsequently, careful consideration of how the scoring methodology is derived is needed to ensure consistency and no 'false positive' hotspots are identified. Here, a colour system can help by clearly identifying negative impacts.

Results: demonstration of the framework

Here we provide two examples to demonstrate the application of the framework to identify hotspots for new CDU processes. These examples show how data should be collected and utilised within the framework, how scoring can be derived and how results can be interpreted to identify hotspots. The indicators selected are those described in the Methodology section. Three commonly discussed CDU technologies from literature were chosen to demonstrate application in different technology areas:

- Methanol production from CO_2 and H_2 *via* water electrolysis[50]
- Polyol production for polymers[51]
- Mineral carbonation of waste ashes to produce construction blocks[52]

Social impacts are not solely reliant on the process; the location scenario will also have an effect. To demonstrate how impacts can vary between countries for the same process, three locations for assessment have been selected: the UK, China and Chile. These locations are diverse in many areas *i.e.* in respect to population, environmental policy and renewable energy production. Hydrogen production is key for a number of CDU processes and the IEA[53] has highlighted China and parts of Chile amongst other countries as promising areas for H_2 production based on costs from hybrid solar photovoltaic and onshore wind systems. It is presumed that the supply chain for each scenario will be predominantly within the scenario country, however, some primary resources are geographically restricted, and therefore the most likely sources of supply should be taken into account.

Goal and scope of examples

Example 1: the goal is to conduct a comparative assessment to determine the social impact hotspots for the production of methanol (MeOH) in three locations (UK, China and Chile) in 2020. In conjunction with varying production location, the supply of electricity for the process will be investigated considering wind and solar power.

Example 2: the goal is to compare social impacts of utilising 1 tonne of captured CO_2 for different CDU technologies, namely methanol production, polymer production and mineral carbonation in the UK with varying energy sources (wind or solar) in 2020. To identify hotspots within the process and supply-chain and to identify which has the least social impact.

Inventory data collection

Data for each process and sub-process was collected from literature and can be found in ESI, Table 2.† The further data sources regarding country specific data are listed in the full impact calculation tables which can also be found in the ESI.†

Table 2 Results of SIA of methanol production in three locations

Subcategory	Indicator	MeOH UK wind	MeOH UK solar	MeOH China wind	MeOH China solar	MeOH Chile wind	MeOH Chile solar	Justification
Delocalisation & migration	Likelihood of forced evictions for technology implementation	0	0	1	2	1	1	Reasonably low risk of displacement for economic development, wind needs larger area though likely offshore. Forced eviction most prevalent in Asia followed by Latin America
Local employment	Locals directly employed due to activity	1	0	1	0	1	0	Higher job creation in solar energy than wind (×2–3 times greater per MW)
	Locals indirectly employed due to activity	1	1	1	1	1	1	Localised supply apart from catalysts
Access to MR	Changes to local land use	1	4	2	1	2	1	China and Chile have considerable prospects for solar deployment. UK has access to large wind resources, though land for solar an issue
	Changes to local water supply & security	2	2	1	2	2	2	China has low level of people living in water scarce areas (36%). UK and Chile are higher (46% and 52% respectively)
	Changes to local electricity supply	2	3	1	1	4	3	Electricity demand for MeOH production is high due to water electrolysis for H_2. China has least capacity issues, UK wind has greater potential for expansion. Solar & wind capacity are small in Chile, where hydro is dominant renewable energy source
	Changes to local access to material produced	2	2	2	2	4	4	Chile exports large amount of methanol. UK and China import more methanol than they export so this will increase local security of supply
Safe & healthy living conditions (LC)	Impact on air quality/pollution levels – production	0	0	2	2	1	1	Air pollution is worst in China and best in UK. The amines from the capture process will add to local air pollution
	Utilisation of hazardous substances in process	2	2	2	2	2	2	Use of amines and H_2 (H_2 needs storage)
Promoting social responsibility	Use of wastes and other sustainable materials	1	1	1	1	1	1	Inputs are sustainable as renewable H_2 production is used, however electrodes use platinum group metals
	Social responsibility in supply chain	1	1	1	1	1	1	Platinum group metals used but sustainable reporting is common for the metals therefore sustainable producer could be chosen
Consumer health & safety	Consumer health & safety risk	2	2	2	2	2	2	Methanol predominantly used in industry rather than by consumers, however poses acute health hazards for oral, dermal and inhalation toxicity and is highly flammable
EOL responsibility	Recyclability of product & process elements	3	3	3	3	3	3	Methanol is not a product able to be recycled directly at end of life will emit CO_2. Can be recycled by air capture of CO_2
	Potential health risks for improper disposal of product & process elements	1	1	1	1	1	1	No issues for product disposal, high use of electrolysers for H_2 = disposal of used electrodes
Child labour	Potential for utilization of child labour in supply chain	0	0	0	0	1	1	Chile has low levels of child labour though these are mainly concentrated in the services and agricultural industries
Forced labour	Potential for utilization of forced labour in supply chain	1	1	1	1	1	1	Higher risk in Africa, Asia and Pacific. Metal catalysts likely to be sourced from Africa however quantities needed are low.
Equal opportunities	Potential for supporting discriminatory practices in supply chain	0	0	1	1	0	0	UK and Chile have high levels of female employment. China has much lower levels of employment which could lead to discriminatory practice
Worker health & safety	Worker health & safety risk	2	2	2	2	3	3	H_2 storage & transportation and possible exposure to amines are biggest issues regarding H&S. UK has a better H&S Chile. Unknown for China
Public commitment to sustainability issues		1	1	2	2	2	2	Chile has very high renewable energy targets, but with China is lower in the Global sustainable competitiveness ranking than UK
Prevention & mitigation of conflicts	Potential for utilisation of goods/materials/servic es	1	1	1	1	1	1	All countries would likely be sourcing metals externally therefore rankings similar
Contribution to economic development	Use of local supply chain	1	1	1	1	1	1	Raw materials apart from metals can all be sourced locally, only CO_2 and water required

Impact calculation and interpretation example 1: comparative assessment of scenarios/locations

For the first example, the production of methanol (MeOH) in three locations (UK, China and Chile) is compared using a functional unit of 1 tonne of methanol. In conjunction with varying production location, the supply of electricity for the process was also varied between wind and solar power. Scores were calculated for each indicator using a five-point scale and a summary is shown in Table 2. A more detailed version of Table 2 can be found in the ESI which details the data sources and scoring mechanism.†

The highest scores (hotspots) were observed in categories where the electricity supply contributes strongly to the scoring, hence indicating electricity supply is

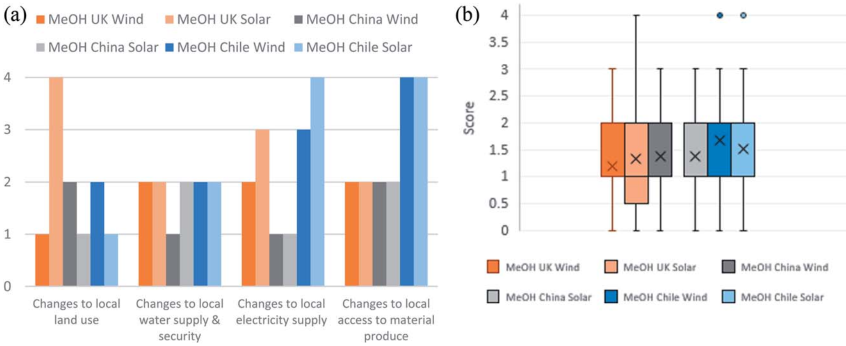

Fig. 2 (a) Comparison of access to material resources indicators. (b) Distribution of score for methanol production.

a significant social impact hotspot. Indicators where the process has a greater contribution than the location broadly result in the same score across all locations. Significant differences in scoring can be observed in the subcategory of 'access to material resource' where the effect of the large electrical energy requirement for the production of H_2 has a significant impact on the indicators for land use and changes to electricity supply (Table 2 and Fig. 2a). Solar and wind energy contribute 23% and 14% respectively to Chile's renewable energy capacity,[54] therefore in these scenarios the large amounts of electricity required could place significant strain on capacity and are hence identified as a hotspot. Looking at alternative sources of low carbon or renewable energy in Chile could reduce the social impacts. Chile exports significantly more methanol than it imports, indicating that increasing production would not positively impact the indicator 'changes to local access to material produced', whilst higher imports in the UK and China could lead to greater security of supply by deploying a CDU methanol plant.

Overall, the impacts for methanol production in each scenario are reasonably low or positive in nature. Fig. 2b highlights the dispersion of the results for each scenario. Across all scenarios the median score is 1, with methanol production using wind power in Chile indicating the highest mean for social impacts. Production in the UK *via* solar power shows the widest variability of scores, whilst production in Chile has a smaller variability but with outlying high scores. Due to the screening nature of this style of SIA, it is the outlying high results, those with the highest median scores and those with the largest range in the 50 to 75% and 75% to max quartiles that should be carefully considered to determine how the impacts could be mitigated.

Impact calculation and interpretation example 2: comparative assessment of technologies

In example 2, different CDU technologies are compared in a deployment scenario of the UK, here a functional unit of 1 tonne of captured CO_2 converted to a product is used to compare diverse technologies. One tonne of CO_2 would produce 0.68 t methanol, 4.4 t polymer or 11 t of mineralised carbonated block. In this assessment the plant location contributes equally across each indicator with

Table 3 Results of SIA comparing production of methanol, polymers and minerals for construction in the UK utilising 1 tonne of captured CO_2

Subcategory	Indicator	MeOH UK wind	MeOH UK solar	Polymer UK wind	Polymer UK solar	Mineral UK wind	Mineral UK solar	Justification
Delocalisation & migration	Likelihood of local forced evictions for technology implementation	0	0	0	0	0	0	Highly unlikely in UK scenario, most land used for MeOH solar but this likely to be agricultural land
Local employment	Locals directly employed due to activity	1	0	3	3	3	3	Higher job creation in solar energy than wind (×2–3 times greater per MW), however polymer and minerals use much lower levels of renewable energy
	Locals indirectly employed due to activity	1	1	1	1	0	0	Localised apart from catalysts, for mineralisation use of waste local materials
Access to MR	Changes to local land use	2	4	1	1	1	1	UK has access to large offshore wind resources, though land for solar an issue. Electricity demand for MeOH is 13–30 times greater than for polymer or mineralisation production
	Changes to local water supply & security	2	3	0	0	0	1	Minimal water needed for polymers and minerals though solar can have high water demand per MW h. Green H_2 production for MeOH requires water
	Changes to local electricity supply	2	2	0	0	0	0	MeOH has higher electricity demand due to H_2 production (13–30 times more than polymers or mineralisation)
	Changes to local access to material produced	2	2	3	3	4	4	More methanol is imported than exported, polyurethane imports and exports are similar therefore increased local production will have limited impact. Mineral imports are lower therefore increased local supply will have little impact
Safe & healthy living conditions (LC)	Impact on air quality/pollution levels – production	0	0	0	0	1	1	Mineralisation has potential to be carbon negative technology reducing CO_2 levels
	Utilisation of hazardous substances in process	2	2	0	0	0	0	Use of amines and H_2 (H_2 needs storage) for MeOH. Much lower level of amine needed for polymers and minerals
Promoting social responsibility	Use of wastes and other sustainable materials	1	1	2	2	0	0	Mineralisation uses wastes as feedstocks, methanol uses some platinum group metals for electrolysis, polymers use more materials that could be sourced from fossil resources, care needs to be taken to reduce this
	Social responsibility in supply chain	1	1	1	1	0	0	Metal catalyst and electrode metals have very low possibility of being sourced illicitly or from conflict areas
Consumer health & safety	Consumer health & safety risk	2	2	0	0	0	0	Methanol predominantly used in industry rather than by consumers, however poses acute health hazards for oral, dermal and inhalation toxicity and is highly flammable
EOL responsibility	Recyclability of product & process elements	3	3	2	2	0	0	Methanol is not a product able to be recycled directly is going to emit CO_2, can be recycled by air capture of CO_2. Polymers recycled until end of life. Minerals do not need recycling, though can be crushed and reused
	Potential health risks for improper disposal of product & process elements	1	1	0	0	0	0	No issues for product disposal, high use of electrolysers for H_2 = disposal of used electrodes
Child labour	Potential for utilization of child labour in supply chain	1	1	0	0	0	0	MeOH uses high level of catalyst/rare metals which can be sourced from areas using child labour
Forced labour	Potential for utilization of forced labour in supply chain	1	1	0	0	0	0	MeOH uses high level of catalyst/rare metals which can be sourced from areas using forced labour
Equal opportunities	Potential for supporting discriminatory practices in supply chain	1	1	1	1	0	0	Not likely in UK however could play a factor within supply chain of metals for catalysts
Worker health & safety	Worker health & safety risk	2	2	1	1	1	1	H_2 storage & transportation and possible exposure to amines are biggest issues regarding H&S for MeOH
Public commitment to sustainability issues		1	1	2	2	1	1	MeOH could be included in renewable energy targets and help with grid balancing, mineralisation can count towards net zero targets as a carbon dioxide sink
Prevention & mitigation of conflicts	Potential for utilisation of goods/materials/services	1	1	0	0	0	0	High level of catalyst used for MeOH which may be sourced from unstable regions
Contribution to economic development	Use of local supply chain	1	1	2	2	0	0	Mineralisation recycles waste products, MeOH predominantly local supply chain though catalysts not local, PO may be externally sourced for polymers

the process and supply chain varying. Indicators are again calculated using a 0–4 point scale and a summary is presented in Table 3 with further details on scoring available in the ESI.† Here, in general a smaller variation in scoring between each technology was observed than in example 1 (Table 3), thus, indicating the deployment scenario can be play a significant role in SIA for CDU. Comparing indicators only in the scenario with wind energy, the largest variation occurred in the 'recyclability of product & process elements', 'changes to local access to material produce' and in 'land use' (Fig. 3a). When the average score is considered for each subcategory in the scenario with wind energy it was observed that methanol has the highest impact in seven subcategories (Fig. 3b). Similarly to example 1, 'access to material resources' is a significant indicator hotspot along with local employment. However, it should be remembered that a high score

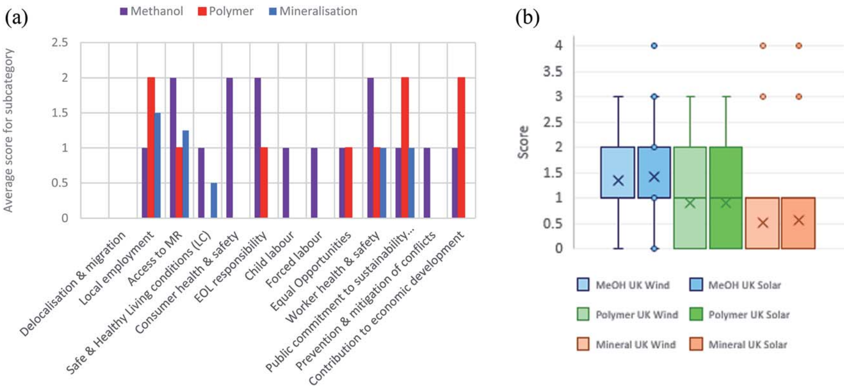

Fig. 3 (a) Social impact scores of CDU technologies in UK using wind energy. (b) 6 variance of scores for CDU technologies in UK.

indicates a hotspot and therefore a high score in local employment reflects few jobs being created. Averaging the indicator scores for each technology option, it was observed that methanol has greater potential for negative social impacts, and mineralisation the most positive impacts. This result was not unexpected as power to X technologies such as methanol utilise large amounts of renewable energy and produce products which have potential health and safety issues factors which can have social impacts. The only indicator with no variation across all three technologies is 'delocalisation and migration'. This indicator is from the stakeholder group of 'local community' therefore, it reflects the process location not the whole supply-chain. Hence, with one location no variation was observed.

Discussion

This framework provides the first steps in developing a methodology for SIA for CDU. By adapting the UNEP/SETAC guidelines for S-LCA (which focus on the assessment of products and organisations) to emerging CDU technologies, a comprehensive SIA screening methodology has been developed. The framework is designed to be adaptive to the practitioner's needs and focuses on the process and deployment scenario rather than the organisation. By using this approach, organisational specific impacts such as decision making around corporate responsibility policies are not included in the analysis, as these impacts are highly specific to individual organisations. However, this framework can highlight issues with certain processes inputs due to known unsustainable practices or negative impacts which could be mitigated by organisational choices. For example; palm oil is only produced in certain countries and there are known sustainability issues; the same is true of a number of metals used in catalysis. Therefore, by flagging these as a hotspot to be addressed in process development alternatives feedstock options could be explored or guidance given to ensure sustainable supply, hence reducing social impact as much as possible. Demonstration through the examples has shown the framework can be used to assess a single technology with various process options and deployment scenarios or used to compare different CDU technologies. Further purposes could include assessing a CDU technology and comparing it with a reference case or other production routes for example *via* biomass.

By focusing the framework on emerging CDU technologies and specifically their process and deployment scenarios, some UNEP/SETAC subcategories and indicators were discarded due to lack of relevance. This leads to a streamlined screening assessment whereby effort can be focused on priority areas for process development research. However, this does not negate the importance of the inclusion of these subcategories if a full S-LCA assessment is desired by an organisation on a deployed technology.

The scoring methodology requires multiple aspects to be taken into consideration for each indicator. In many cases the supply chain as well as the process deployment scenario and scale of deployment all contribute to the total impact and the practitioner must exercise judgement as to how each aspect is considered. This frequently occurs throughout the framework (particularly where COMTRADE or PRODCOM type statistics are used as data sources). An example of this is how the scoring of child labour indicator in 'CDU methanol in the UK using wind power' example case is derived. Using this indicator as an example two aspects can be discussed, firstly as to how the assessment process is derived and secondly to demonstrate the advantages and limitations of such an approach. The indicator utilises a combination of key data sources:

(1) Process data for the CDU methanol plant, including mass and energy balance data

(2) LCA database datasheets for the relevant material inputs, including where possible infrastructure (in this example, the construction of the wind turbines is also considered). In instances where this data is not available to the assessor estimations from available literature data will be required

(3) COMTRADE/PRODCOM type data that allows for the determination of material (mass/volume units) and value (currency units) flows by harmonised system coding (HS codes), to either the 4-digit or 6-digit level where applicable. In some instances, for materials such as fossil fuels and primary electricity, additional data sources with more granularity may be viable to augment or use in place of trade data (*e.g.* the digest of UK energy statistics – DUKES)

(4) World Bank statistics on the required assessment subject (*e.g.* child labour)

Utilising the above data, the aim of the assessment is to trace material inputs to their initial extraction from the environment. This begins with gathering all relevant data on the process and a consideration of the whole value chain (from primary material extraction to end of product life) to determine which elements are key to assessment. A similar approach can also be taken tracing the product to end of life if necessary, as an addition or an alternative. The process data are used to identify key process inputs, with this then coupled with the LCA datasheets to trace inputs back to extraction or an identified cut off point. Where inputs such as heat and electricity are used, the assessor should determine the likely provider of these and factor this into the process. Identified material inputs required for production can then be traced to their likely origins using COMTRADE data. COMTRADE data allows the assessor to examine global trade flows of materials, allowing for an estimation to be made on the materials likely origin for a specific location, such as the UK. This then allows for a qualitative assessment to be made on the risk of encountering negative social impacts through the supply chain: in this specific example the utilisation of child labour. It is recommended that not all material inputs are traced fully, as this will likely be a resource intensive process for diminishing returns. Given the scope of this framework and its intended audience there is likely to be a significant level of uncertainty as to exactly where a material is sourced from in the supply chain. This is expected, considering the previously discussed example of illicit gold mining where it was stated that supply chain complexities were a problem for even large multinationals, but ultimately leaves an inherent element of uncertainty in the analysis. Given the complexities of global trade it is also impractical to assess all exporters of a given material to a country: for example, UN COMTRADE data on United Kingdom imports of HS 7604 (aluminium; bars, rods and profiles) in 2018 returns a total of 53 individual country entries, covering a global import of 148.2 kt of material with a total trade value of $620 million. Ultimately a cut-off is likely to be needed, with the assessor presented with the choice of determining whether to use a value or mass/volume. It should be noted that these options may result in differing lists of countries for assessment. For example, continuing with the prior consideration of HS 7604 in the UK, imports from China account for 29.8% of mass but only 17.0% of trade value.

A demonstration of how this method can be applied is shown in Fig. 4, where a partial study is illustrated investigating the potential risk for child labour in the production of aluminium to be used in a wind turbine for the CDU methanol example included in the Results section. All other elements of the study have been substituted out for ease of illustration. Fig. 4 shows the breakdown of each stage into specific elements as described above from process data and LCA datasheets. At each stage the risk of the utilisation of child labour can be assessed in parallel, with the number of stages ultimately determined by the cut-off criteria selected by the user – in this case the importation of aluminium or its ore for manufacturing a wind turbine in Germany.

The example in Fig. 4 shows clearly the relative ease of application of the framework; however, it does also highlight the main limitations of the approach

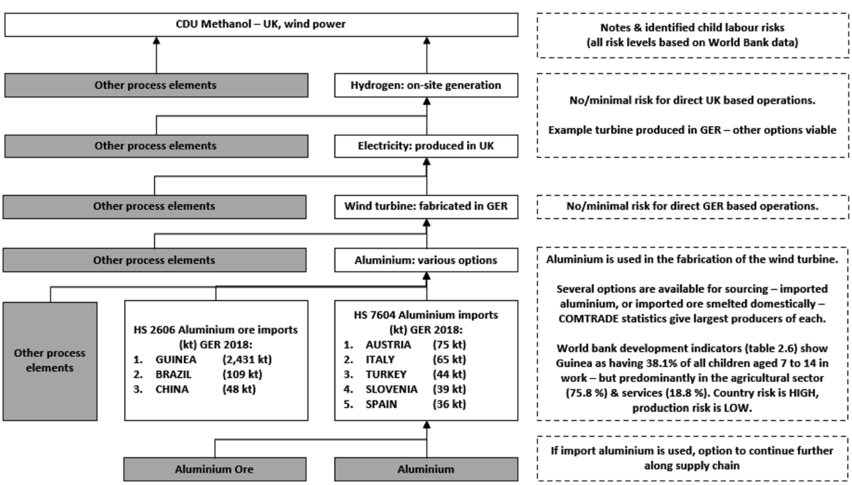

Fig. 4 Illustrative example of framework application, using World Bank data and UN COMTRADE data.

that have been previously mentioned. The first is that for every level of assessment there is a broadening number of process elements to consider – each with potentially complex supply chains. Whilst individual process element assessments may be relatively quick, the potential for exponential growth is problematic.

Secondly, the assessment result remains relatively uncertain. Whilst ore imports for aluminium are dominated by Guinea, the picture for aluminium itself is more complex (the five countries included in the figure are the dominant by mass, but the rest of the top 10 supply more than 20 kt of material and the HS codes, even when taken to the 6-digit level, may not allow for a narrowing of suppliers even for specific materials). In some instances, data may also be missing if it is not reported to the UN – in the example above no COMTRADE data are available on whether all Guinean exports to Germany are mined within the country or are imported from elsewhere (although this data may be available in other databases). However, as stated in the research question the aim of this framework is to primarily augment sustainability assessment and decision analysis for CDU technology development, given the relative ease and significant overlap in data required to conduct other CDU technology assessments such as LCA and TEA it is fit for purpose as a screening-type approach.

The framework can be further developed by the practitioner to include multi-criteria decision analysis (MCDA) to provide preferencing or weighting to specific criteria. In the presented examples weighting was not included, therefore all indicators have been given equal importance. This approach is useful for identifying hotspots for decision makers to then consider how significant the impacts are in relation to the overall social impact of the process. However, it does not put any emphasis on the significance of the impact on humans, for example an impact that could cause significant harm to health or even death would be given the same importance as one that benefited employment. By adding weighting/MCDA to the assessment a greater level of nuance can be added to the assessment and so this approach should be considered when the methodology is applied. However, it should be noted that MCDA/weighting is entirely specific to the goal and scope of the study and the aims/priorities of the study commissioner and decision makers. Therefore, results from such studies should only be considered in the context to which they were applied.

Conclusions

Social impact assessment needs to be included in the analysis of CDU technologies to ensure holistic sustainability assessment. SIA forms the third strand of a triple helix assessment approach encompassing economic, environmental and social impact. The presented framework enables practitioners to conduct SIA screening of emerging CDU technologies by identifying hotspots both within the process and the deployment scenario. The framework is a first step in enabling practitioners to include social impacts in CDU technology assessment. Its application to a range of CDU technology cases studies will enable further refinement of the methodology.

It is concluded that raw materials contribute significant social impacts within CDU and therefore, careful consideration of sources is required. Depending on the technology, differing stakeholder groups are impacted to differing degrees.

Therefore, it cannot be concluded that one stakeholder group is most important in CDU; all should be investigated. In particular, when assessing technologies that have a significant H_2 requirements, as is the case for many power to X technologies within CDU, the social impact of the demand for considerable quantities of renewable energy must be carefully considered. CDU technologies can have positive social impacts particularly in regard to reducing CO_2 emissions and the use of wastes. These benefits can be seen within the impact categories focusing on health and safety. Impacts concerning employment and labour are complex to assess due to most impacts being within the supply chain, however risks should be highlighted. Both positive and negative impacts can be observed, with increased high value job creation as pay for chemical plant jobs was found to be higher than the national average however negative impacts can occur if care is not taken in sustainably sourcing metal catalysts and other raw materials.

This framework could further enhance CDU assessment by integrating with LCA and TEA to form a triple helix of assessment. By integrating these assessments, hotspots and potential trade-offs within the process from economic, environmental or social perspectives can be identified for consideration. If this integration is further expanded to include multi-criteria decision analysis through weightings or optimisation, decision making for process design can be enhanced and trade-offs between aspects explored.

Author contributions

Stephen McCord: conceptualization, methodology, formal analysis, investigation, data curation, visualisation, writing – original draft, writing – review & editing; Katy Armstrong: conceptualization, methodology, formal analysis investigation, data curation, visualisation, writing – original draft, writing – review & editing; Peter Styring: supervision, writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

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