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SOCIETAL LCA

Development of a methodological framework for social life-cycle assessment of novel technologies

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Abstract

Purpose Environmental life-cycle assessment (LCA) is broadly applied and recently social and economic LCA have emerged. However, the development of a general framework for social LCA is still at an early stage of development. The aims of this paper are to systematically discuss general considerations regarding social LCA, to build a consistent and operationalized framework for a number of indicators and to test the framework through application on a case study.

Methods The first step was to define the scope of the framework starting from a comprehensive review of concepts of social sustainability and social well-being, focusing on the conditions potentially affected by large-scale introduction of novel technologies. Secondly, main areas of concern for social well-being were defined. This resulted in the identification of four main areas of concern. The third step was to make an inventory of potential social indicators and select a number of indicators that could make the framework operational. Additionally, factors for weighting and normalization were developed.

Results and discussion The framework developed in this paper is based on four categories and 11 indicators and follows a life-cycle perspective. Six of the indicators are quantitative and are assessed using an input-output model linked to databases from the International Labour Organization. The remaining five indicators are qualitative indicators which are mapped using expert elicitation and a literature review. Identified concerns regarding the qualitative indicators are "flagged" and provided alongside the results of the quantitative assessment, which are aggregated into one single score by means of a weighted and normalized arithmetical mean. The paper illustrates the application of the methodology in a case study examining the deployment of carbon capture and storage technologies in Europe.

Conclusions The paper presents a framework that can be used to explore potential impacts on social well-being resulting from the large-scale implementation of novel technologies. The selection of a limited number of indicators (11) keeps the methodology simple and transparent. Although the framework provides a useful approach in allowing both quantitative or qualitative identification of potential areas of concern, the results remain highly explorative in nature. The inherent value-laden and context specific nature of social aspects remains one of the key challenges for developing a general applicable framework.

Keywords Methodology development · Novel technologies · Social impacts · Social indicators · Social life-cycle assessment (s-LCA)

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1 Introduction

Sustainable development is a concept much referred to, ever since the World Commission on Environment and Development (WCED) addressed it in its report 'Our Common Future'. They defined it as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" (WCED 1987, pp. 383). In the field of sustainability, methods for assessing environmental impacts were the first to be broadly practiced. Stemming from a study by the Projektgruppe Ökologische Wirtschaft (P.Ö.W. 1987) and further elaborated within Agenda 21 (UNCED 1992), evaluation of social and economic impacts are also proposed to be included in sustainability studies. These three basic pillars of sustainability—social, economic, environmental—are often referred to as people-planet-profit, or the 'triple bottom line' (Elkington 1994).

For environmental assessments, applying a life-cycle perspective has become a common approach, as it includes all life-cycle stages, from production, consumption to disposal. Life-cycle assessment (LCA) has been developed since the early seventies and is now broadly applied in accordance to ISO standardization (ISO 2004; ISO 2006a; ISO 2006b). Recent initiatives have aimed to include the social and economic dimensions of sustainability within the traditional framework for LCA (see e.g. ENEA 2009; Griesshammer et al. 2007; Valdivia et al. 2012; Blok et al. 2013). These studies acknowledge that an evaluation of impacts along the chain should not only include environmental aspects but also key social and economic issues such as child labour, unemployment and poverty.

However, a methodological framework that provides a comprehensive structure for systematically conducting social assessment of products along their life cycle is still at an early stage of development. The most complete proposals currently available are those of Benoît et al. (2009; 2010; 2011) and Benoit-Norris et al. (2011, 2012a, b; 2013). Benoît et al. (2009; 2010; 2011) propose a general framework, providing methodological sheets for 31 sub categories of assessment. However, for general applicability this method requires large amounts of data which is not always available, and there is a large influence of the subjectivity of the individual researcher (Blom and Solmar 2009). In a different study (Benoit-Norris et al. 2012a; Benoit-Norris et al. 2012b; Benoit-Norris et al. 2013), the social hotspots database is used which expresses per country and sector risk assessed social themes and worker hours. The database is based on a multi-regional input output (MRIO) model and detailed Global Trade Analysis Project modelling (GTAP 2013). The database uses a limited set of sectors and does not distinguish between foreground and background systems. Norris (2006) proposed a methodology connecting economic development to an endpoint indicator on human health which is used as a proxy for social well-being. However, the indicator is solely based on GDP, whereas social well-being is affected by other issues. Hutchins and Sutherland (2006) propose a framework that is based on input/output modelling of social issues, yet no proposal was done for indicator data (except for an example). Hunkeler (2006) also proposes a framework, yet only data is included on using employment for measurement of indicators. Dreyer (2006) proposes a framework for which only some indicators have been tested by case studies and normalization, weighting and aggregation are still lacking. Dreyer et al. (2010) present a framework based on indicator scoring, which inherently means a translation is necessary from impacts to interpretation. Feschet et al. (2013) propose a methodology based on a relationship between GDP per capita and the real life expectancy at birth of a country's population. Several methodologies for s-LCA translate data into scoring systems (e.g. Finkbeiner et al. (2010); Öko-Institut (2007); Müller and Saling (2011); Franze and Ciroth (2011), Hutchins and Sutherland (2008)) which require the definition of target levels. For a full overview of the available literature on social LCA and their classification see e.g. Chhipi-Shrestha et al. (Chhipi-Shrestha et al. 2015) and Wu et al. (2014).

The current study aims to systematically discuss the main issues encountered when applying life-cycle thinking to social assessment; to build a consistent framework for a number of indicators that is fully operationalized and aggregated, and to test the developed framework through application on a case study example. The research was carried out as part of the European FP7 project PROspective SUstaInability Assessment of Technologies (www.prosuite.org).

2 Approach

The development and operationalization of the framework was done in five steps. The first step was to define the scope of the framework starting from a comprehensive review of concepts of social sustainability and social well-being. Selecting a single definition from literature is not a straightforward task because definitions from literature often cover varying domains. For instance Keyes (1998, p8) defines social well-being as "the appraisal of one's circumstance and functioning in society" while USIP (2013) defines it as "an end state in which basic human needs are met and people are able to coexist peacefully in communities with opportunities for advancement". For the World Health Organization, social well-being is one of the three pillars determining human health (WHO 2002). Their definition of human health focuses on quality of life, contrary to a narrow definition focusing on the absence of decease (WHO 1997). The social determinants of health are the conditions in which people are born, grow, live, work and age, including the health system (WHO 2013). Issues of social well-being include education, equality, freedom of expression, poverty, slavery and terrorism (OHCHR 2013).

The scope of the current study is defined by the conditions that are potentially affected by the *large-scale* introduction of (novel) technologies. Biophysical impacts on human health by exposure to pollutants are excluded, because these impacts can be included in environmental LCA practice (see e.g. Gilbertson et al. 2014; Hischier 2013; Wernet et al. 2010). The framework shows a partial overlap with economic studies because it covers socio-economic effects. There is however a difference in perspective as in an economic assessment profit is the main target, whereas the socio-economic perspective examines how this productivity is achieved (e.g. kind of labour).

The second step was to define main areas of concern for social well-being. There are many aspects that can be considered when assessing (social) development, for instance, sustainability development goals, human rights, etc. In this paper, based on the work of Weidema (2006), four main areas of concern (categories) were identified, namely:

- *Autonomy*. Defined as being in control of oneself and one's resources, autonomy is negatively impacted by for example, forced labour or slavery.
- *Safety, security and tranquillity*. It is a combination of freedom from threats to human health and property. It also includes aspects related to the beneficial impact of employment (which goes beyond receiving a salary but also include issues such as satisfaction).
- *Equality*. It represents the level of disparity among countries and or regions. Equality is for example negatively impacted by increasing disparity in income distribution.
- *Participation and influence*. Defined as 'the act of taking part or sharing in something and affecting the course of event' (Farlex Inc 2012). It includes the level of participation in decision-making processes.

The third step was to carry out an extensive literature review on potential social indicators, which resulted in a list of approximately 600 indicators for social well-being that are reported in literature. From this long list of indicators a pre-selection was conducted (Sellke et al. 2011) based on the following criteria: clarity (to measure a clear and measurable entity), logic and simplicity (an unambiguous measurement rule and needs to be logically linked to the criterion it is supposed to measure), applicability (applicable to different regional settings across Europe), relevance (representing central aspects of social sustainability), coverage (indicators must cover main aspects of social sustainability), feasibility/data availability (indicators must draw on information that is possible to obtain). A procedure for including expert judgement into an assessment is applied for determining these indicators' perceived importance for social sustainability (for more information see Reiner et al. 2012). A final refined selection of indicators was performed based on possibilities for implementation, feasibility and adaptability of the framework. The list should cover both qualitative/quantitative aspects, differences in geographical focus, timelines and ethical dilemmas. A detailed summary of the methodology for indicator selection can be found in the Electronic Supplementary Material.

The fourth step in the approach was to identify and or develop methodologies to operationalize the selected indicators (see Section 4). The fifth and final step was to develop weighting and normalization factors that allow aggregating the indicators into a single score (see Section 5).

3 Results—general considerations

This section addresses some of the key challenges for social LCA as well as their implications for the framework.

3.1 Functional unit

The concept of functional unit is one of the core principles of LCA. Its primary purpose is to provide a reference to which all inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. With identical quantified performance or function, the indicators' performance of products can be reasonably compared in order to identify the best alternative (e.g. product A in Fig. 1). It is argued that the functional unit also provides a useful basis for comparison in economic and social studies.

An aspect to take into account when dealing with the concept of a functional unit for social is the "social utility" of a product. The "social utility" is the potential positive social impacts; a products' additional benefit beyond its quantified function. The UNEP/SETAC guidelines require that the "social utility" of a product is integrated into the definition of the functional unit (Benoît et al. 2009, p. 53). However, strictly speaking, the functional unit tries to capture the quantified performance or function of a product. Social impacts of an investigated product are an assessment result, which are only available after the assessment. Examples are multi-output processes that credibly avoid comparable products with high impacts. In these cases, the functional unit is not adjusted[1] (Ciroth et al. 2014). Considering social impacts in the functional unit introduces circular reasoning and such an iterative approach is not really necessary. If positive social impacts are found as a consequence of the introduction of the technology, these are accounted for, and may disappear in the overall net results. However, they are not used to adjust the functional unit, which strictly reflects the quantified performance or function.

In the current framework, the functional unit is the point of departure for building the prospective and reference scenario. The current and prospective scale of the technology is explicitly taken into account in the studies. The framework generates

[1] In the sense: this product has a quantified performance or function of xyz and in addition avoids environmental impacts of abc.

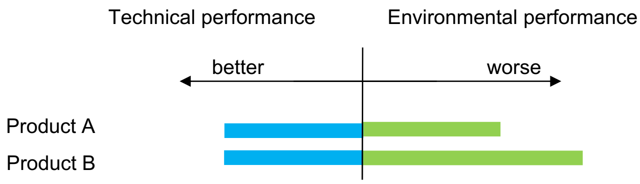

Fig. 1 The principle of a functional unit in LCA

results that can be analyzed on the system level and on the functional unit level. See Section 3.5.

3.2 System boundaries

From a LCA perspective, all economic activities can in principle somehow be part of the analyzed system. This however could lead to the unfeasibility of the assessment. Therefore, system boundaries are needed that define which processes and what parts of the life cycle are included in the assessment. There are several approaches to define system boundaries in LCA. An example is to define *identical* boundaries for all dimensions of sustainability. However, since databases for social LCA are at an early stage of development gathering information for all processes would make most analyses unfeasible, and it is not necessary as some aspects which are relevant for one assessment (e.g. economic, environmental, social) are not relevant for the others. A second possibility, which is more suitable for a social LCA framework, is to have *equivalent* system boundaries. In this approach processes that are relevant for each system are included, which allows accounting for the fact that each process does not have the same relevance for all dimensions of sustainability (Ciroth and Franze 2011). An essential element of equivalent system boundaries is that the same cut-off criteria are set. The scoping of the study should result in the development of cut-off criteria that allow selecting the processes that are of interest for the study. Major process stages within conventional LCA and life-cycle costing should not be excluded. Considerations include, for instance, quantities of the material used (if the process is a key input for the product or technology in terms of quantities used, such as coal for the CCS case study); type of materials used (scarce and toxic material used is more relevant than abundant and non-toxic materials); the costs and macro-economic impacts of the product (processes with a high impact on the economic system have a higher relevance). In the current framework equivalent system boundaries for selection of foreground processes are combined with the background system modelling of the entire economy.

3.3 Definition of foreground and background processes

In order to reduce the number of processes that are included, it is possible to distinguish between foreground and background systems (see Ciroth and Franze 2011). Foreground processes are processes specific to the system, whereas background processes are those where a homogeneous market with average or equivalent generic data is assumed (JRC 2010). For background processes a less comprehensive indicator system is applied considering data on the country-specific sector level, i.e. on a more general level, whereas data for foreground processes can be more specific depending on the goal of the study. In the current framework the supply chain data from foreground processes are linked in a hybrid input-output model to a background input–output system modelling the rest of the economy (see Section 4). Examples of criteria that can be used to define foreground processes are the number of actors in the life-cycle stage, fluctuation of actors in a life-cycle stage, and the relevance of the life-cycle stage regarding social issues.

3.4 The baseline

Traditional LCA studies, focusing on the deploying novel technologies, compare the potential impacts of the novel technologies with a reference case (for instance one that does not have the technology). Results are expressed in absolute terms[2] and, very frequently, in relative terms (i.e. difference in impacts between the two cases). For conducting a social LCA, a similar approach could be followed by comparing the social impacts of a scenario in which the technology is deployed to a non-implemented scenario, which is used as the baseline for the assessment (e.g. Jørgensen et al. 2010). However, such a "non-implemented" scenario is often very difficult to assess. Therefore, it is proposed to perform the assessment *relative* to the implementation of a technological reference (a counterfactual approach). It is argued that the novel technology will most likely replace a technology with a similar function, as there will be old(er) technologies that will be less often used because the novel technology is better suitable for fulfilling the specific function (such as telephones and desktop computers in the case of a tablet). The results are compared for different products, systems or services that usually perform the same or similar function (similar to comparative life-cycle studies; JRC 2010). When a reference technology is not available results can be compared to the background economy. The benefit of using a counterfactual approach is that the effect of implementing the novel technology can be compared to a baseline situation that is defined in a detailed manner.

[2] For instance, impacts on climate change are expressed in kg CO_2 equivalents and impacts on the natural ecosystems are expressed in potentially disappeared fraction of species (PDF).

3.5 Level of analysis

In macro-economic studies, dynamic models are used to study the whole economy regarding impacts on a micro-economic level (within life-cycle costing) as well as on a macro-economic level (within macro-economic modelling, including the whole technology and macro-level effects). Similarly, for social assessment the macro-level perspective is important, because social impacts do not happen in isolation, instead regard impacts on a *society* as a whole. The macro level for social assessment encompasses studying the life-cycle stages in interaction with the society where these stages take place, including the modelling of background processes that are affected by large-scale consequences (Sellke et al. 2011; JRC 2010). In turn, societal conditions influence the impacts of the novel technology on social well-being. In the current framework, similar to macro-economic studies, the scale of the technology deployment (production capacity or market penetration) is explicitly taken into account, including the scale of the operations in society and the indirect effects.

There are two approaches to conduct a technology assessment. First, start with analyzing the economy-wide results, primarily taking into account the macro-societal effects. This requires analyzing macro-societal developments and indirect effects. The impact of a single technology at the macro level is generally small, but could potentially be large, when, for example, looking at levels of imports when there is large-scale replacement of oil based products by bio-based products. Second, conduct the analysis per functional unit, where potential impacts would generally be larger. In this paper it is recommended to use both approaches when assessing the results of each indicator. Note that in both cases, the focus is on the relative change between the prospective and reference scenario and not in the absolute numbers produced for each.

4 Results

4.1 Measuring social well-being: selection of indicators

Fig. 2 shows the categories and indicators used in this study while Table 1 shows the definitions and criteria that were used. This set of indicators, though not exhaustive, allows key challenges inherent to social assessment to be addressed, such as the value-ladenness of social aspects; the unavoidable inclusion of qualitative data; and the geographical and time specificity character of social aspects.

A specific aspect that needs to be taken into account when designing social indicators is the direction of the impact. Indicators for LCA are in principle considered to have a negative impact, and the objective function is therefore to decrease the impact. This is not necessarily the case for social indicators. For some indicators such as knowledge-intensive jobs, total employment, trust in risk information, stakeholder involvement and long-term control functions, the objective would be to maximize the impact as this would be translated into a positive impact on social well-being. For other indicators, e.g. possibility of misuse, risk perception, child labour, forced labour, income inequalities and regional inequalities, an increase would have a negative effect on social well-being and the objective would be to minimize the impact.

4.2 Operationalizing the indicators: performance assessment

4.2.1 Quantitative indicators

Background For social life-cycle assessment, data is required on the foreground and background processes of the technology throughout its life cycle. Therefore, a database that allows connecting the technology foreground processes to different sectors of the economy across regions is required. An alternative explored here is to link data on micro-economic cost and labour costs of all foreground processes per functional unit to a Multi-Regional Input Output model (e.g. the THEMIS MRIO model; Wood et al. 2012; Wood et al. 2013; Gibon et al. 2015). THEMIS is a scenario based input-output model which covers both the production and consumption perspectives. Input data is required for the foreground processes on life-cycle costing which could, for instance, be extracted from cost estimation tools (see e.g. Ereev and Patel 2012). The life-cycle costing data of foreground processes is then linked to the background processes in the input–output tables that have aggregated sector level data but distinguished intermediate and primary inputs (see e.g. Wood and Hertwich 2012). The model includes 9 global regions, and for each country/region there is a breakdown in 138 economic sectors and 3 income groups (resulting in 3726 income groups). It makes estimates on future consumption and production scenarios by means of coupling global MRIO modelling (EXIOBASE; as explained in Tukker et al. 2013; Wood et al. 2014; 2015) with additional data on changes in consumption habits, shifts in decarbonizing inputs, growth in productivity, and technological change from dynamic models of climate mitigation pathways (Wood et al. 2012).

For the operationalization of the indicators covered in this section, the user needs to provide input in the form of detailed cost data for each foreground process. This involves identifying the major pieces of equipment in each process; estimating the purchased and the installed costs for each piece of equipment and estimating the fixed capital investment (including direct and indirect costs). This cost data is used in THEMIS to link the different economic sectors. Furthermore, information on the potential market volume of the technology over time needs to be provided. This can require a survey or another form of market research. Estimation of the market is necessary because social aspects become relevant or apparent only if the

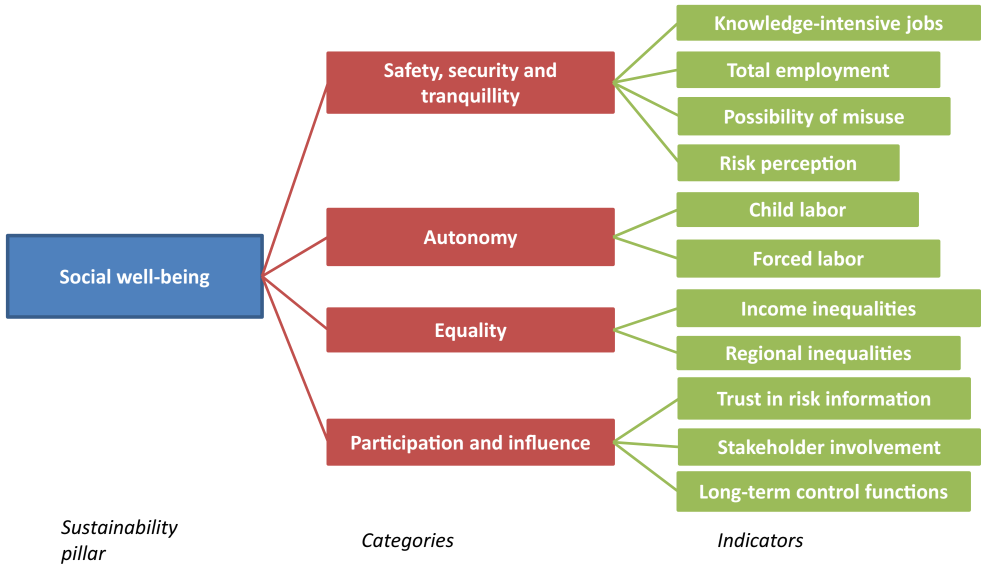

Fig. 2 Indicators and categories used in this paper (Ciroth et al. 2014)

Table 1 indicators used for assessment of social life-cycle impacts

Indicator (unit)	Definition	Type	Desired direction for sustainability
Safety, security and tranquillity			
Knowledge-intensive jobs (h)	High-skilled employment. Includes workers as managers, professionals, technicians and associate professionals for which education is required	Quantitative	Positive
Total employment (h)	Share of the labour force—the total part of society that is available for work—that is working	Quantitative	Positive
Possibility of misuse	Potential use of the technology that causes harm to people or society. The vulnerability of the novel technology to be used in hazardous ways such as sabotage or terrorism.	Qualitative	Negative
Risk perception	Observation of hazard by the general public. The perception of risk can cause instability because of decreasing overall feeling of safety in a society	Qualitative	Negative
Autonomy			
Child labour (h)	Work that deprives children of their childhood, their potential and their dignity, and that is harmful to physical and mental development (ILO 2013). It concerns hazardous work done by children and other severe forms of child labour	Quantitative	Negative
Forced labour (h)	Work or service which is exacted from any person under the menace of any penalty and for which the said person has not offered himself voluntarily	Quantitative	Negative
Equality			
Income inequalities (GINI coefficient)	Structural disparities between salary levels, representing a gap between rich and poor. The indicator regards the degree to which global income inequalities are affected by the introduction of the novel technology	Quantitative	Negative
Regional inequalities (€)	Disparities between GDP levels around the world, comparing the GDP levels of developing countries with those of developed countries	Quantitative	Negative
Participation and influence			
Trust in risk information	Confidence of being informed in case of hazard. The indicator regards the degree to which the general public feels confidence that they will be informed in case of hazard.	Qualitative	Positive
Stakeholder involvement	Active participation of interested parties within decision-making processes. The indicator regards the degree to which the interested parties are involved within decision-making processes concerning the novel technology	Qualitative	Positive
Long-term control functions	Governance or technical instruments such as regulating authorities or redundant systems that ensure long-term control will. The indicator regards the degree to which people trust that the technology is adequately controlled	Qualitative	Positive

technology reaches and exceeds a certain level of implementation.

Indicators

- *Knowledge-intensive employment*. This indicator uses information on direct and indirect high-skilled labour requirements for the studied technology, which can be modelled for instance by economic input-output models. Data on requirements of high-skilled labour is available in THEMIS and is used to represent knowledge-intensive employment (Simas et al. 2015). This indicator regards the relative increase or decrease in high-skilled employment caused by the introduction of the novel technology in comparison to the high-skilled employment caused by the introduction of the reference technology. The indicator is used as a proxy for the effect on the knowledge-intensive economy which contributes to productivity and economic growth (OECD 2013).
- *Total employment*. It uses data on direct and indirect labour requirements, which can be obtained from economic input-output models. This information is similarly available as knowledge-intensive employment. This indicator regards the relative increase or decrease of total employment caused by the introduction of the novel technology in comparison to the total employment caused by the introduction of the reference technology. The indicator is used as a proxy for the value of employment in society (see Ciroth et al. 2014).
- *Child labour*. This indicator requires information on whether there is child labour involved for the studied technology across its life chain, including the number of children involved per economic sector per country. This information was not directly available in THEMIS so data on child labour from the U.S. Department of Labor's List of Goods Produced by Child Labor (U.S. DOL 2012) as well as data on the amount of persons involved in child labour per sector per region from the ILO (2010; 2012) was linked to information on total employment which could be extracted from THEMIS (Simas et al. 2014). The data on the number of persons working in child labour per sector is multiplied by an assumed average of 2020 working hours per year. This gives the total number of child labour working hours per region per sector. The share of child labour hours for aggregate sectors can then be calculated by dividing the total number of child labour hours per sector per country by the total number of working hours (total employment) per sector per country. The total number of child labour hours caused by the introduction of the novel technology can be calculated by multiplying the total employment caused by the introduction of the novel technology with the share of child labour hours per country per sector. A detailed discussion of the methodology as well as of the benefits and drawback of this approach can be found in Simas et al. (2014).
- *Forced labour*. Data is required on whether there is forced labour involved for the studied technology in the specific country and the number of persons involved per sector per country. Following a similar procedure to the one use for child labour, data of forced labour can be extracted from the U.S. Department of Labor's List of Goods Produced by Forced Labor (U.S. DOL 2012) in combination with the amount of persons involved in forced labour per sector per region from the ILO (2012, 2010). The data on the number of persons working in forced labour per sector is multiplied by an assumed average of 2020 working hours per year. This gives the total number of forced labour working hours per region per sector. The share of forced labour hours for aggregate sectors can then be calculated by dividing the total number of forced labour hours per sector per country with the total number of working hours (total employment due to the implementation of the technology as modelled in THEMIS) per sector per country. The total number of forced labour hours caused by the introduction of the technology can then be calculated by multiplying the total employment caused by the introduction of the novel technology by the share of forced labour hours per country per sector. See Simas et al. (2014) for full details.
- *Income inequalities*. The indicator is measured as the change in the global income Gini as a result of the introduction of the novel technology. The baseline for the assessment is the global income Gini when only the reference technology is implemented. The Gini coefficient is a standard measure of income inequality (OECD 2011) defined as the relationship of cumulative shares of the employees (in %) arranged according to income levels, to the cumulative share of the total income (in %) received by that share (Eurostat 2013). The index is modelled with THEMIS which is calculated following a standard procedure that is described in Ciroth et al. (2014). A value of zero in the Gini coefficient expresses perfect equality (e.g. where everyone has an exactly equal income). A Gini coefficient of one expresses maximal inequality among values.
- *Regional inequalities*. This indicator represents the effect of introducing the novel technology to the economic disparities between world regions. For this indicator the effect is calculated for OECD countries and for non-OECD countries, both expressed as ΔGDP. In a second step, the difference between these ΔGDP values is calculated. If prosperity increases in developed countries, but decreases in developing countries, this can be interpreted as an increase in global inequality. Regionalized GDP data is extracted from THEMIS.

4.2.2 Qualitative indicators

The framework developed in this paper contains five qualitative indicators (possibility of misuse, risk perception, trust in risk information, stakeholder involvement, control functions—Table 1). These indicators are characterized by a large(r) influence of process management and the (social) circumstances in the outcome of the indicator which can therefore be more relevant than the functional unit that is being evaluated.

Note that while for the *quantitative* indicators, background and foreground processes are both taken into account and are related via THEMIS, the *qualitative* indicators focus only on foreground processes. The indicators apply life-cycle thinking, which allows for a systematic assessment of impacts outside the factory gate. Furthermore, "converting" information gathered on these indicators into a numerical scale- although is mathematically possible- it is not desirable as it would cause most of the information to be lost. Instead, for each indicator a supportive narrative on the potential impact of the technology should be provided together with a judgement on whether 'no concerns', 'moderate concerns' or 'major concerns' are expected -compared to the reference scenario-. Such explorative assessment is based on literature review and expert elicitation. The results from the qualitative indicators are therefore not translated into a score which can be aggregated to the score from the quantitative indicators, but are used to identify potential concerns.

5 Results

5.1 Aggregation

The *quantitative* indicators can be aggregated into one final score, which is required if results between different technologies are to be compared. Aggregation is done by means of a weighted and normalized arithmetical mean (Eq. 1). This method is selected because of its simplicity and the fact that bad performance cannot be compensated with good performance, which makes the aggregation more sensitive to bad performance than a straightforward arithmetical mean.

$$S_{\mathrm{wB}} = \sum_{i=1}^{n} W_{a,i} \times \left(\frac{I_{\mathrm{i}}}{N_{\mathrm{i}}}\right) \tag{1}$$

where S_{WB} is the final score for social well-being. I_{i} is the value of an indicator (*i*), W_{i} is the weighted factor for indicator *i*, and N_{i} is the normalization factor for indicator *i*.

As previously noted, the indicators have different directions with respect to social well-being. Here, it is considered that a net increase in total employment and knowledge-intensive Jobs is positive for social well-being while an increase in child labour, forced labour and inequalities is negative. In Eq. 1 positive impacts should be included as positive numbers and negative impacts as negative numbers. The value of the aggregation is then the net result on social well-being.

In Eq. 1, normalization factors have been included which are needed to aggregate the different values from the indicators. Per capita global normalization factors are taken from THEMIS, giving consistency to the results obtained from the indicator calculations. These factors were selected in order to harmonize the assessment with the others in the framework (see Table 2). Equation 1 allows the importance of different indicators to be addressed via weighting factors. These factors can be obtained through e.g. consultation with stakeholders.

5.2 Case study example: electricity power sector with carbon capture and storage

This section aims to provide a short example of the application of the framework to a specific case study. For additional details in this case study, including detailed technology description and life-cycle inventory and several sensitivity analyses, we refer to Ramirez et al. (2014). The case explores potential social impacts that could be generated from large-scale deployment of carbon capture and storage (CCS) in coal-fired power plants in OECD Europe. CCS includes the capture of CO_2 emissions from electricity generation plants and/or industrial processes, transport (by pipeline or ships) and sequestration in storage sites such as deep aquifers or depleted oil and gas fields. Included life-cycle stages are extraction of raw materials, resources, transport and infrastructure. Upstream processes included coal mining and transport by ship. The coal production chain is assumed to be represented by the average Dutch coal imports in 2012 (73 % Colombia, 9.7 % Russia, 8.7 % South Africa, 4.4 % USA, 4.2 % others). Power production, CO_2 capture and CO_2 storage were assumed to take place in Europe. Downstream processes included CO_2 transport via pipeline and offshore storage. The reference technology is a coal-fired power plant in OECD Europe without CCS. The assessment is based on the following assumptions:

- The functional unit is 1 kWh electricity (kWhe) delivered to the grid.
- The penetration of CCS will largely be regulated and is modelled against the backdrop of a carbon tax. This tax is taken from the IEA Energy Technology Perspectives scenarios for 2030 (IEA 2013). With the carbon tax applied, the cost of a unit of electricity is higher for the non-CCS case than the CCS case.
- The IEA Blue Map scenario of electricity from coal production for CCS is used as basis to establish potential market penetration. The reference case assumes all electricity from coal is produced without CCS, and the prospective case assumes all electricity from coal is produced with CCS (as per Blue Map)[3].

[3] While in reality a range of technologies would be employed to fill the production gap left by CCS not being an available technology, for this case, we assume only coal-fired electricity would substitute CCS to keep a clear signal.

Table 2 Normalization factors for the social assessment

Name	Unit per capita	Per capita global normalization
Total employment	Hours	8.98E + 02
Knowledge-intensive jobs	Hours	1.95E + 02
Regional inequalities (GDP)	OECD GDP (€) - non-OECD GDP (€)	−2.19E + 03
Income inequalities (GINI)	N/A	9.13E − 11
Children in hazardous labour	Hours	1.96E + 01
Forced labour	Hours	2.22E + 00

- The cost data were taken from Matuszewski et al. (2012). The costs are expressed per functional unit, in the report given as the costs (dollars) per kWh for the first year of operation. The total costs provided in the report were used as an allocation key between components, and hence sectors in the input-output model. Due to this calculation method, only the costs per functional unit were converted to Euro.

5.2.1 Quantitative indicators

Table 3 shows a summary of the results obtained for the indicators. The total values are shown in Appendix 1. A brief discussion per indicator is provided below.

- *Total employment*. Introducing CCS in the EU electricity sector has positive repercussions for the employment opportunities; with more work per unit output of electricity. The total working hours increase between the prospective and reference scenario due to the increased economic activity. The total working hours per functional unit increase by 73 % (71 % in the EU and 81 % in non-EU) which indicates that the impact of CCS in coal power plants in Europe have a slighter larger (positive) impact outside Europe. This is most likely due to the increase on material raw products (e.g. coal) that are needed (per unit of output) as a consequence of the reduction on efficiency of the power plant induced by CCS.
- *Knowledge-intensive jobs*. There is a higher increase in high-skill working hours than in the medium- and low-skill working hours per functional unit in the prospective system than in the reference system. Results from the model also show the shares of working hours, split into skills levels and sectors (Appendix 2). The introduction of CCS only has a minor effect on the structures, both in terms of skill level and sectors. As most differences in the structures are on a decimal percentage level, it is not possible to refer to structural changes. The increase in the high-skilled working hours is larger in non-EU- than in EU member states.

- *Child labour*. The impact of CCS on this indicator for the whole economy, though negative, is very minor (less than 0.001 %). However, in terms of hours per functional unit, the implementation of CCS results in a 70 % increase. Results of the model also allow examining the contribution of different sectors to child labour hazardous activities per functional unit. They show that fossil fuel exploration (coal mining, oil and gas exploration) has the largest contribution to the number of child labour per f.u. (see Appendix 3).
- *Forced labour*. The results show similar trends to those shown by the indicator on child labour, that is, an insignificant effect of CCS in the forced labour of the total economy. In terms of forced labour per functional unit, there is an increase of about 65 % as a consequence of CCS implementation. Appendix 4 shows the contribution of different sectors to the force labour (per functional unit). For both scenarios, the largest share is due to fossil fuel exploration. Forced labour within the EU accounts for about 50 % of the forced labour per f.u., in the reference

Table 3 Summary of results

Indicator	Absolute difference (prospective to reference)	Observed trend	Desired trend
Total employment	5.1 + E05 h	Increase	Increase
Knowledge-intensive jobs	9.2E + 04 h	Increase	Increase
Child labour	4.0E + 03 h	Increase	Decrease
Forced labour	3.8E + 02 h	Increase	Decrease
Income inequality (GINI)	1.0E − 08	Decrease	Decrease
Global inequality	−1.3E + 07 Euro[1]	Decrease	Decrease

scenario and a slightly lower share (47 %) in the prospective scenario.

- *Income inequality*. The model results indicate that implementation of CCS leads to a very small decrease in the GINI index. Furthermore, the global GINI points out that there is significant inequality worldwide. Results of the model allow exploring the GINI by region which indicates large differences in income inequality across regions, with the EU showing the lowest index and India the highest.
- *Global inequalities*. In terms of GDP per f.u., the results indicate a relative increase of about 80 % in OECD countries and a relative decrease of about 20 % in non-OECD countries. Nonetheless, in the macro-level studies this results in a (very small) decrease in the differences between OECD and non-OECD countries (note that non-OECD countries have a larger GDP than OECD countries). The impact of deploying CCS in the EU electricity sector can be considered as insignificant (<0.0001 %) when assessing macro-level effects.

5.2.2 Qualitative indicators

- *Risk perception*. Risk perception of CCS has, for instance, been examined by Wallquist et al. (2010) using a representative survey in Switzerland ($n = 654$). The authors indicate that predictors of risk perception are: socio-economic concerns, i.e. a perceived unsustainable character of CCS by the public (CCS as an end-of-pipe solution; CCS competing with renewable energy technologies; rebound effect), and concerns about leakage and the perception of pressurization in the geological reservoir. Their research also indicated that knowledge about CO_2, storage mechanisms and the awareness of climate change decreases risk perception. Schakel et al. (2007) interviewed stakeholders across Europe ($n = 512$). The results indicate that those issues which are identified as being with the highest risk are: additional fossil fuel use because of the energy penalty, human health and safety from onshore CO_2 storage and environmental damage from both onshore and offshore CO_2 storage. The lowest levels of perceived risk are associated with accidents arising from inclusion of CO_2 capture at power stations and human health and safety risks from offshore CO_2 storage site leakage. Literature indicates that a moderate increase in risk perception can be expected when applying the prospective technology. The indicator therefore will be flagged in the final results as "Moderate concerns".
- *Possibility of Misuse*. This indictor requires exploring potential economic consequences and consequences for safety risks. However, as it is not the intention at this stage to perform a full risk analysis, the focus is on identifying whether the implementation of CCS would increase the (infrastructure) vulnerability of the power plants (including up- and downstream). Vulnerability is examined in terms of likelihood of an attack. In this analysis it is argued that the implementation of CCS will not change the vulnerability of coal mining or coal transport, as CCS does not change the extraction or transport methods used. However, implementing a CO_2 capture unit in the power plant changes the plant (from a technical point of view). Instead of sole combustion processes, also chemical processes are included, and therefore its vulnerability could increase as chemical plants have a higher risk of sabotage. The two new steps in the chain are CO_2 transport and CO_2 storage. In the scenarios CO_2 is transported in pipelines in dense phase at large pressure (>80 bar), which is analogous to the transport of oil and liquefied natural gas. Oil and gas pipelines could be targets for terrorists, due to the direct large effects for the owners of the pipelines in the form of lost revenues and finding and repairing the leak. Besides, pipelines are relatively easy targets, since they are stretched out over large distances and therefore cannot entirely be protected and monitored. Uncertainties for CO_2 storage are related more to safety and leaking risks than to the possibility of misuse. CO_2 transport and CO_2 storage have been further examined regarding the likelihood of loss. The method uses expert judgement to evaluate different aspects (see Appendix 5). Note that for this exploratory analysis, a group consultation with 8 experts was conducted. These experts have knowledge on energy systems and CCS but not specific knowledge on vulnerability assessment. Preliminary results flag CO_2 transport with a moderate vulnerability and CO_2 storage with a low vulnerability. Summarizing, the deployment of CCS in the chain will not change the vulnerability of coal mining and coal transport and will increase the vulnerability of the power plant (to level similar to those found for chemical plants). The two new steps (CO_2 transport and CO_2 storage) have a medium and lower vulnerability respectively. Taking into account the low economic value of CO_2 and the fact that CO_2 is considered to be transported in Europe, the whole chain is flagged with "low concerns" for increased vulnerability in the prospective scenario.
- *Trust in risk information*. Although it is not possible to forecast whether population will have trust in risk information when CCS is implemented in large-scale, it

is possible to explore whether trust is considered a bottleneck in the current implementation of CCS projects. Reiner et al. (2012) examined shaping factors towards CCS in five European countries. Their results show a significant statistical relationship between perceptions about outcome risks of CCS technology and their trust in industry and national governments/politicians. The study also indicated a difference in the concerns on risk for different stages of the CCS chain. For CO_2 storage, respondents who lived within 100 km of the storage site tended to be more concerned about risks than those who lived further away. For the capture site, the relationship was found to be more complex, with those who live quite near to the capture site were more positive towards the local project than those who live farther away. The authors expected local economic benefits from the project may explain this more positive attitude. Riesch et al. (2013) conducted a European study on public perception of CCS in Poland and Spain. Their findings point out a positive correlation between trust and perceived justice in the planning process and more favourable views on the CCS developments. Terwel et al. (2012) examined how the local public perceived a proposed CCS demonstration project in Barendrecht, the Netherlands. The survey was administered to a large sample of the Barendrecht population ($n = 811$) shortly before it was decided to cancel the project due to public opposition. More than half of the respondents (55 %) stated that they did not trust those who would ultimately decide about the CCS plan and only 10 % of the respondents had "quite a lot" or "very much" trust. Dütschke (2011) compared the drivers of local public acceptance in two cases from Germany (Jänschwalde and Ketzin). In the first case, the CCS demonstration project was stopped due to strong public opposition, the second case (Ketzin) has successfully been implemented. The author's findings show that while in Ketzin public feels safe due to the minor quantities injected and the fact that the project would have to be stopped in case of leakages. The researchers from GFZ are trusted by the public and by community representatives. In Jänschwalde, however, the project developer was not trusted. A similar conclusion was drawn by a report on the lessons learned from the Jänschwalde project (European CCS demonstration project network, 2012). Based on the information available, trust in risk information appears as a potential bottleneck for CCS development. There is a large amount of research conducted at the moment on the drivers and potential strategies to manage public communication. The indicator is at the moment flagged as "Major concerns".

- *Stakeholder involvement*. Ideally, stakeholder involvement should improve the quality of the decisions and their legitimacy among those involved and affected (Lippin Malone et al. 2009). A survey ($n = 811$) to a large sample of the population in Barendrecht (Terwel et al. 2012) indicated that most residents perceived the decision-making process as unfair. They further felt that project developer and the national government had too much influence in the decision-making process and that the people of Barendrecht had too little influence. Reiner et al. (2012) show that respondents who agreed that the current planning process gives sufficient voice to local concerns and that their local community was treated fairly in the past were more likely to be positive towards the local CCS projects. Similar conclusions were drawn by Dütschke (Dütschke 2011). In this study it was found that local history played a role in the level of acceptance (or opposition) towards a CCS demonstration project. The study also concluded that, if a society wants to include CCS as a part of its energy strategy, this also needs to be supported by several (local) stakeholders in order to convince people on a local level that it is worthwhile to take the risk of living above / near a storage site. Similar conclusions are drawn by several studies including the guidelines published by the World Resource Institute (Forbes et al. 2010). Based on the information available, stakeholder involvement appears as a key element for deploying CCS projects. Note that this indicator and the indicator on trust in risk information are interlinked (low level of trust will most likely be due to a perceived low level of stakeholder involvement). The indicator is at the moment flagged as "Major concerns".
- *Long-term control functions*. Under this indicator the presence of governance or technical instruments that ensure long-term control will are included. In the case of coal power plants with and without CCS, the time frames at which storage occurs have been pointed as a main point of concern. Steenhouse et al. (2005) identified two independent timeframes that regulators would have to deal with for CCS. The first one relates to the ability of the storage to retain the total amount of CO_2 injected, i.e. several hundred years. The second timeframe refers to the potential for CO_2 stored underground to leak. The authors indicated that the time frame should take into consideration the potential impact for a long period of time (i.e. thousands of years). Given the longevity of the storage component of CCS projects, there is agreement that liability should be shifted from the private sector to the public (as represented by the state), but there is continuing debate as to when, by whom and how extensive this

Table 4 Weight sets used for the aggregation of social indicators

Indicator	Normalization factor	Weights set 1	Weights set 2
Total employment	8.98E + 02 h/person	0.167	0.197
Knowledge-intensive jobs	1.95E + 02 h/person	0.167	0.093
Child labour	1.96E + 01 h/person	0.167	0.293
Forced labour	2.22E + 00 h/person	0.167	0.166
Income inequality	9.13E-11 GINI/person	0.167	0.158
Regional inequality	−2.19E + 03 €/person	0.167	0.093

assumption of liability should occur (Bachu 2008). Zakkour and Haines (2007) identified key gaps in permitting regimes for the CCS chain and phase of operation. The authors indicate that permitting systems for capture and transport require little modification but major developments are needed for the subsurface element. Based on this information, the indicator is flagged as "moderate concerns".

5.3 Aggregating the results

To aggregate the results into a final score, equation 1 is used as well as two weight sets (see Table 4). The first set assigns all indicators the same weight, the second set was derived from a survey conducted among members of the Prosuite team (see Appendix 6). Results are shown in Table 5. In both cases, the prospective scenario shows a potential increase in social well-being. However, when applying weight set 2 this increase almost halves due to the large weight factor allocated to the indicator child labour, which increases in the prospective scenario.

Summarizing the results of the case study, in the scenario studied applying CCS results in an increase in total employment and knowledge-intensive jobs, and a (minor) decrease in income and global inequality as shown in section 6.1. However, increases in child and forced labour are also observed. When all indicators are considered, the results indicate that there is an increase in the social well-being indicator (Table 5). The qualitative indicators (section 6.2) reveal that issues such as trust in risk information, long-term control functions and stakeholder involvement can become bottlenecks for the deployment of the technology and need to be carefully addressed as part of project development and implementation.

6 Discussion and conclusions

This article developed a framework for assessing potential social impacts of novel technologies through their life cycle. The framework is explorative in character and is based on four areas of concern and 11 indicators. The paper aimed to develop a methodology consistent with core LCA principles (e.g. functional unit, system boundaries, foreground/background processes, baseline state and level of analysis). However, the inherent value-laden and context specific nature of social aspects was and remains one of the key challenges for developing a general applicable model.

In this article, the assessment of potential impacts strongly relies on the construction of scenarios (prospective vs. reference). Beyond the uncertainties that are encountered when developing scenarios for technologies that are currently available, additional uncertainties are introduced when novel technologies are examined in prospective assessments, including those related with defining which technologies are replaced and their development in the future market.

Table 5 Final score obtained from the explorative assessment of CCS in OECD Europe

	Using weight factors 1		Using weight factors 2	
	Absolute difference (prospective to reference)—persons	Direction of change	Absolute difference (prospective to reference)—persons	Direction of change
Social well-being	1100.7	Desired	627.1	Desired

An inherent limitation of input-output models is the use of average sector data. More detail is desired when aggregating two technologies that have very different impacts, or when the uses of the aggregated product outputs are for different purposes (e.g. gold for rings; uranium for power and blowing things up). However, although there can be large differences in the types of environmental impacts, it is expected that social impacts such as employment opportunities do not differ that much. Moreover, the country-specific sector data do not regard the foreground processes but rather the background processes, and can therefore still give valid information with regard to suppliers in sectors and countries with high risk. Although in the last years there has been a significant improvement regarding the availability and accessibility of international databases that contain socio-economic data at the sectoral level (e.g. exiopol, hot spot database), there is still a long way to go before these databases reach a satisfying level of detail.

The current framework does not methodologically connect with an attributional conception of life-cycle assessment because it assesses forecasted consequences of decisions. Consequences of decision alternatives are concerned including direct and indirect effects (see e.g. JRC 2010).

Rebound effects are not included in the case study results. However, the framework allows for comparing the results to results including consumer only rebound effects to put the results into context. The consumer only rebound effects are obtained by modelling price impacts of a technology and the impacts of (average) re-spending.

Furthermore the list of indicators used in this paper is limited, but can easily be expanded. The list was not intended to be prescriptive but should offer an organizing framework which can be adapted to the needs of the user. The selection of a limited number of indicators served the purpose of keeping the methodology simple and transparent. Furthermore, they allow examination of key social issues such as the mix of qualitative and quantitative aspects. The inclusion of additional social indicators can be a topic of further research. Social indicators are time, region, circumstance specific and often management-related and are therefore, by definition, difficult to predict. The approach recognizes the inherent qualitative character of many social aspects and does not attempt to mathematically integrate all aspects as quantification is not the driving force behind the assessment. Instead, the approach leaves part of the indicators to be dealt with qualitatively. For the assessment, the inclusion of participatory based approaches for expert elicitation is needed on a case-to-case basis as they can allow including context specific and ethical issues. Social well-being might often give rise to contradicting interests among groups in society, which is included in the current framework by the definition of weighting factors. Advanced methods for expert elicitation may highlight contradicting stakeholder interests within further framework development. A potential problem with the qualitative indicators is that their evaluation is subjective in nature (the conclusion is the result of an interpretation process). In the current framework, it is recognized that many aspects of social well-being are inevitably subjective and what is important is that their assessment is based on a transparent, informed and highly contextualized narrative. The subjectivity component in the analysis however will limit the degree to which results of a social LCA can be fully compared with other studies.

An interesting approach is, similar to environmental LCA, to develop characterization factors that allow for translation between changes observed in the indicators, as a consequence of introducing a novel technology, and their impact on social well-being. An example of a social impact calculation is developed by Feschet (2013) based on a change in potential life expectancy, yet this is only applicable to GDP and its effects on life expectancy. Development of characterization factors towards quality-adjusted life years (QALY) could be a way forward (Weidema 2006) although it gives rise to value-choices, inaccuracies and large uncertainties. The outcome of the current framework could be of help in this context as input for QALY characterization factors.

Regardless of the mentioned limitations, the framework developed in this paper provides a useful approach to develop explorative social impact assessments as it allows identifying, either quantitatively or qualitative, potential areas of concern taking into account the life cycle of the technology. The framework allows conducting comparable case study research. Further research is needed in the form of case study testing and improving the applicability of the approach. In addition further research could improve the procedure for including qualitative issues—providing more transparent, complete and feasible procedural steps for including qualitative indicators into the framework that improves consistency among future case studies (and thus mutual comparability).

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Appendix 1

Table 6 Output from the model (Ramirez et al. 2014) regarding the implementation of CCS in the electricity system in OECD Europe (prospective system) compared to an electricity system without CCS (reference system)

	Reference system	Prospective system	Relative difference (prospective to reference)	Absolute difference (prospective to reference)
Labour (h per f.u.)	2.8E − 03	4.6E − 03	6.8E − 01	1.9E − 03
Labour economy-wide (h)	7.5E + 12	7.5E + 12	6.8E − 08	5.1E + 05
Labour high-skilled (h per f.u.)	4.9E − 04	8.2E − 04	6.9E − 01	3.4E − 04
Labour high-skilled—economy-wide (h)	1.6E + 12	1.6E + 12	5.6E-08	9.2E + 04
Child labour hazardous activities (h per f.u.)	2.2E − 05	3.7E − 05	6.7E − 01	1.5E − 05
Child labour hazardous activities—economy-wide (h)	1.5E + 11	1.5E + 11	2.6E − 08	4.0E + 03
Forced labour total (h per f.u.)	2.2E − 06	3.6E − 06	6.4E − 01	1.4E − 06
Forced labour total—economy-wide (h)	2.0E + 10	2.0E + 10	2.0E − 08	3.8E + 02
Income inequality	0.65	0.65	−1.6E − 08	−1.0E − 08
GDP produced in OECD countries (€ per f.u.)	2.4E − 03	4.4E − 03	8.2E − 01	2.0E − 03
GDP produced in NON-OECD countries (€ per f.u.)	1.1E − 01	8.8E − 02	−1.9E − 01	−2.1E − 02
GDP produced in OECD countries—economy-wide (€)	5.7E + 13	5.7E + 13	9.8E − 09	5.6E + 05
GDP produced in NON-OECD countries—economy-wide (€)	5.9E + 13	5.9E + 13	−2.1E − 07	−1.2E + 07
Difference between OECD and non-OECD countries—economy-wide (€)	−1.4E + 12	−1.4E + 12	−9.0E − 06	1.3E + 07

Appendix 2

Table 7 Increases in working hours from reference to prospective system per functional unit (Ramirez et al. 2014)

	Low-skilled	Medium-skilled	High-skilled
Increase EU	70.9 %	71.3 %	72.1 %
Increase non-EU	77.6 %	80.2 %	86.7 %
Increase in total economy	72.2 %	72.1 %	74.2 %

Table 8 Share of sectors and skill levels in economic activity per functional unit (Ramirez et al. 2014)

Reference system				
Sector	Low-skilled	Medium-skilled	High-skilled	Total
Primary	5.6 %	17.3 %	4.1 %	27.0 %
Secondary	7.6 %	33.3 %	8.0 %	49.0 %
Tertiary	3.5 %	14.0 %	6.5 %	24.0 %
Total	16.7 %	64.6 %	18.7 %	100.0 %
Prospective system				
Sector	Low-skilled	Medium-skilled	High-skilled	Total
Primary	5.2 %	15.9 %	3.8 %	24.9 %
Secondary	7.8 %	33.8 %	8.1 %	49.7 %
Tertiary	3.7 %	14.8 %	6.9 %	25.4 %
Total	16.7 %	64.4 %	18.8 %	100.0 %

Appendix 3

Table 9 Share of different sectors in the child labour hazardous activities (hours per f.u.—Ramirez et al. 2014)

Sector	Reference system (%)	Prospective system (%)
Fossil fuel exploration	39.8	37.9
Metal, stone, sand	15.0	15.4
Industrial sector	14.1	15.7
Other	31.1	31.0

Appendix 4

Table 10 Shares of different sectors to forced labour (per f.u.) for the system with and without electricity with CCS as resulting from THEMIS (Ramirez et al. 2014)

	Reference system (%)	Prospective system (%)
Fossil fuel exploration	58.6	56.8
Metal, stone, sand	11.4	10.6
Industrial sector	11.2	12.3
Other	18.9	20.3

Appendix 5

Table 11 Assessment of infrastructure vulnerability

Likelihood loss given attach	Scale	CO_2 transport		Offshore CO_2 storage	
		Score average ($n = 8$)	Standard deviation	Average ($n = 8$)	Standard deviation
Accessibility	1–5	3.5	0.9	1.6	0.5
Extremely difficult to access; numerous obstacles	1				
Not readily accessible; requires extensive planning and resources to gain access; numerous obstacles to overcome; asset location difficult to reach	2				
Asset somewhat difficult to reach	3				
Assets is accessible with adequate planning; minimal obstacles; minimal obstacles to overcome to reach assets	4				
Easily accessible (ingress or egress); no obstacles; access is in the open or near the perimeter; access is reachable without accessing the site	5				
Sophistication of attack	1–5	3.1	0.9	1.9	0.6
Difficult to damage; hardened site to prevent damage; virtually impenetrable or prone to sabotage	1				
Hardened to prevent damage; requires extensive knowledge, skills and abilities to destroy, damage or steel the asset	2				
Requires some knowledge and training; requires limited resources and time to destroy, damage or steel the asset	3				
Requires limited knowledge, skills, and abilities to neutralize; requires few resources and little time to destroy, damage or steel the asset	4				
Requires little skill, few resources and minimal time	5				
Degree of control over outcome	1–5	3.4	1.1	2.6	1.2
Success depends on complex sequence of events following initiation of attack; attack highly susceptible to attack factors	1				
Device is complex; attack quite susceptible to outside factors	2				
Simple sequence of events involved; some susceptible to outside factors	3				
Attack harms target almost directly; minor susceptible to outside factors	4				
Attack directly harms target; attack not susceptible to outside factors	5				
Security	1–5	3.4	1.1	2.8	0.8
High security level; 100 % armed security force; located in large built area	1				
Medium level of security; located in large, built-up area	2				
Limited security measures; located in remote area	3				
Minimal security (fence only); remote site	4				
No security measures for asset; no susceptible to outside factors	5				
Total		13.4	3.1	8.9	2.4

The methodology used in this indicator is based on work developed by the US DOT (2001), which uses the likelihood of asset loss combined with expert elicitation. For each aspect that wants to be explored, four aspects are evaluated, namely accessibility, sophistication of the attack, degree of control over outcome and security measures. The assessment uses a ranking scale which is shown in the table below. The value of each aspects is based on expert judgement and, when possible, experience with the technology or analogous situations. Once each of the aspects is evaluated, the ranking values are added and the total score is then evaluated used the ranges provided at the end of the table

Rate score: high (17–20), moderate (13–16), low (9–12), minimal (4–8)

Appendix 6 Weighting factors consultation

A questionnaire was formulated to support the definition of weighting factors used in the CCS case study example. The questionnaire is based on the approach used by work package 5 to define weighting factors for the sustainability endpoints on human health, exhaustible resources, natural environment, prosperity and social well-being (Laurent et al. 2013).

The work package leaders and the partners in charge of the case studies are asked to reflect upon the relative importance of the different performance indicators and areas of concern. Following the descriptions found in Ciroth et al. (2014) they are first asked to weight the indicators per area of concern and subsequently weight the areas of concern overall. A theoretical example is provided of how to rank the indicators and the areas of concern. The participants are invited to provide input taking into account the following considerations:

1. The participant ranks the indicators per area of concern from most to least important.
2. Ties are allowed, i.e. if two or more indicators have the same importance they should be placed side-by-side.
3. Blank cells can be introduced between successive indicators or areas of concern in order to express difference in relative importance between two indicators or areas of concern.
4. The participant informs how many times the last criterion is less important than the first one in the ranking.
5. The same is done for indicating the relative importance of the areas of concern.

The final weights are computed averaging the results of the consulted expert team, resulting in a default weighting set. An additional weight set is used for comparison applying equal weights for every indicator. It is emphasized that further research can shed a light on refining the current weighting set and determining the effect of different weight sets.

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