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EXPLORING THE GLOBAL AND LOCAL SOCIAL SUSTAINABILITY OF WIND ENERGY TECHNOLOGIES: AN APPLICATION OF A SOCIAL IMPACT ASSESSMENT FRAMEWORK

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ABSTRACT

A transition to renewable energy sources is needed in the EU countries to achieve their goal of a low-carbon economy. This transition may come with potentially negative impacts on the well-being of the population, both globally and locally. Such social impacts are not yet systematically assessed for renewable energy technologies. In this paper, a social impact assessment framework for renewable energy technologies is developed and applied for a wind energy case study. The assessed social categories comprise impacts on human health, human rights infractions, working conditions, local job creation, quality of residential life, landscape quality. In order to cover this broad field of social impacts, four distinct social impact assessment methods were combined in a common social impact assessment framework. The application of the framework was demonstrated by means of the wind energy case study. The results are presented in the form of a social sustainability dashboard comprising 23 social impact indicators covering both global and local well-being impacts. The analysis showed that the life cycle material demand of offshore wind projects has larger impacts on global well-being than the onshore alternatives. For the local dimension, the offshore case was found to be less intrusive for the local population.

KEYWORDS

social impact, social life cycle assessment, renewable energy technologies, sustainability, wind energy

1. INTRODUCTION

The energy transition is an important part of the EU policy to reach climate-neutrality by 2050. To achieve a sustainable transition, it is not enough to concentrate exclusively on carbon emissions reduction but likewise, the larger effects on living environment and the society as a whole are relevant. Sustainability is characterized by Elkington [1] as activities considering the dimensions of People, Planet, and Profit, calling this the triple bottom line. Accordingly, energy policies need to consider the "side effects" on the environment, economy and society. Social sustainability, although presented as pillar of equal relevance, is in sustainability communication often treated as supporting argument for environmental or economic efficiency. To strengthen the study of social impacts, the definition should be independent from the environmental and economic pillars, i.e. focus on the characteristics of society rather than on the physical environment. Social sustainability is thereby characterized by maintaining of or contributing to an equitable, diverse, connected, and democratic society that ensures a good quality of life [2].

An indication of the scope of social impacts and contributions is provided by the UN Sustainable Development Goals [3] with goals referring to health (SDG 3), decent working conditions (SDG 8) and the reduction of inequalities (SDG 10). In the energy sector potential social impacts range from supply chain effects due to the specific material requirements of the energy technologies to local effects at the location of energy generation. There is no agreed framework for the social sustainability assessment of energy technologies. As a consequence, social aspects are covered with irregular frequency and level of detail [4]. Based on a review of several (life cycle) sustainability studies, the main impact areas of energy generation are impacts on human health, human rights infractions, working conditions, local job creation, quality of residential life, and landscape quality. In order to systematically include the assessment of these impact into sustainability studies, this paper aims at the development and application of a social impact assessment framework and will therefore discuss and expand upon already existing assessment frameworks and used methods, most prominently social life cycle assessment (SLCA).

1.1. SLCA METHODOLOGY

SLCA is the starting point for an extended social impact assessment of energy technologies. Life cycle thinking is key for the assessment of sustainability as it goes beyond immediately observed impacts and aims at incorporating all the associated impacts along the life cycle stages into the decision-making process [5]. In life cycle thinking, the triple bottom line is considered with respective assessment frameworks for each of the sustainability dimensions: Environmental Life Cycle Assessment (ELCA), Life Cycle Costing (LCC) and SLCA. Historically, the main focus was on the development and standardization of environmental and economic life cycle methods [6,7]. The development of SLCA methods has accelerated in the last 10 years and (according to Ramos Huarachi et al. [7]) only recently entered an era of standardization. This line of research highlights the importance of the further development of SLCA and social impact assessment in order to comprehensively cover the impacts of the energy transition and complement the sustainability assessment.

A first standardization step of social impact assessment methods was taken with the guidelines on SLCA published by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) [8,9]. The guidelines differentiate between two types of SLCA characterization models, type I and type II models. These models use different strategies for quantifying social impacts along the life cycle.

According to the definition of the UNEP SLCA guideline [9], type I models measure impacts with regard to a performance reference point i.e. use a Reference Scale approach. This approach evaluates the social performance of an activity in the product life cycle in relation to a reference point, e.g. salary paid to workers in the production process is compared to the reference of statutory minimum wage. The focus here lies on standards observed in involved companies rather than the production process itself [10]. The impacts are expressed as social performance or risk of violation of defined standards [9]. As the reference points of type I impact categories are defined individually for each category, it is difficult to establish a relationship between them or to aggregate results [11].

The Type II model or Impact Pathway approach includes a clearly defined impact pathway, that is the causal relationship between processes (e.g. burning of fuel) and impacts (e.g. respiratory diseases). The impact pathway approach is also frequently used in ELCA, which comes with the advantage of decades of experience and well-defined impact pathways. Therefore, social assessments of this type are often incorporated or used as an extension of ELCA to add an evaluation of societal well-being to a mainly environmental assessment [12].

1.2. CONSIDERATION OF LOCAL IMPACT IN SOCIAL SUSTAINABILITY ASSESSMENT

SLCA methods take a central role for the social impact assessment of energy technologies but need to be complemented in order to bridge shortcomings of existing quantification approaches and expand the variety of assessed social issues. Local decision criteria for or against an energy technology, such as the response of the population neighboring the energy generation sites and the significance for the local economy, are not captured by current life cycle methods. Such local criteria are of particular importance to allow for a localized evaluation of projects where the decision-makers consider the well-being of the affected population as important criteria to accept the implementation of the project.

With the transition to renewable energy technologies, the system of power generation changes from a few large power plants to a larger number of distributed generation sites. Energy generation comes closer to the population and while Environmental Impact Assessments prior to building permits are common practice, impacts on the local population seldom go beyond the accounting of immediate emissions. However, energy projects often deal with public opposition based on expected and experienced impacts of the projects on the public's living environment. Opposition from the local population should not be dismissed and rather investigated as a valid concern about changing living environments [13]. Therefore, the public's opinion and the magnitude of experienced disturbances need to be considered in the social impact assessment and thereby be part of democratic decision-making [14].

SLCA methods are not well equipped to cover such local impacts, even more so as public attitudes are based on individual experiences. The assessment of local attitudes, expectations and experiences constitutes its own field of research offering insights of impact quantification based on public perceptions. This study makes the case for the differentiation between impacts on the well-being of the world population globally and the local population at the site of energy generation. As the energy transition accelerates the demand for certain materials, societal conditions in the mining and processing sectors are of growing importance. Global well-being refers to the responsibility to ensure safe and fair living conditions for communities involved in the material supply chain. At the same time, the land use change at the site of energy generation specifically impacts the well-being of the local population. The wide range of global and local well-being impacts requires the extension of existing assessment frameworks in order to fit for a holistic social sustainability assessment study.

1.3. EXISTING SOCIAL SUSTAINABILITY FRAMEWORKS

Since the publication of the UNEP/SETAC guidelines, the number of published SLCA studies increased, although, compared with the ELCA studies, the absolute amount remains low [15]. In the energy sector, SLCA studies are commonly conducted as add-on to an ELCA where emissions to the environment are assessed with regard to both the impact on the environment and on human health [16–18]. As these studies come from the origin of ELCA, their scope is limited to the impacts of physical process outputs. There are few examples of SLCA going beyond the assessment of emissions and focusing on a broad mix of social impacts and hotspots. Until today, such broader SLCA studies were conducted for specific technologies, such as photovoltaic modules [19], concentrated solar power [20], biodiesel [21,22], fuels for the transport sector [23] or for permanent magnets used in energy technologies [24]. As these studies are pioneering in the field of SLCA, the scopes and assessed impact categories differ significantly and it is not possible to compare results. Moreover, only few studies consider the expansion of SLCA to also include local social impacts. Examples of considering local alongside global impacts were found for the waste management sector [25] as well as the case study of solar PV [26]. The later study by Abu-Rayash and Dincer [26] uses a number of indicators to account for social aspects including local job creation and social acceptance while the majority of results refer to globally experienced impacts. An extensive amount of sustainability indicators is used and aggregated into a single index. Although local impacts are included in the assessment, their significance in the overall index is not discussed. Santoyo-Castelazo and Azapagic [27] consider public acceptability as a local issue including the perception of health and safety risks with a qualitative measure. In the end, the qualitative social indicators were not integrated into the multi-criteria decision analysis of the study of Santoyo-Castelazo and Azapagic [27], which excludes the local perceptions from the decision processes. The cited studies took a first step to account for local well-being impacts in a sustainability framework. Further work is needed to have a balanced presentation of the social sustainability in comparison with the environmental and economic dimension, as pointed out by Martín-Gamboa et al. [6] and Buchmayr et al. [4].

In conclusion, experiences exist for both the use of SLCA and the assessment of personal experience, acceptance, and opposition of new energy technologies but the combined use in one framework is not common. The connection between the different fields of SLCA and local impacts expressed as experiences and attitudes is still a challenge that is repeatedly discussed by practitioners of sustainability assessment [18,28]. The larger integration for a social sustainability assessment is not well covered. Therefore, further work on a comprehensive social impact assessment framework is needed.

1.4. OBJECTIVE

This paper proposes a social impact assessment framework for quantifying both global and local well-being impacts of energy technologies. First, the focus lies on the identification of social impact categories relevant for the description of energy technologies and the review of appropriate assessment methods. Second, the reviewed methods are tested by means of a case study for wind energy systems. The wind energy case study was selected as this technology is of great significance for reaching the EU climate goals and decarbonizing the electricity mix. Offshore wind capacities are forecasted to provide 16% of the EU electricity demand by 2040 [29]. At the same time, the wind energy expansion comes with societal challenges that need to be addressed. The technology has the potential to have a major impact on both the global population, e.g. due to dependency and human rights issues in the course of material sourcing needed for wind turbines [30], and the local population, e.g. due to a significant impact on local landscapes [31]. No study has been found that addresses social sustainability, considering both the global and the local impacts of wind energy.

This study will provide a first comprehensive social impact assessment of wind energy technologies. Using the concrete case study, SLCA and social impact assessment methods will be investigated for their suitability to quantify a wide range of social impacts, including responsible material sourcing and local public opposition. The expansion of SLCA with local assessment methods will contribute to the discussion on an integrative life cycle sustainability framework.

As a result, this study presents a dashboard of global and local social impacts that contribute to a holistic evaluation of energy technologies and transition pathways. Such social impacts need to be considered alongside techno-economic and environmental criteria by decision-makers in order to facilitate a truly sustainable energy transition.

2. MATERIALS AND METHODS

2.1. DESCRIPTION OF THE WIND ENERGY CASE STUDY

In this study, offshore and onshore wind energy set-ups are compared with regard to their various social impacts. The EU onshore wind market today is dominated by turbines using induction generators. An alternative technology are generators using permanent magnets, which makes them lighter in design and require less maintenance. This technology makes about 30% of the onshore market [32]. A strong growth is predicted in the coming years with permanent magnet generators representing the main share of onshore wind generation by 2050. In offshore applications, where maintenance operations are more challenging and labor-intensive, permanent magnet generators are already the main technology [32].

For the manufacturing of permanent magnets, rare earth metals are required, whose predominant production in China comes with the risk of human rights infractions and high supply dependencies. Life cycle thinking is needed to balance the advantages of reduced material demand and higher efficiency against the risk of social infractions along the supply chain of permanent magnets.

Different types of wind turbines are investigated in this case study to identify social hotspots depending on the project design and highlight the risks of growing permanent magnet demand. An offshore installation is compared with two types of onshore wind turbines. The offshore wind turbine is assumed to use a permanent magnet synchronous generator (PMSG) as this is the dominant technology in the European offshore wind market. This offshore installation is compared to two types of onshore wind turbines: one wind turbine using a double fed-induction generator (DFIG) and one using a PMSG. Thereby, the study offers a direct comparison of the most prominent onshore technologies, that is DFIG, and the growing field of PMSG.

The turbine types, key properties and assumptions used for the modelling of the three cases of wind energy are summarized in Table 1. The case study is situated in the region of Flanders, Belgium. A total lifetime of 20 years was considered for the wind turbines, cabling and transformer infrastructure. The material demand during all phases of the life cycle is listed in the Life Cycle Inventories in the Supplementary Information.

Table 1. Case study characteristics for compared wind turbines

	Offshore wind – PMSG	**Onshore wind – PMSG**	**Onshore wind – DFIG**
Turbine type	Three-bladed upwind turbine	Vestas V112	Vestas V112
Generator type	Permanent magnet synchronous generator (PMSG)	Permanent magnet synchronous generator (PMSG)	Double fed-induction generator (DFIG)
Capacity	5 MW	3 MW	3.45 MW
Annual full load hours	4,000 full load hours [33]	2,808 full load hours (4% increase compared with DFIG [34])	2,700 full load hours [33]
Annual electricity production	20,000 MWh	8,424 MWh	9,315 MWh
Bill of materials	[35], [36]	[37]	[38]

To allow for a good comparison between the DFIG and the PMSG technology, the same wind turbine model – Vestas V112 – with different generator types was used for the case study. For the offshore case a generic inventory for a 5 MW wind turbine provided by Raadal et al. [35] was used which is based on a baseline wind turbine model developed by the National Renewable Energy Laboratory [39]. The inventory was complemented with the assumption for the permanent magnet content in the generator of 160 kg/MW [36].

The energy production is estimated per location using 2,700 full load hours for the onshore location and 4,000 for offshore. Pyrhönen and colleagues [34] reported an efficiency increase of 2 to 8% for PMSGs depending on the wind speed. For the onshore comparison, an increased electricity output of 4% for PMSG in comparison with DFIG was assumed. For the offshore location, it is assumed that this is already included in the estimated full load hours as PMSG is the prevalent technology for this case.

The case study is described in more detail by differentiating between activities of global relevance and activities with local relevance. The approach presented in this study aims to highlight the impacts on the population at the point of power generation additionally to global impacts, which are usually captured by SLCA. The locally affected population needs to be considered in the decision-making process by providing an indication of how their own (local) well-being is impacted by the project. To accomplish this separation between impacts on global and local well-being methodically, it is necessary to differentiate between process outputs, such as emissions and waste, with global and local relevance. Outputs with global relevance affect the world population. On the one hand, these can be impacts that are experienced by the global society, e. g. climate change. On the other hand, it also includes impacts that are relevant due to a shared responsibility of the global society to provide safe and fair living conditions for all members of society, e.g. human toxicity impact during international material sourcing. Outputs with local relevance affect only a delimitated population that needs to be defined in the scope of the study, e.g. particular matter formation affects the population living and working in the neighborhood of the emission source.

In LCA the foreground system includes the processes under investigation, which are of immediate interest for the decision maker. The processes in the foreground system often rely on inputs from a background system that encompasses all other processes such as supply of materials, energy and infrastructure, which contribute to the overall impact due to their consumption by foreground processes [40]. Usually it is sufficient to differentiate between one foreground and one background system. But in this study, in order to highlight the difference between globally and locally relevant impacts, the investigated life cycle is split into two foreground systems. The location of energy generation, i.e. the wind park and the surrounding community is considered as "local".

In foreground system 1, globally relevant impacts along the complete life cycle are aggregated to a measure of global well-being impact. In foreground system 2, only locally relevant processes, i.e. the construction and use phase of the wind turbine, are aggregated to a measure of local well-being impact. Figure 1 shows these separate foreground systems for the Flemish wind energy case study. The location of the component assembly was assumed to be in Denmark for the wind turbines and in Flanders for foundation material and the inverter station. In order to avoid double counting of impacts, a strict separation of global and local impact categories was observed for all life cycle stages. To facilitate this separation, an impact matrix was drawn up in order to specify which impact flows were considered for the calculation of different impact categories. The impact matrix for the proposed framework can be found in the Supplementary Information document in Table A 1.

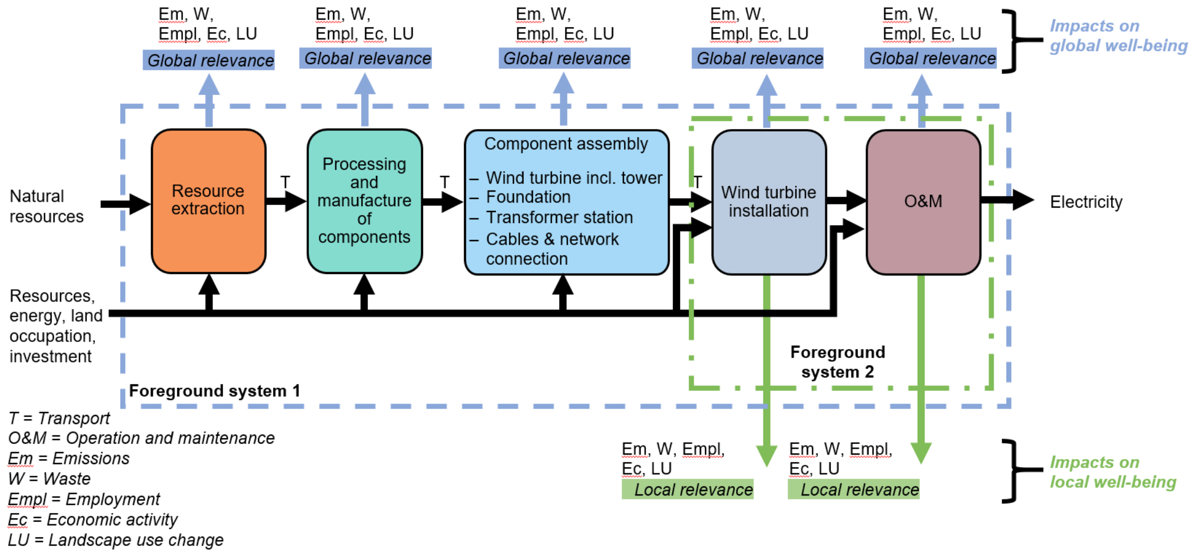


Figure 1. Life cycle of wind energy technologies with delimitation of two foreground systems for global and local well-being assessment

The life cycle of the wind turbine case studies is assessed from cradle to gate, where the "gate" is the point of delivery of electricity to the electric grid. The end-of-life of wind turbines is not considered in this study as there are still uncertainties regarding disposal, reuse and recycling of wind turbine materials in Europe. The functional unit for the assessments is 1 MWh or 1 TWh electricity delivered to the electric grid.

2.2. ESTABLISHING A SOCIAL IMPACT ASSESSMENT FRAMEWORK

A social impact assessment framework considering both global and local well-being, which refers to the two foreground systems depicted in Figure 1, needs to be established. The challenge lies in the identification and development of adequate assessment methods, including the definition of impact pathways and according characterization factors. In LCA, the characterization factors are the embodiment of the impact pathway and are used to convert the physical outputs, such as emissions or waste, to impacts indicators. Depending on the research field, characterization factors translate outputs to either mid- or endpoint impact indicators. Indicators at the midpoint typically display the immediate impact with connection to the cause-effect chain, e.g. an indicator quantifying particulate matter formation as a consequence of the burning of fuels, while endpoint indicators are less specific and characterize the impact with regard to a broader area of concern, e.g. human health and ecosystem impact.

Such characterization factors for SLCA are readily available for the health assessment and partially for the quantification of social risks. For the quantification of a wide range of social impact categories, it is necessary to look beyond the existing SLCA methods and define additional characterization factors.

The aim of the proposed social impact assessment framework is to provide a decision basis for local stakeholder groups, such as policy-makers, project implementers and the population in general. In particular, the framework focuses on the energy sector of Western Europe, as the wind energy case study is situated in Belgium, but the framework is as well applicable to economically and socially similar regions of the world.

The life cycle of an energy project, as depicted in Figure 1, is the cause of a number of effects that can be translated to social benefits or impacts. The review of Buchmayr et al. [4] narrowed down the field of social impacts related to energy supply technologies and identified the following six social impact categories as relevant: 1) human health, 2) human rights, 3) working conditions, 4) job creation, 5) quality of residential life, 6) landscape quality.

The assessment framework for the wind energy case study is based on these six impact categories with an additional differentiation between global or local well-being impacts. The list of all impact categories for both the global and the local dimension can be found in Table 2. For each of these categories a decision was made about the inclusion or exclusion into the framework. Reasons for the exclusion were e.g. to avoid the double counting of impacts or missing relevance for a social sustainability assessment. Table 2 provides the additional information regarding the impact categories that were selected for the framework.

Table 2. Consideration of global and local well-being categories for the social impact assessment framework based on the social impact categories identified by Buchmayr et al. [4]

Impact categories	Spatial dimension	Assessment method	Within framework scope	Reasons for inclusion/exclusion in the framework
Human health and safety quality	Global	Social LCA type II	Y	Maintenance of health environment to ensure human well-being
	Local	Local impact assessment	Y	Source of concern for local population and possible benefit in changing to non-polluting technologies
Human rights	Global	Social LCA type I	Y	Social responsibility to ensure healthy living conditions for all communities along the supply chain
	Local	Local impact assessment	N	Not relevant in Western European context
Working conditions	Global	Social LCA type I	Y	Social responsibility to ensure a peaceful and prospering life and counter the implications of raw material demand connected to new energy technologies
	Local	Job quality assessment	Y	Shows the impact of transitioning to "green jobs"
Job creation	Global	Accounting for jobs created	N	On the global dimension relevant to describe the potential for economic growth and efficiency but less suitable to describe the social implications as these strongly depend on the affected societies
	Local	Accounting for jobs created	Y	Not the global job creation metric but the local one is relevant for local stakeholder groups to evaluate the impact on society
Quality of residential life	Global	Social LCA type I but no standardized characterization factors available yet	N	Covered in parts already with global human rights and working conditions assessment.
	Local	Survey research	Y	Major source of local opposition
Landscape quality	Global	Social LCA type I but no standardized characterization factors available yet	N	Experiences of the affected populations along the supply chain are too ambiguous
	Local	Survey research	Y	Major source of local opposition

As Table 2 shows, human rights infractions are only considered along the global material supply chain but are assumed to be not relevant in the use phase located in Western Europe (local) as these countries have ratified a high number of human rights treaties [41] and score high on Sustainable Development Goals related to peace, justice and strong institutions [42]. Moreover, residential life and landscape quality were only considered for the local dimension with the aim to anticipate possible sources of population opposition. For a global assessment of these categories, characterization factors and common endpoint indicators are missing.

The global job creation category describes the potential for economic growth and technology efficiency but is less suitable to describe the social implications as these strongly depend on the affected societies. Therefore, only local job creation is considered in the assessment framework.

For the assessment of working conditions, different methods are proposed to allow for different quality criteria. While the assessment of the global supply chains evolves around issues of just and responsible working conditions according to ILO standards [43], the local dimension in Western Europe needs to go beyond that and include the quality of employment, that is in particular the quality of "green jobs" generated in the renewable energy sector. Prominent examples for the assessment of the quality of European working conditions are the European Working Conditions Survey [44], the OECD Job quality assessment [45] or the European Job Quality Index [46]. In these frameworks, indicators such as job satisfaction, development opportunities and work-life balance are assessed.

The impact categories within the scope of the proposed social impact assessment framework, as discussed in Table 2, can be measured using four different types of assessment methods, being SLCA type I, SLCA type II, job quality assessment (including the accounting for jobs created), and local impact perception surveys. While the first three methods produce objective measures, the latter depends on the subjective evaluation of impacts by the population. A subjective measure is preferred in this framework to assess the quality of residential life and landscape quality in order to incorporate components of well-being that are based on perceptions and personal preferences of the population [47]. The advantage of a subjective measure in this case is that they include a direct indication of the population's attitudes which objective measures lack.

The included impact categories in the framework along with their respective assessment method type are summarized in the categorization matrix in Figure 2.

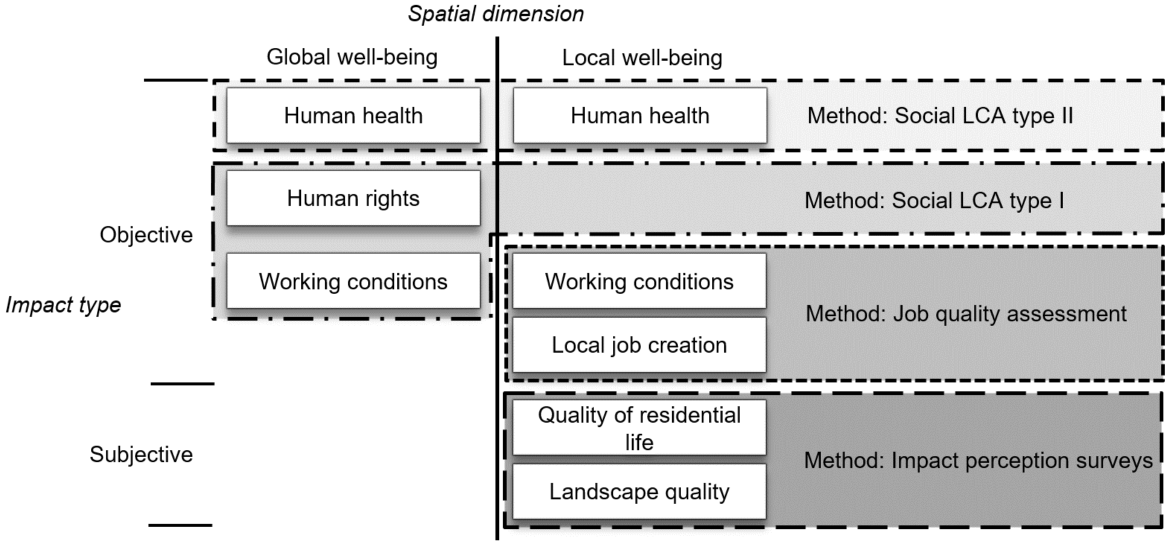


Figure 2. Categorization of social impacts in the proposed assessment framework for energy technologies

The four identified assessment methods and their implementation for a case study of wind energy are described in the following sections.

2.2.1. HUMAN HEALTH ASSESSMENT USING SLCA TYPE II

The life cycle impact assessment on human health is well established and, depending on the type of emissions, practitioners can choose from different methods. Methods such as Eco-indicator 99 [48], IMPACT World+ [49], LIME [50], or ReCiPe [51] offer assessment frameworks that can cover a range of impact pathways relevant for the assessment of human health, partly at midpoint as well as endpoint level. As these methods make use of different characterization models and cover a different range of impact categories, the choice of method might significantly influence the results [52]. To facilitate this selection process, the Joint Research Centre (JRC) of the European Commission provides guidance documents and recommendations for the choice of emission models [53].

The ReCiPe2016 method [51] was chosen for the human health assessment, as it provides characterization factors for all the health-relevant impact categories and incorporates the life cycle impact assessment methods recommended by Fazio et al. [53]. Moreover, it provides global characterization factors to translate emissions to an endpoint indicator expressed in Disability Adjusted Life Years (DALYs). Only for the category of particulate matter formation, an improved model [54] was published, which is recommended by Fazio et al. [53], but not yet included in ReCiPe. The global characterization factors used in ReCiPe present an average for the emission uptake and distribution irrespective of the specific location. For the assessment of the local impact, spatially explicit characterization factors should be used. Van Zelm and colleagues [55] provide such factors for quantifying the local impact of particulate matter formation and photochemical ozone considering weather conditions and population distribution of several European countries. Comparable regionalized characterization factors are not available for other locally relevant categories such as human toxicity and ionizing radiation. Therefore, in the assessment, global factors provided by the ReCiPe method are used.
As the ReCiPe method bases the quantification on cause-effect chains, it can be classified as type II SLCA method according to the UNEP/SETAC classification [9].

For the wind energy case study, the assessment of life cycle human health impacts was done in compliance with the general requirements of ISO 14040:2006. The global human health impact from cradle to gate was assessed using foreground system 1 as depicted in Figure 3. The local human health impact singles out locally relevant impacts for the constricted foreground system 2 focusing on local installation, operation, and maintenance processes.

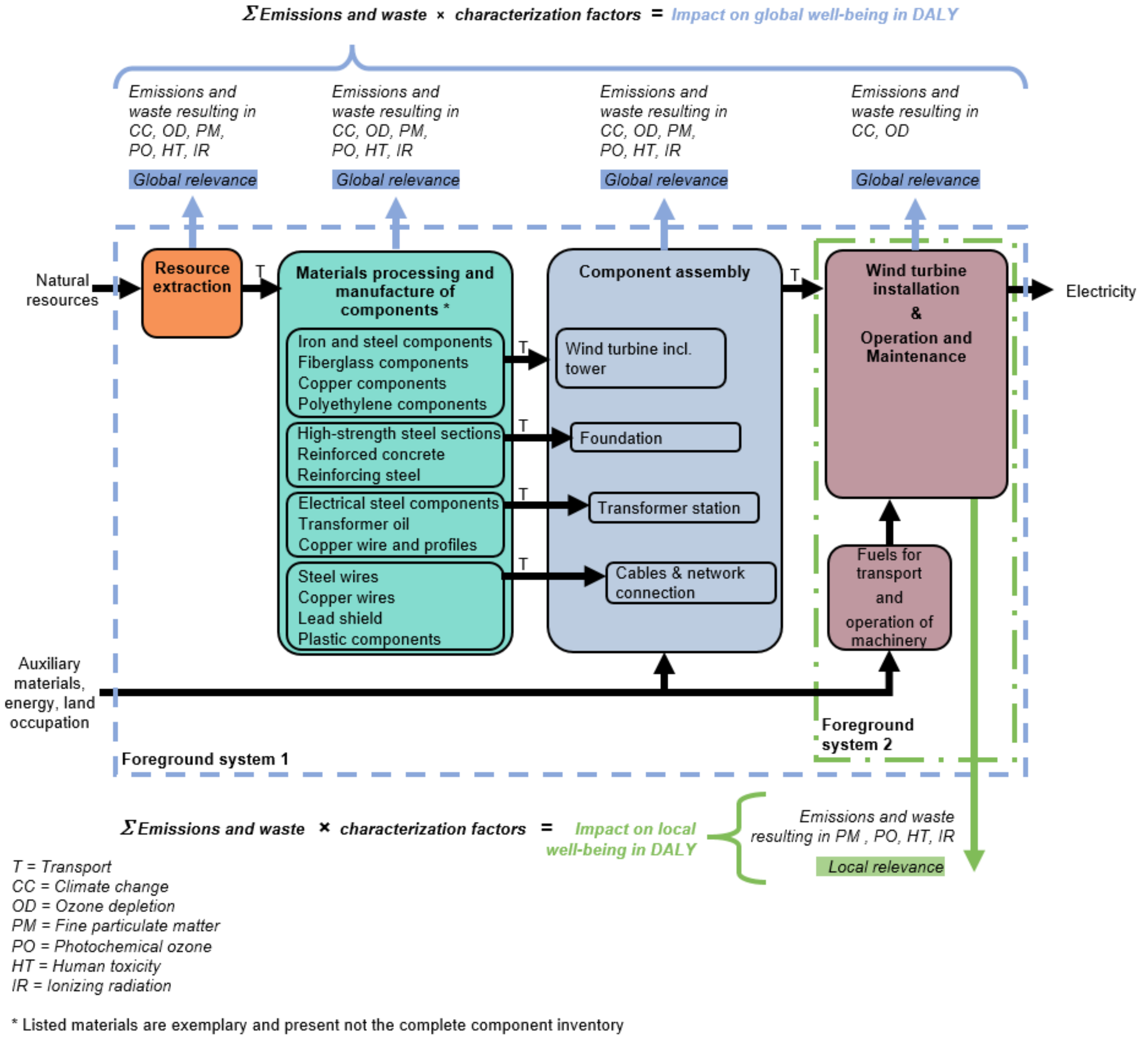


Figure 3. Life cycle scheme for the assessment of human health impacts of wind energy case study

For background processes, the ecoinvent database version 3.6 was used. The life cycle inventories of the case studies are provided in the Supplementary Information in Table A 2.
The life cycle was modeled using SimaPro 9.2.0.2 software.

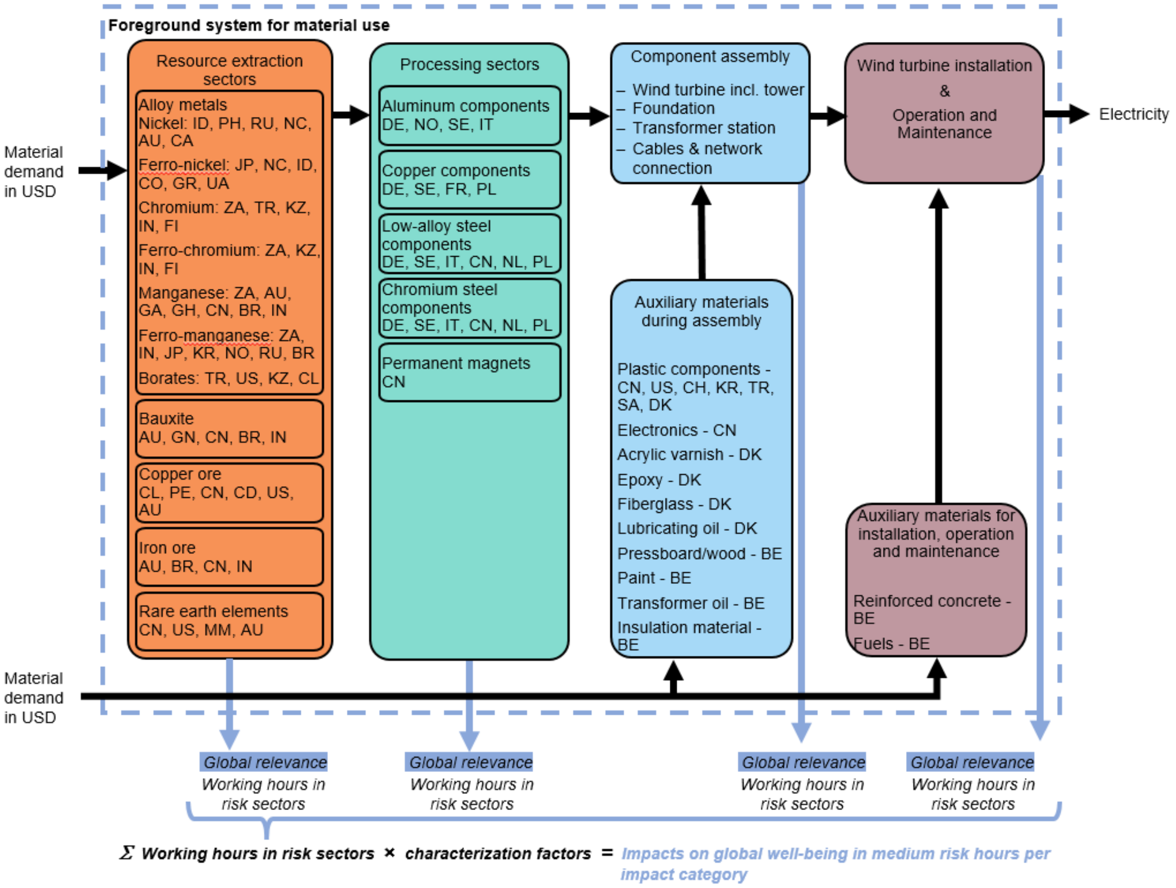
2.2.2. HUMAN RIGHTS AND GLOBAL WORKING CONDITIONS COMPLIANCE ASSESSMENT USING SLCA TYPE I

The compliance with human rights and working condition standards needs to be considered as a globally relevant impact where it is the obligation of the society as a whole to ensure compliance along the supply chains. While the life cycle human health impact is determined mostly by the characteristics of the production process, the compliance with social standards depends on the conduct and social responsibility policies of involved companies [10]. The global supply chains required to realize the energy transition in Europe carry the risk of constituting or cementing poor conditions for workers and the general population of involved developing nations. The lack of transparency in supply chains poses a major challenge for the quantification of infractions. Quantification methods therefore concentrate on the accounting of risks for the involved economic sectors rather than specific supply chains. Databases such as the Social Hotspot Database (SHD) [57] and the Product Social Impact Life Cycle Assessment (PSILCA) [58] offer a collection of social well-being indicators and provide a risk quantification on the basis of involved country-specific sectors. They can be classified as type I SLCA as the quantification is based on reporting the performance with regard to a reference point, e.g. weekly working hours over an accepted maximum.

Both SHD and PSILCA are increasingly applied SLCA methods. While the majority of studies in the past used SHD, PSILCA is gaining traction in recent years [7].

For the present framework, the PSILCA method was chosen due to the transparency of the used sector indicators and resulting risk factors. In direct comparison with the SHD, PSILCA offers a more detailed differentiation of sector activities. Such level of detail was considered important to allow the differentiation of risks for several raw materials. In PSILCA, sector activities are based on the Input/Output database EORA [58]. The systematic of EORA offers a varying level of detail regarding the economic sectors in each country. Thereby, the sector-wise specification can be more or less accurate for the investigated materials depending on the country. This needs to be considered while interpreting the results. The PSILCA method quantifies risks using the unit medium risk hours, that are the weighted working hours (representative for the economic value) using the medium risk level as reference point. High risks thereby receive a large weight (larger than 1) and low risks a small one (below 1) [58].

The SLCA of the wind energy case study focuses on the material use along the supply chain. With the aim to identify social hotspots of material use, the analysis traces the main materials needed in the product. The assessment scope includes the production of processed materials but not the assembly of components. This means that e.g. copper sourcing and processing to a copper wire is included in the assessment but the manufacturing of coils and assembly of a generator are not included. This has the advantage that value-adding processes that are not connected to responsible material sourcing are excluded from the analysis which focuses on the results on the social impacts of material use only. As a result, material transport, handling, and assembly, as well as accompanying processes such as project planning, are excluded from the SLCA. Figure 4 shows the product system used for the SLCA including a simplified inventory of relevant countries and sectors along the material supply chain.



AU = Australia, BE = Belgium, BR = Brazil, CA = Canada, CD = Democratic Republic of the Congo, CH = Switzerland, CL = Chile, CN = China, CO = Colombia, DE = Germany, DK = Denmark, FI = Finland, FR = France, GA = Gabon, GH = Ghana, GR = Greece, ID = Indonesia, IN = India, IT = Italy, JP = Japan, KR = Korea, KZ = Kazakhstan, MM = Myanmar, NC = New Caledonia, NL = the Netherlands, NO = Norway, PE = Peru, PH = Philippines, PL = Poland, RU = Russia, SE = Sweden, TR = Turkey, UA = Ukraine, US = United States of America, ZA = South Africa

Figure 4. Life cycle scheme for the assessment of global human rights and global working conditions quality of wind energy case study

For the PSILCA method, Figure 4 shows that the process inputs are expressed in economic values – in this case in USD. The outputs are also expressed in economic values but in working hours that took place in a risk sector. The output presents the share of every invested USD that goes into sectors with low, medium, and high risk of infractions. Characterization factors, which provided weights to each of the risk levels, are used to calculate the risk indicators expressed in medium risk hours. Both the assigned risk levels and the characterization factors depend on the investigated impact category and are provided by the PSILCA database.
To make use of the PSILCA method, the bill of materials for the wind turbine case studies (as used for the human health impact assessment) was converted from weight units to monetary values per economic sector. The used conversion factors can be found in the life cycle inventories in the Supplementary Information in Table A 3 and Table A 4.

The described procedure is used for the assessment of several PSILCA impact categories to describe risks regarding fair working conditions and human rights infractions. First, considering the field of working conditions, PSILCA provides indicators in eight sub-categories covering major risk areas for workers. These sub-categories of working conditions are further investigated for the wind energy case study: 1) Child labor, 2) Forced labor, 3) Fair salary, 4) Working time, 5) Discrimination, 6) Safety measures, 7) Social benefits, legal issues, and 8) Workers rights. The selected categories can be seen as a first selection necessary to identify important and redundant categories for a further reduction and aggregation to a comprised single index. This aggregation step though, is not part of this case study.

Next, for the assessment of human rights, indicators from the following PSILCA sub-categories are used: 9) Respect of indigenous rights, 10) Industrial water depletion, and 11) Risk of conflicts. Background processes were provided by the PSILCA version 3 database. The life cycle inventories of the case studies are provided in the Supplementary Information in Tables A 3, A 4 and A 5.

2.2.3. LOCAL JOB CREATION AND LOCAL WORKING CONDITIONS QUALITY ASSESSMENT

The local dimension of working conditions in the proposed framework includes both the assessment of employment quantity as well as quality. Existing databases and surveys covering European working conditions quality are interesting for an assessment of the local context. Prominent examples are the OECD job quality framework [45], which measures earnings quality, labor market security, and quality of working environment on a country level. The European Job Quality Index proposed by Leschke and Watt [46] combines data of several sources to an aggregated index on country level. This provides not enough information to suggest the impact of different job profiles.

The EU Labor Force Survey records detailed household data including job characteristics such as professional status, working hours, overtime, and education. The European Working Conditions Survey [44] elaborates on quality criteria of working conditions such as work intensity, working time quality, social environment, and prospects. The PSILCA database used in the assessment of global working conditions includes indicators that are also relevant for the local dimension, such as working time and occupational safety. However, all these databases aggregate information on sector level or use a condensed occupation classification that does not provide enough detail to differentiate between local jobs within the energy sector. For the assessment for energy technology cases, a more differentiated measure is needed to cover quality characteristics of specific job profiles within the energy sector.

For this reason, an original measure of working conditions quality is proposed here, consisting of the absolute number of jobs created and working condition quality criteria based on the OECD job quality framework [45].

First, the number of created jobs for energy projects is quantified using employment factors (EF) as proposed by Rutovitz et al. [59]. Temporary and stable employment are quantified using different units. Temporary employment $EF_{tem,\ annual}$ is measured in job-years per MW, where one job-year stands for one year of work for one person. Stable employment EF_{st} is expressed in continuous jobs per MW over the whole lifetime of the plant. To facilitate the comparability of the employment numbers, the temporary jobs measure is averaged over the energy plants lifetime (LT) resulting in EF_{tem} in jobs/MW, see (1). The total employment factor is the sum of stable jobs and temporary jobs both expressed in jobs/MW, see (2).

$$EF_{tem}[jobs/MW] = \frac{EF_{tem,annual}}{LT} \tag{1}$$

$$EF_{total}[jobs/MW] = EF_{tem} + EF_{st} \tag{2}$$

Rutovitz et al. [59] provide employment factors for different energy technologies based on the average situation in the OECD member countries. In order to adjust that OECD average to the labor market situation in specific countries, Rutovitz et al. [59] propose the use of adjustment factors, see (3).

$$EF_{total,country\,X}[jobs/MW] = \frac{GDP_{OECD} \,/\, E_{OECD}}{GDP_{country\,X} \,/\, E_{country\,X}} * EF_{total,OECD} \tag{3}$$

Here *GDP/E* stands for the average labor productivity calculated with the gross domestic product (GDP) divided by the total number of employment (E) in this economy.

Second, the assessment of working conditions quality is done on the basis of the involved job profiles. The OECD job quality framework [45] proposes the evaluation of employment using criteria for earnings quality, labor market security, and quality of the working environment. The aim is the approximation of these criteria at the level of single job profiles using the following indicators: Salary S is used as indicator for earnings quality and is expressed in EUR/year gross annual income. Education level ED is assessed with reference to the European Qualifications Framework and accordingly expressed in EQF levels between 1 to 8 [60]. An occupational risk (OR) indicator is used to quantify the quality of working environment by providing a categorization in three levels; 1 high risk, 2 medium risk and 3 low risk. Additionally, the ratio of temporary to stable jobs can be considered an indicator for labor market security. Temporary jobs are considered in relation to the plant's lifetime, see formula (1), and have less weight in the total employment factor as their contribution to labor market security is lower.

A weighted average over several job profiles *i* is calculated. The relevance of each job profile for the installation, operation and maintenance of the energy plant is expressed as weighting factor, either W_{tem} or W_{st}, in relation to the proportion of total of temporary and stable jobs created, as can be seen in (4), (5), and (6) respectively.

$$S_w = \sum_{i=1} S_i * \left(W_{tem,i} * \frac{EF_{tem}}{EF_{total}} + W_{st,i} * \frac{EF_{st}}{EF_{total}} \right) \tag{4}$$

$$ED_w = \sum_{i=1} ED_i * \left(W_{tem,i} * \frac{EF_{tem}}{EF_{total}} + W_{st,i} * \frac{EF_{st}}{EF_{total}} \right) \tag{5}$$

$$OR_w = \sum_{i=1} OR_i * \left(W_{tem,i} * \frac{EF_{tem}}{EF_{total}} + W_{st,i} * \frac{EF_{st}}{EF_{total}} \right) \tag{6}$$

For wind energy cases, Rutovitz et al. [59] provide employment factors for OECD countries for offshore and onshore wind that are converted to the Belgian case using formula (3) with GDP and employment values of 2019 [61,62]. The inventory of job profiles can be found in Supplementary Information in Table A 6.

2.2.4. LOCAL RESIDENTIAL LIFE QUALITY AND LANDSCAPE QUALITY IMPACT ASSESSMENT USING LOCAL IMPACT PERCEPTION SURVEYS

The objective for the assessment of the local quality of life and landscape quality impacts is to incorporate the specifics of the affected population. Therefore, subjective measures are preferred in the presented social impact assessment framework. Other methods, such as Hedonic pricing [63], GIS simulation [64], and development of specific aesthetics indicators [65] provide an objective measure of the living environment and landscape disamenities, but do not account for the affective dimension of public attitudes.

Although, most prominently discussed in connection with wind energy [31,66,67], the experienced impact on the living environment and landscape quality is relevant for all energy technology projects to explain and predict public opposition [68,69]. Moreover, the proximity of projects has to be considered as a potential influence factor on attitudes and is discussed as

NIMBY behavior, where the attitude towards a close-by project is considerably worse than the general positive attitude towards the technology or development project would suggest [68]. NIMBY is frequently investigated although the results are ambiguous with studies now pointing out that a NIMBY reaction alone is too simplistic to explain attitudinal positions [70,71]. Devine-Wright [71] proposes that public opposition can be traced back to the disturbance of landscape attachment rather than being a function of proximity. As experiences and perceptions play an important role for public acceptance [72], public participation activities were found to reduce mistrust and provide information where there might be wrong perceptions [73]. Studies also show that the familiarization with changing energy landscapes through first-hand experience or e.g. photo simulation, can ease public opposition [74]. As the importance of personal experiences is highlighted in literature, subjective measures for residential life and landscape quality impact are recommended in this social impact assessment framework to provide a realistic representation of how the public receives and lives with different energy technologies.

For the wind energy cases, perception surveys were conducted to assess the subjective impact on local residential life quality and landscape quality. The survey for the offshore wind case was conducted at the Belgian coast close to several offshore wind parks (n=200). The data was collected in face-to-face interviews between August and September 2019 using a standardized questionnaire. The survey location is close to a well-developed area of the Belgian Part of the North Sea where at the moment of the survey six wind parks were operational. The wind parks are located approximately 30km distance from shore and the wind turbines are visible on clear days as well as their lights during night.

The survey of the onshore case was conducted close to a wind park in East Flanders (n=200) in the time period from January to April 2020. The data was collected in a hybrid mode of face-to-face interviews and online survey, which was distributed via a specialized newsletter and subsequently filtered to include only participants living in the target area. Participants were sampled in municipalities located in the vicinity of one of oldest Flemish wind parks. The characteristics of the survey design are summarized in the Supplementary Information Table A 7.

The used questionnaire was designed for surveying and comparing experiences related to power plants and was tested in different energy neighborhoods [69]. The surveys were conducted in Dutch and a translated version of the used questionnaire can be found in the Supplementary Information Table A 8. For the evaluation of local residential life quality, survey participants were asked for the level of disturbance due to noise and due to increased traffic. The landscape impact was assessed in three categories that are based on the principle of cultural ecosystem services as put forward in the Common International Classification of Ecosystem Services CICES [75]. These qualities of landscape are recreation, aesthetic experiences, and personal attachment. The results are presented as arithmetic means of several question items for each of these three fields.

The sample was corrected using post-stratification weights in order to be representative for the actual demographic characteristics of the region of Flanders. Gender, age, and education level were adapted in the samples. Moreover, the onshore wind sample needed to be corrected to avoid a undesired concentration of participants being part of an energy cooperative which was observed in that sample. The weights were determined using iterative proportional fitting according to Lumley [76]. Supplementary Information Table A 9 shows the stratified distribution of characteristics in the samples.

In the samples no significant difference between the people living in direct line of site of wind turbines and people living further away was detected. Therefore, the presented average evaluation is representative for the population living in the general region.

3. RESULTS AND DISCUSSION OF THE SOCIAL LIFE CYCLE IMPACT ASSESSMENT FOR THE WIND ENERGY CASE

The proposed social impact assessment framework results in a dashboard of social indicators, which is presented in section 3.5. The dashboard combines the results coming from four different assessment methods. Analogue to the description of the methods in section 2.2.1 to 2.2.4, the partial results are presented and discussed separately in the following sections. As basis for the result discussion of the life cycle methods (for human health, human rights and global working conditions impact assessment), the life cycle inventory was analyzed prior to the impact assessment.

Figure 5 shows the weight share of materials required along the life cycle of the wind energy cases. The main difference between the types of materials required for the offshore and the onshore cases lies in the composition of the foundations. While in the onshore cases around 70% of the weight share can be allocated to concrete for the foundations, the offshore wind project uses a steel monopile foundation. Although, the offshore foundations thereby have a lower share in the total life cycle inventory, the provision of steel and the installation of the offshore foundation is more resource-intensive. In total, the offshore case requires only 51.2 kg of materials per MWh energy produced, in contrast to 175.7 kg/MWh for the onshore case using a PMSG and 166.4 kg/MWh for the onshore DFIG. This points at the higher efficiency of offshore wind energy production when considering only the weight of required materials per generation site. A comparison of the specific weight of the wind turbines without foundation and infrastructure shows similar results with 30.0 kg/MWh for the offshore case and 43.8 and 47.1 kg/MWh for the onshore case using a PMSG or DFIG respectively. The permanent magnets used in the turbines constitute a negligible share of the total weight, but PMSG turbines have the known benefit of having a smaller specific weight than turbines using a DFIG. PMSGs therefore contribute to material use efficiency. Sections 3.1 and 3.2. present the results of the social life cycle impacts assessment and provide a more detailed analysis how the use of permanent magnets and the according change in the turbine configuration impact the performance of the wind energy cases for different social indicators.

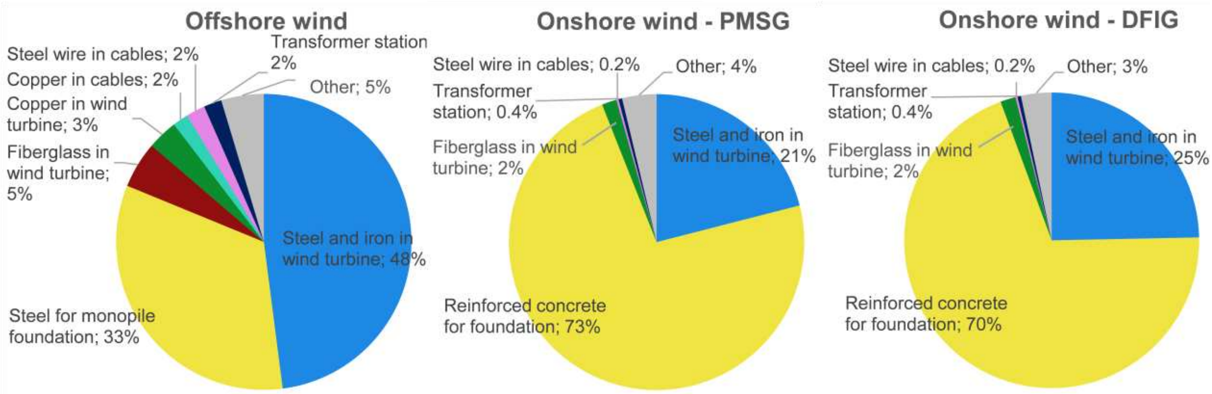


Figure 5. Relative weight share of materials required along the life cycle (excl. end-of-life) of the three wind energy cases

The life cycle inventory was also analyzed focusing on the total cost per material category, as this is required for the assessment of supply chains according to the PSILCA method. The analysis of the economic inventory showed that the concrete foundation is of less importance for the total material supply while the use of permanent magnets and electronics now have a visible share as these components have higher specific cost. The shares of materials per total cost per material can be found in Figure A 1 in the Supplementary Information.

3.1. HUMAN HEALTH IMPACT

The human health impact of the wind turbines was quantified based on the emissions associated with the provision of materials and energy along the whole life cycle. ReCiPe2016 [51] characterization factors were used. Table 3 and Figure 6 show the results of the impact characterization for the investigated life cycles. The results of the global and local human health impact assessment show a different ranking of the wind cases. Due to a high material demand for the construction of foundations, the offshore case shows the highest global human health impact. For the local human health impact assessment, the onshore PMSG turbine shows the highest result, which can be traced back exclusively to the amount of fuel needed for the use of building machinery.

Both for the global and local assessment, the onshore PMSG turbine is more impactful than the DFIG counterpart. Although the PMSG turbine requires overall less material than the DFIG counterpart, the human health impact of the onshore PMSG case is higher. The result can be attributed to the high use of copper. Copper mining is associated with the handling and treatment of toxic tailing and in this case outweighs the overall lighter construction of the PMSG. The use or non-use of permanent magnets plays a negligible role in the bill of materials and the human health assessment.

Table 3. Human health impact of wind energy case studies in Disability Adjusted Life Years (DALY) per TWh.

Impact category	Unit	Offshore wind	Onshore wind - PMSG	Onshore wind - DFIG
Global human health impact	DALY/TWh	35.9	33.3	32.4
Local human health impact	DALY/TWh	0.635	0.704	0.637

The global human health impact is mainly determined by processes required for the manufacturing of the wind turbine components. Only considering the impact related to the wind turbine itself, the impact per TWh is comparable for the offshore and the onshore PMSG wind turbine, with 24.92 and 24.95 DALY/TWh respectively. The comparison of the pro rata contribution of components for the three wind energy case studies shows that in the offshore case the foundation and the copper present in connection cables (between the turbine and the transformer station and to the shore) adds a large part to the final impact value. Although the offshore wind turbine can provide more electricity to the grid, the high weight of the offshore foundation and the network connection to the shore eliminates this advantage. The main influencing factor is the weight-to-electricity-generation ratio.

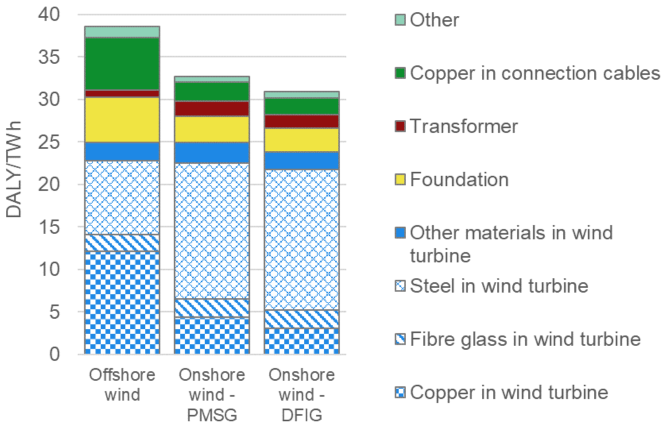


Figure 6. Global human health impact of wind energy case studies

With regard to the local human health impact, the assessment shows that the offshore wind case has a smaller impact on the local population per TWh electricity produced. Health-relevant local emissions, such as particulate matter or nitrogen oxides are generated during the combustion of diesel fuel to operate building machines during the installation phase of the wind turbines. Although the installation of an offshore wind farm needs more fuel than for an onshore case, the specific impact of the first is less, again due to the high efficiency of offshore electricity generation.

The SLCA for the assessment of human health is the most advanced of the four investigated methods as its development benefited from existing emission models and inventory databases established for ELCA. A shortcoming of the human health assessment is that a differentiation between global and local human health impact is rarely done. The ReCiPe method provides an impact quantification based on generalized population and exposure data. To provide a more accurate assessment of the local impact specific for the Flemish population conditions, spatially-differentiated characterization factors were used when possible. For the human health impact of particulate matter emissions, regionalized characterization factors were applied. Due to a lack of local characterization factors for the local human toxicity impact, generalized factors were used. Further research in the area of regionalized impact models is needed. Moreover, further regionalization should also account for the impact of local air pollution at the sea. For the case study of offshore wind energy, the same intake fractions as on land were used under the assumption that the wind pushes the emissions towards the populated coast. A more specialized model for population exposure in affected coast cities is required. In this case study particulate matter emissions were found to be the most prominent emission with impact on the local population. As local characterization factors were available for this emissions impact, the overall results of the local assessment were considered robust. However, for the expansion to other energy technologies, additional local characterization models need to be investigated.

Going beyond the impacts due to emissions, energy technologies involve potential safety risks to human health, e.g. due to accidents. The LCA would need to be extended to cover more human health risks, e.g. by incorporating data collected in the Energy-related Severe Accident Database [77]. The database registers historical accidents along the supply chain of energy carriers and technologies and based on that provides a safety risk quantification on a global level. While safety risks of workers along the wind energy supply chain are incorporated in the assessments of global and local working conditions, the safety risk for the general population can be a topic for further research.

3.2. HUMAN RIGHTS AND GLOBAL WORKING CONDITIONS COMPLIANCE

The risk of working conditions and human rights conditions infractions along the life cycle of material use was assessed using the PSILCA method. The risk quantification according to PSILCA compiles risk values based on two components of the material inventory: the risk level assigned to countries and sectors of material origin and the economic value of the material as weighting factor for the relevance of the risks in the complete life cycle. Table 4 and Figure 7 show the calculated risk values of the life cycle models. The results showed a clear order for the investigated wind cases in all the impact categories. The supply chain of the offshore wind technology is associated with significantly higher risks of infractions than the supply chain of the onshore technologies. This can be attributed to the high material demand to provide the offshore foundation, requiring a high amount of steel. The offshore wind turbine alone, not considering the foundation, performs better than the onshore alternatives in many impact categories. This can be attributed to the higher electricity yield of the offshore wind turbine while the specific material demand is comparable for all cases. The contribution of permanent magnets to the overall risk is low, as can be seen in the comparably close results of the two onshore alternatives. Permanent magnet use comes with a high risk for severe working conditions in Chinese mines and processing plants. However, in the PSILCA characterization the use of steel or copper (e.g. sources in South African or Congolese mines) is assigned a comparable high risk level and is needed in much greater amounts than the magnets. The additional risk of the magnets therefore is of little consequence for the social risks presented here. Although the PMSG wind turbine in total required less material to provide 1 MWh of electricity, the social impact is larger in most impact categories due to the higher proportions of copper (e.g. risk of child labor in Congolese mines) and electronics (risks in Chinese electronics processing plants) than in the DFIG. This means that in the PSILCA characterization model the absolute material demand and countries of origin are of more relevance for the risk quantification than the type of material. Conflict-ridden raw materials in the supply chain will therefore not automatically be identified as social hotspot, in particular if the weight share of the materials are small.

Moreover, the provided sector classification in PSILCA is quite generic, which was especially observed for the mining sector where a differentiation between the mining of different ores was often not possible. A too generic sector classification cannot appropriately represent the potential risks involved, e.g. the illegal mining of conflict materials that per definition is done under nontransparent conditions.

Table 4. Risk of human rights and working conditions infractions for wind energy case studies. The higher the values are, the higher the risks are.

Impact category	Offshore wind [med risk hrs* per MWh]	Onshore wind - PMSG [med risk hrs* per MWh]	Onshore wind - DFIG [med risk hrs* per MWh]
Global working conditions			
Child Labor, total	6.5	3.0	2.3
Frequency of forced labor	0.2	0.1	0.05
Fair Salary	38.8	26.5	23.6
Weekly hours of work per employee	0.9	0.5	0.5
Gender wage gap	2.6	1.1	1.0
Safety measures	0.5	0.2	0.2
Social security expenditures	9.6	5.0	4.4
Association and bargaining rights	18.6	12.8	8.3
Human rights conditions			
Indigenous rights	0.7	0.4	0.3
Industrial water depletion	5.5	3.7	3.3
Risk of conflicts	4.2	1.9	1.6

* medium risk hours. The risk values are specific to the respective risk category and not comparable between categories

Figure 7 shows three exemplary impact categories and the distribution of risks according to the material categories. The complete results for all impact categories can be found in the Supplementary Information in Table A 10. Due to the large share of steel in all technologies (82 to 89% of the total weight), it is the largest contributor to overall risks regarding child labor, insufficient safety measures and infractions of indigenous rights. The mining and processing of copper is also a large risk contributor, in spite of copper having only a small percentage by weight in the total installation. Another large contributor with small weight share is electronic equipment that is produced in China. Although the distribution between the material categories is quite similar, e.g. for risk of child labor and risk of indigenous rights infractions, the contributing country-specific sectors are different depending on the impact categories. While for working conditions high risks are associated with China and South Africa, as origin of iron and steel products, the risks for support of national conflicts originate mostly from materials imported from Turkey and Ukraine. In all categories, the sourcing of copper in the Democratic Republic of the Congo comes with a high risk of infractions.

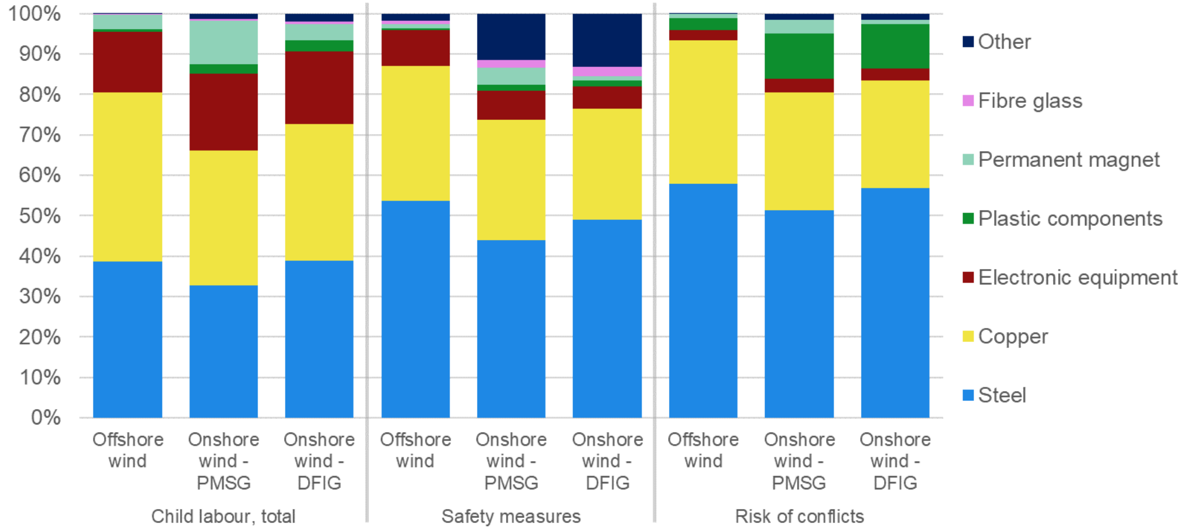


Figure 7. Relative risks of infractions per material category

The PSILCA method is well equipped for identifying social hotspots along the supply chain. The various impact categories contribute to a full understanding of working and living conditions in supplier countries. To contribute to the operability of PSILCA results in a broader social or sustainability assessment, the aggregation into one risk indicator, e.g. aggregating the eight working conditions indicators, should be considered. A possible aggregation strategy is the reduction of the number of assessed impact categories by summarizing categories with comparable risk levels, e.g. sectors with high risk of child labor usually also show a high risk for inadequate occupational safety measures. Such a strategy would provide a reduced set of indicators and would prevent that one category compensates the bad performance of another, which would be the case in simple weighting approaches. As such an approach requires further investigation of sector-specific data, more research is needed in order to come to a standardization that allows the comparison across independent studies.

3.3. IMPACT ON LOCAL JOB CREATION AND WORKING CONDITIONS QUALITY

For the assessment of local jobs and working conditions, the three wind energy cases are reduced to two, according to the affected sites: the offshore case and the onshore case. It is not feasible to differentiate between the type of onshore generator technology as is done for the SLCA of human health, global human rights, and working conditions. The effort needed for the local installation and operation and maintenance (O&M) is assumed to be the same for the two types of onshore wind turbines.

The local employment effect of offshore and onshore wind energy can be divided between temporary employment during the installation of the wind turbines and continuous/stable employment in O&M. Table 5 presents both temporary and stable jobs averaged over the plant’s lifetime based on Rutovitz et al. [59] and corrected according to formula (3).

While offshore wind generates more jobs during the installation phase, onshore wind is more labor-intensive in O&M. The difference is visible in the employment factors provided by Rutovitz and colleagues [59], i.e. 0.15 and 0.23 jobs per MW in O&M for offshore and onshore wind respectively. The difference is even more pronounced considering the electricity output per MW for the two locations, i.e. 38.0 and 84.5 jobs per TWh in O&M.

The distribution of job profiles, as laid out in Figure 8, was used as weighting factors to calculate performance benchmarks for salary, education level, and occupational risk. The weighted averages can be found in Table 5. The average salary is higher for the offshore case while required qualification is on average lower and occupational risk higher.

Table 5. Local job creation and average local working conditions quality of wind case

Impact category	Unit	Wind offshore	Wind onshore
Local employment temporary	jobs_{tem}/TWh	76.1	45.1
Local employment stable	jobs_{st}/TWh	38.0	84.5
Weighted average salary	EUR/a	59,229	53,495
Weighted average required qualification	European Qualification Framework level	4.5	5.2
Weighted average occupational risk	Score in 1: high risk to 3: low risk	1.2	1.8

To explore the differences between the wind cases, Figure 8 shows the distribution of temporary and stable employment and the required job profiles. The distribution of job profiles was obtained based on the given employment factors and IRENA reports [78,79] on human resources requirements. The figure shows that in the offshore case a large share can be attributed to offshore personnel in the installation phase (50.4%) and also during O&M (10.0%). A comparable profession for the onshore case would be construction workers in the installation phase (26.8%). The distribution of stable O&M job profiles is similar for both cases with the majority being wind technicians followed by personnel for monitoring and administration of operation. The offshore wind case shows a high reliance on offshore personnel such as pilots for ships and helicopters, crane and machine operators on ships and offshore platforms. Due to the strenuous working conditions and high occupational risks, these jobs are better paid than equivalents in onshore environments while a lower level of formal education is required. This explains the higher average salary and higher average occupational risk for the offshore wind case as presented in Table 5.

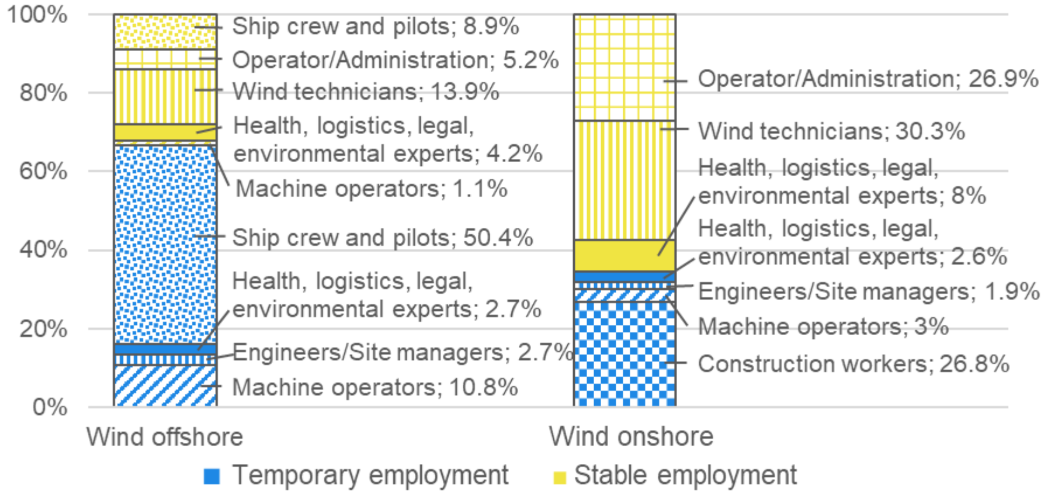


Figure 8. Relative distribution of job profiles required for offshore and onshore wind application

While employment generation due to growing renewable energy sector is well covered in literature, there are few attempts to define job quality [80]. Literature shows that employees evaluate job quality in industries with green business practices not automatically as better than for conventional industries. Depending on the industry, job quality can also be worse, e.g. due to the missing skill development for new technologies or less representation by unions and collective agreements [81]. A unique approach that considered both quantity and quality of energy-sector based jobs is proposed by Llera Sastresa et al. [82]. They used quality factors to compare renewable energy jobs in Spain and found quality differences between wind power and solar applications. The quality factors were calculated based on the attributes of jobs in the different development stages of energy facilities, while the approach presented in this paper aims to provide more detail by assessing quality per job profile. The results in Table 5 show that there are clear differences between the type and number of jobs only looking at the wind energy sector. The assessed quality criteria can still be extended to offer a more complete picture of working conditions quality in the European context. For example subjective measures such as criteria considered in the European working conditions survey [44] could be included to incorporate employer-specific benefits as well as subjective benefits of actually working in a sustainable industry.

In this assessment, local jobs were defined as being located at the wind turbine site or during operation and maintenance. But with the number of wind energy installations rising, administrative jobs in planning and operation of wind parks might be conducted by centralized operators that are located outside the immediate neighborhood or even the larger region and might not be considered “local”. In a small country with extensive road infrastructure and a mobile population like Belgium, it is especially challenging to delimitate what is still considered locally added value. Decision-makers have to be aware of the specific situation in the region and if necessary, adapt the used employment factors.

3.4. LOCAL RESIDENTIAL LIFE QUALITY AND LANDSCAPE QUALITY IMPACT

To provide insights regarding the impact of wind turbines as they are perceived by the local population, data from population surveys was analyzed. Table 6 shows the valuation of the participants regarding the residential quality impact. Table 7 presents the perceptions of landscape quality impact in three categories. The presented values are arithmetic means of several topical questionnaire items, see Table A 8 (Supplementary Information) for the exact question wording. The surveys showed that disturbance levels due to noise and increased traffic were rather low in these populations, as also reported by Buchmayr et al. [69]. Due to the distance of the offshore wind park to the shore, noise impacts were evaluated significantly lower than for the onshore alternatives.

Also in the subjective evaluation of landscape quality, the offshore wind park was evaluated as less impactful with regard to aesthetics, recreational value and the individual connection to landscape, see Table 7.

Table 6. Population evaluation of impact of noise and increased traffic for wind energy case studies

		No impact (1) **in %**	**Somewhat negative (2)** **in %**	**Negative (3)** **in %**	**Very negative (4)** **in %**	**Mean***
Disturbance due to noise	Onshore wind	48	20	19	12	2.0
	Offshore wind	93	4	3	0	1.1
Disturbance due to increased traffic	Onshore wind	70	24	3	3	1.4
	Offshore wind	76	15	7	2	1.4

*on a scale from 1 no impact to 4 very negative impact

Table 7. Population evaluation of landscape quality impact for wind energy case studies

		Strongly disagree (1) **in %**	**Disagree (2)** **in %**	**Neutral (3)** **in %**	**Agree (4)** **in %**	**Strongly agree (5)** **in %**	**Mean***
Negative impact on attachment and feeling of belonging	Onshore wind	19	33	28	12	8	2.6
	Offshore wind	22	48	14	13	3	2.3
Negative impact on aesthetic value	Onshore wind	7	15	27	30	20	3.4
	Offshore wind	8	38	16	30	8	2.9
Negative impact on recreation	Onshore wind	22	24	32	11	12	2.7
	Offshore wind	27	47	10	12	4	2.2

* on a scale from 1 very positive impact to 5 very negative impact

The surveys provide a snapshot in time and specific locations for attitudes towards wind energy but they are the most direct way to assess experienced impact. With regard to wind energy, a number of studies were conducted to describe and explain attitudes of the population. Especially landscape quality impact depends strongly on the personal significance of the landscape for the population [71]. Acceptance and perceptions change with time [83] and level of engagement [84].

A Cultural Ecosystem Services approach proved valuable for quantifying aspects of landscape impact. Moreover, these results will be valuable to complement the ecosystem services assessment of energy landscape with a quantified impact assessment where other studies relied on a qualitative description of cultural impact, e.g. see Picchi et al. [66].

3.5. THE SOCIAL SUSTAINABILITY DASHBOARD

The comparison of all impact categories showed that the offshore wind system was the most impactful for the categories reporting impacts on global well-being (assessed using SLCA methods). These results can be attributed to the high material demand needed for offshore foundations and infrastructure. The SLCA methods used for the assessment of global human health impacts, and for the risk assessment of infractions regarding working conditions and human rights standards, build upon the impact characterization on the basis of material and energy flows. The type of materials used is decisive for the comparison of very similar technologies, such as the two onshore wind turbine models. The PMSG onshore wind turbine requires less material to provide 1 MWh of electricity than the DFIG counterpart, but the social impact of the PMSG turbine is larger in most impact categories due to the higher share of copper and electronics. The use of permanent magnets, although seen in literature as problematic due to the supply concentration in China, does not add much additional risk in this case. The weight share of the permanent magnets is too low to be of significant consequence.

For the local assessments, the offshore wind case showed to be more preferential for many of the impact categories. Locally generated emissions are limited to the burning of fuels during the installation phase of the wind turbines. The local human health impact showed to be less severe in the offshore case than for onshore cases due to the higher efficiency of offshore turbines, i.e. high electricity output per installation. Also in terms of local life quality and landscape quality impact, the offshore case was reported to be less impactful than the onshore counterpart. The jobs created in the offshore sector require on average a lower education level, have a higher occupational risk but are also better paying.

Figure 9 shows the results of the discussed assessments in the form of a social sustainability dashboard. Note that the values were normalized so that the case with the largest is always displayed as 100% at the right of the dashboard. The other results are shown relatively to the largest value. The indicators used for the majority of categories display negative impacts, meaning the case with the largest value has the worst negative impact. However, indicators used for quantifying local employment and local working conditions display beneficial impacts of the energy cases, meaning the largest value stands for the highest benefits. Accordingly, the dashboard was split into 2 sections: The first section shows negative impacts on a scale starting from the absolute best value on the left (e.g. no impact) to the value of the worst case from the three wind energy cases. The absolute best value is for most of the impact category 0, i.e. zero health impact or zero risk. The second section shows benefits on a scale from minimum benefits to the maximum value, being the best case. For the indicators quantifying local working conditions quality, i.e. average salary and average required qualification level, it was not applicable to use zero as starting point of the scale. Therefore, the boundary values were chosen based on the inventory of job profiles involved in the wind energy cases. The scale thereby reached from the salary of the lowest paying job in the inventory (i.e. 40,340 EUR/a) as worst value to the value of the best case, i.e. the offshore wind case. The same systematic was also used to choose the scale for the indicator related to the qualification level.

The dashboard allows the comparison of 23 social impact categories next to each other. This large number of indicators presented in the dashboard comes with the disadvantage that a general judgment of the best or worst case is often challenging. Decision-making could be simplified by either a reduction of assessed indicators or the aggregation to an index. Both options would mean that information is lost for the decision-maker. Moreover, aggregation always includes some kind of weighting of impact categories. Weighting and aggregation usually compromise the notion of strong sustainability where weak performance in some impact (sub-)categories can be compensated through good performance in others. To provide decision-makers with the full information about social impacts, we propose the use of the full social sustainability dashboard.

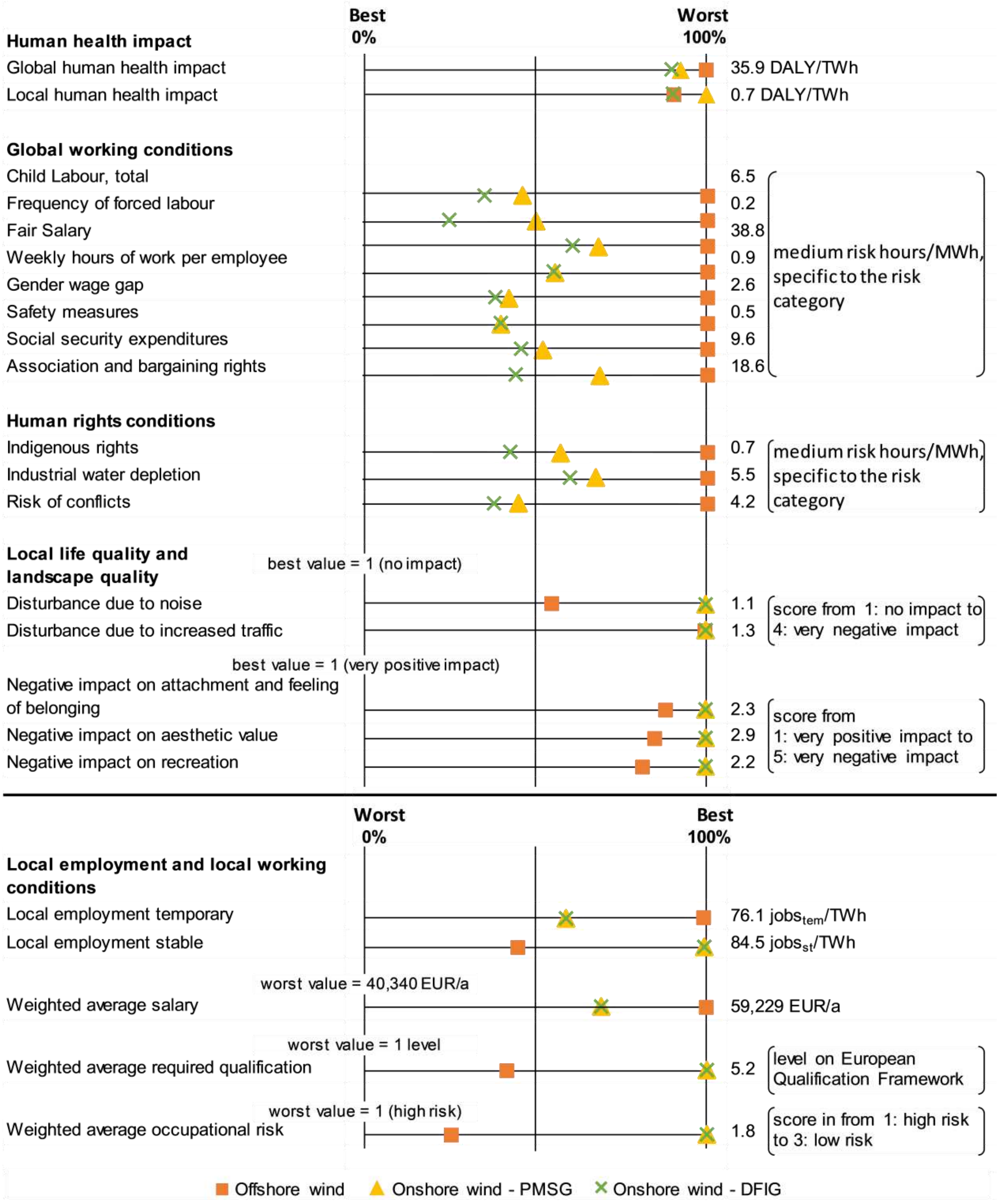


Figure 9. Social sustainability dashboard for the three wind energy cases. In the section on the top, the case with the most negative impact or highest risk is displayed on the right side of the scale and constitutes 100%. In the section on the bottom, the case with the highest benefit constitutes 100%.

4. CONCLUSION

While the literature provides ample evidence of the environmental benefits and implications of different energy technologies, the impacts on society are rarely investigated. Existing social

impact assessments tend to focus on only single aspects, e.g. either human health impact or local landscape quality impact, and not on the issue of overall social sustainability. This paper aims at providing an assessment framework that broadly covers social impact categories in order to contribute to informed decision-making on energy technologies. In order to achieve a comprehensive coverage of the social dimension, both global and local well-being impacts need to be assessed. This paper shows that four distinct social impact assessment methods are needed to cover all relevant social impact categories. These assessment methods are SLCA type I, SLCA type II, job quality assessment, and local impact perception surveys. The usability of these methods in a social impact assessment framework was evaluated through the application to a case study of wind energy technologies.
The results of the case study assessment showed that offshore wind has a greater negative impact on global well-being than the onshore alternatives that are investigated. However, the social risk attributed to permanent magnets and therein required rare earth elements was not found to be decisive in the results presented. In general, the material use efficiency per unit of produced electricity determined the performance of the wind energy technologies in the global assessment and not the use of permanent magnets as these make only a small share of the total weight. In the offshore case, the additional material demand for offshore foundations and infrastructure contributed a significant share to the impacts. Regarding the local impact on the surrounding residential area, the offshore case was preferred. This is not surprising since the activities take place at a large distance from the population and therefore are not perceived as disruptive. The remote location is associated with inhospitable working conditions, as the local job quality indicators showed on average a higher occupational risk and a lower education level for offshore wind energy jobs in comparison with onshore counterparts.

More importantly, this case study highlighted the need for a systematic assessment of social impacts in a combined framework. A range of impact assessments methods are available and show potential for the application in a social impact assessment framework for energy technologies. For example, the SLCA methods ReCiPE and PSILCA make use of the same life cycle inventory but are still at rather different stages of development in terms of the available characterization models. A closer integration of these two methods would particularly benefit the dissemination of the PSILCA method, as the identification of social risks using PSILCA is widely untested for energy case studies at the moment. Further integration is also needed for the assessment of local well-being, which has so far not been systematically included in social impact assessment frameworks. By proposing a characterization method for both the job quality and residential life and landscape quality, the first step for the systematic application in social impact assessments is taken. Especially, the quantification of landscape quality impacts presented a challenge, as the matter of landscape perception and valuation is a subjective one. In order to systematically include subjective impacts into social sustainability assessments, a standardized method of measurement is required. Accordingly, an approach using impact perception surveys to evaluate life quality and landscape quality aspects relevant for energy technologies was applied in this framework.

In the current assessment, the end-of-life of wind turbines and recovered materials was considered out of scope but the material flows after disassembly need to be further investigated in the future. There is a lack of experience with the decommissioning of wind turbines as the majority of commercial wind parks are still operational. Nevertheless, the question of recycling and reuse strategies will have to be answered in the next decade as the first generation of wind parks will then be retired. If recovery and recycling of wind turbine materials takes place in Europe, the risk of new social hotspots is small but as the end-of-life path for wind turbines has not yet been clearly defined, there is a certain risk of old technology being shipped to low-

income countries for material recovering or disposal. Therefore, further research would also contribute to a complete social impact assessment.
The social sustainability dashboard gives a first overview of social impacts and benefits, however, due to the large number of indicators they are not convenient to be used in decision-making. In order to make the results more accessible for decision-makers, first, the number of indicators should be reduced and second, the weighting of different dimensions considered. The definition of weighting factors poses a challenge as weighting always introduces subjectivity. Experts might weight the risk of forced labor or landscape disamenities differently than the general public and again differently than the directly affected public.

As renewable energy technologies are central for the ongoing energy transition, it is necessary to provide more information on the social implication of these technologies. The presented social impact assessment framework and the review of different types of assessment methods contribute to a more holistic consideration of the social impacts of the energy transition. The investigated assessment methods still need to be further developed both with regard to the usability and the integration into sustainability frameworks. Nevertheless, the present study provided an important step to put social sustainability into the spotlight and clear the way for informed decision-making that gives equal consideration to all dimensions of sustainability.

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SUPPLEMENTARY INFORMATION

Supplementary information related to this article can be found at http:// XXXX.

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