The path to sustainable energy supply systems: Proposal of an integrative sustainability assessment framework

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Abstract

Energy supply is essential for the functioning and well-being of a society. Decision-makers are faced with the challenge to balance burdens and benefits of energy supply practices with the aim to achieve environmental, economic, and social sustainability. Literature exhibits a broad variety of sustainability assessment frameworks for energy supply technologies. However, there is no consensus on which aspects need to be covered for a comprehensive assessment of sustainability. While some aspects, such as environmental emission damage, receive predominant attention, there is a lack of coverage and adequate quantification for others. This led in the past to an unbalanced basis for decision-making.

Based on an analysis of literature, 12 impact categories were identified for the assessment of energy technologies. The analysis included the judgement of quantification approaches regarding their significance for describing the impact categories and their maturity resulting in the proposal of 12 concrete indicators. A framework is proposed to manage and integrate the assessment of single impact categories. The framework produces normalized and weighted output indicators to use in the form of a dashboard or alternatively a single sustainability index for informed decision-making.

Finally, the proposed sustainability assessment framework relies on life cycle, local impact, and supply chain risks assessment. It consists of both well-established assessment methods as well as suggestions for new indicators in order to allow a full assessment of all impact categories. It thereby goes beyond the isolated assessment of impacts and offers the basis for comparison of complete energy supply mixes.

Highlights

- Proposal of a novel integrated sustainability assessment framework
- Identification of sustainability impacts with regard to a society’s energy supply
- Holistic coverage of environmental, economic, and social sustainability impacts
- Side-by-side use of life cycle, local and risk assessment methods

Keywords

Sustainability assessment; Life cycle assessment; Local impact assessment; Risk assessment; Energy supply; Energy technology

Word Count

9,997 / 10,000 for review articles

List of abbreviations including units and nomenclature

CBA	Cost Benefit Analysis
CED	Cumulative Energy Demand
CExD	Cumulative Exergy Demand
ELCA	Environmental Life Cycle Assessment
EU	European Union
JRC	Joint Research Council
kWh	Kilowatt-hour
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCOE	Levelized Cost Of Energy
LCSA	Life Cycle Sustainability Assessment
MJ	Megajoule
MW	Megawatt
NIMBY	Not In My Backyard
PSILCA	Product Social Impact Life Cycle Assessment
SA	Sustainability Assessment
SETAC	Society of Environmental Toxicology and Chemistry
SLCA	Social Life Cycle Assessment
UN	United Nations
UNEP	United Nations Environment Programme

1 Introduction

Energy supply practices and energy consumption are substantial contributors to environmental degradation and the major source of greenhouse gas emissions [1]. At the same time, energy is an essential part of modern society and a limited access hinders societal and personal or household development. For good reason, the UN Sustainable Development Goal 7 is dedicated to the provision of “affordable, reliable, sustainable and modern energy for all” [2]. The sustainability term is hereby the hardest to assess.

Concrete goals for the energy sector are directly related to the pledge of the Paris agreement to reduce greenhouse gas emissions and keep global temperature increase below 1.5°C. The EU Member States committed to the transition to a climate-neutral economy by 2050, meaning that the energy sector has to change dramatically in the coming decades [3]. The current practice of energy supply is not sustainable in the long term. The discussion of sustainability is firmly rooted in the notion of intergenerational equity. The Brundtland Report [4] provides the most prominent definition of sustainability as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. To achieve sustainability, it is necessary to consider elements from the environmental, economic, and social dimension in one coherent framework and give all dimensions a similar treatment. Elkington [5] labels this the triple bottom line. These three dimensions are interconnected, meaning that mutual interference has to be considered [6]. It is critical that each dimension is given sufficient attention as well as to be transparent about the balancing and weighting of the dimensions.

The consideration of sustainability needs to be part of every notion of development and is critical for the planning and implementation of an energy transition. It needs to be clearly defined what sustainable energy means, how competing objectives of the triple bottom line can be harmonized, and how to communicate this message to decision-makers. Existing frameworks for quantifying sustainability show no generalized theme and rather rely on individual approaches. A consolidated Sustainability Assessment (SA) framework for energy technologies is needed in order to provide transparency of global, local, and long-term impacts and facilitate informed decision-making.

SA is an umbrella term for a range of methods which are used in combination in order to provide a broader context for decision-making [6]. Hence, sustainability requires a transdisciplinary assessment [7]. Due to the fact that the term sustainability is interpreted broadly, there is not one universally agreed-upon approach for SAs. Assessment methodologies are interlaced and contributions from different fields are constantly evolving. As a result, SAs are increasingly complex [8].

Life Cycle Sustainability Assessment (LCSA) is such a transdisciplinary approach accounting for and aggregating impacts along the whole life cycle. LCSA was first proposed by Kloepffer [9] consisting of a combination of Environmental Life Cycle Assessment (ELCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA). The approach was picked up by others and expanded, e.g. by Finkbeiner et al. [10] who focused on effective communication of LCSA results. Moreover, the joint life cycle initiative of the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) argued to incorporate stakeholders engagement in a holistic assessment of product life cycles [11]. Although the triple bottom line is covered with this approach, the main point of criticism is that the three assessment methods can be performed in isolation from each other without the need to consider interrelations and linkages [12, 13].

Guinee et al. [14] advocated to use LCSA not as a model in itself but as a framework to integrate models of various disciplines to cover all sustainability dimensions. Sala et al. [7] pointed out that life cycle-based methodologies have limits when dealing with complex sustainability issues. Accordingly, it is necessary to go beyond a pure life cycle perspective and expand SA in different thematic fields in order to adequately cover the sustainability term.

For the energy sector, several attempts to quantify sustainability can be found. Dewulf et al. [15] proposed a comprehensive selection of assessment indicators covering the environmental, economic, social, and technical dimension. However, this theoretical framework needs to be adapted specifically for the energy field and the social dimension expanded to cover e.g. public acceptance. Santoyo-Castelazo and Azapagic [16] relied in their approach at large parts on LCA databases covering environmental and human health impact quantification and expanded the sustainability definition by including qualitative data to describe additional social impacts. The aggregation of quantitative and qualitative data, though, remained a challenge. Abu-Rayash and Dincer [17] provided a comprehensive framework with a number of indicators for different sustainability fields. But the high number of indicators comes with the risk of double-counting impacts or involuntary weighting through the accumulation of similar indicators. Hadian and Madani [18] presented a well-integrated SA by using a footprint approach to assess and present aggregated impacts. However, there is a limit to the impact categories that can be assessed using a footprint methodology. Roth et al. [19] and Maxim [20] concentrated on electricity production and the application of their frameworks could be expanded to e.g. the provision of heat energy.

In addition to general SA frameworks, examples are available for SAs tailored to the assessment of one technology or one specific aspect of the energy sector, for e.g. nuclear energy [21, 22], bioenergy [23-25], wind [26, 27], energy planning [28] or for the energy supply of whole cities [29]. The applicability of these frameworks for other fields in the energy sector and their usability for a fair comparison of different energy technologies is unclear and would need further investigation.

It is obvious that there is no standard approach for an energy SA. Three shortcomings of sustainability frameworks are repeatedly pointed out in literature and will be addressed in more detail. SAs differ significantly with regard to (1) the selection of impact categories, (2) the differentiation between life cycle and local impact and (3) the integration of diverse assessment methods. The background regarding these shortcomings is explained below.

Broadening sustainability assessments

There is no consensus on the relevant impact categories to be included for the assessment of energy technologies. Energy assessment literature shows that although sustainability is clearly stated in the objective, the three dimensions of sustainability – environmental, economic, and social – are not equally considered in the criteria selection [30-32]. A consensus on a comprehensive selection of relevant impact areas still needs to be found. At the same time, the coverage of sustainability impacts has to be equally suitable to assess all energy technologies and not introduce a bias towards specific technologies.

Spatial differentiation of impacts

Although an LCA provides – in comparison with local impact assessment – a more complete picture of a product's impact, the methodology typically does not consider the spatial distinction of impacts [6]. This can be considered an advantage which contributes to a fair comparison of products. By considering the whole supply chain, all upstream impacts are accounted for and not only the "visible" local impact. Still, considering a specific territory for the LCA can provide additional details with particular relevance for local decision-makers [33, 34]. Although a number of authors use life cycle and local impact assessment in combination [17, 19, 35], the rationale behind the selection of methodologies is not further discussed. More research is required to propose characterisation factors which would allow spatial differentiation in LCA [6, 36, 37].

Considering the social dimension, certain energy technologies have a public acceptance issue [38-40] which makes it necessary to put the focus on the local dimension. The impact as perceived by the population is an indicator for support/opposition of certain energy technologies [41, 42] and should be considered as part of the social sustainability dimension.

Integrated framework

As the SA is broadened, a framework for energy carriers needs to integrate not only observed and quantified impacts but also risk assessments, hotspot identifications, and qualitative evaluations such as attitudes, depending on the relevant impact areas. Dewulf et al. [15] for example proposed, in their framework for the SA of raw materials and primary energy carriers, the integration of different methodologies such as an ecosystem services approach and a criticality assessment. Grafakos et al. [43] on the other hand concentrated on the integration of resilience indicators into SA.

The integration step is necessary to present a comprehensive framework that considers interrelations between impact categories, rather than applying several assessments in parallel. An integrative framework allows the identification of sensitivities and trade-offs between impact categories.

This is not the first attempt to quantify the sustainability of energy technologies. The objective of proposing yet a new framework is to address the identified shortcomings and come to a reliable and comprehensive assessment for sustainability of energy supply technologies and energy mix options. Accordingly, this research aims to bring order in the wide field of assessment frameworks and proposes an SA framework that can be a point of reference for decision-making. That is decision-making on either single energy supply technologies or whole energy scenarios as defined in EU, national, or local policies. The framework stands out by incorporating methods of various disciplines which will be tailored for the assessment of sustainability aspects of energy supply. The sustainability aspects need to be valid and meaningful for all energy technologies in order to allow a fair comparison.

2 Methodology

The research methodology is presented in Figure 1. The different phases of the SA framework development correspond to the previously defined research gaps.

First, the scope of the SA framework was outlined, including the definition of system boundaries and of the functional unit, following the recommendation of ISO 14040 which refers to LCAs but is also applicable for the SA presented here. A clear definition of system boundaries is needed in order to judge which impact categories are relevant for the presented framework.

The identification of relevant sustainability impacts was based on an analysis of literature. Literature reviews with a comprehensive analysis of sustainability impacts or indicators already exist [30, 31, 44]. Rather than duplicating these, their results were substantiated by analyzing the most recent additions of the last 10 years. It was the aim to analyze assessment approaches which are valid for all energy carriers rather than ones that are tailored to one specific technology. The available reviews did not specify this issue in their analyses. Accordingly, the focus was on recent literature presenting approaches on SA of whole energy systems or for a range of energy technologies. The reviewed literature thereby was taken from the years 2009 to 2019 and concentrated on the keywords “sustainability”, “assessment” and “energy” or “electricity” respectively.

Of the original sample of 156 studies, 32 were chosen for a detailed analysis as these provided concrete sets of criteria for a range of energy carriers – studies concentrating on one specific technology or case study were excluded. The sample also included three review studies which provided a list of the most frequently used indicators. The analysis aimed at covering all relevant areas of sustainability. The frequency of named indicators was of secondary importance.

The identified assessment criteria, with the same underlying cause, were grouped into impact categories. The impact categories were found in an iterative process and judged against a set of principles in order to ensure their applicability for an assessment framework. The chosen principles are consistent with the literature on the evaluation of sustainable development progress [45-47] and sustainability indexes in general [43, 48]. The following principles were applied:

- Relevance: The categories have to be relevant regarding the objective of the decision-making process and considering the established system boundaries. The impact categories need to be suitable to describe a specific impact of energy supply and be meaningful for all energy supply technologies.
- Measurability and comparability: Impact categories should be describable by indicators with quantitative values as far as possible or through qualitative description. These indicators need to be applicable to all energy technologies to ensure comparability.
- Sensitivity: Impact categories have to be sensitive to changes in the set-up and to alternative scenarios.
- Independence: Impact categories should describe independent root causes and suggest no overlaps.

A subsequent literature analysis reviewed concrete indicators and calculation models used for the quantification of the impact categories in order to move from a set of abstract categories to a calculation framework. The identified quantification methods were judged according to their maturity in order to determine their applicability for the framework.

The last step is the integration of the set of individual assessments in a holistic framework. This includes the definition of normalization, weighting, and aggregation requirements for the handling and computation of results per category.

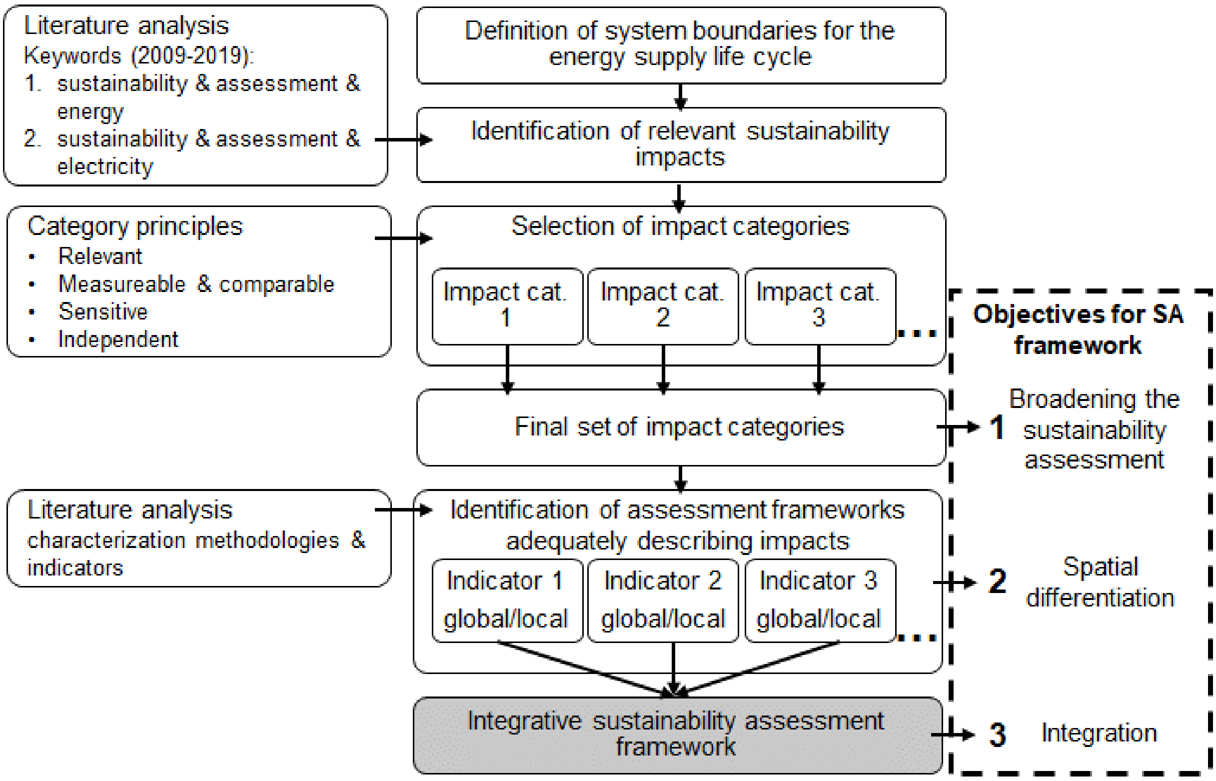


Figure 1: Scheme of research methodology

3 Constructing the sustainability assessment framework

3.1 Energy supply life cycle and system boundaries

Including a life cycle approach is of paramount importance for an SA as it allows to comprehensively capture the impacts of the system. ISO 14040 states that an LCA has to start with a clear definition of the goal and assessment scope. Accordingly, Figure 2 illustrates the energy supply life cycle and outlines system boundaries for the impact assessment. Moreover, the differentiation of these life cycle stages in the assessment process facilitates the spatial differentiation of impacts, which is missed in most LCAs.

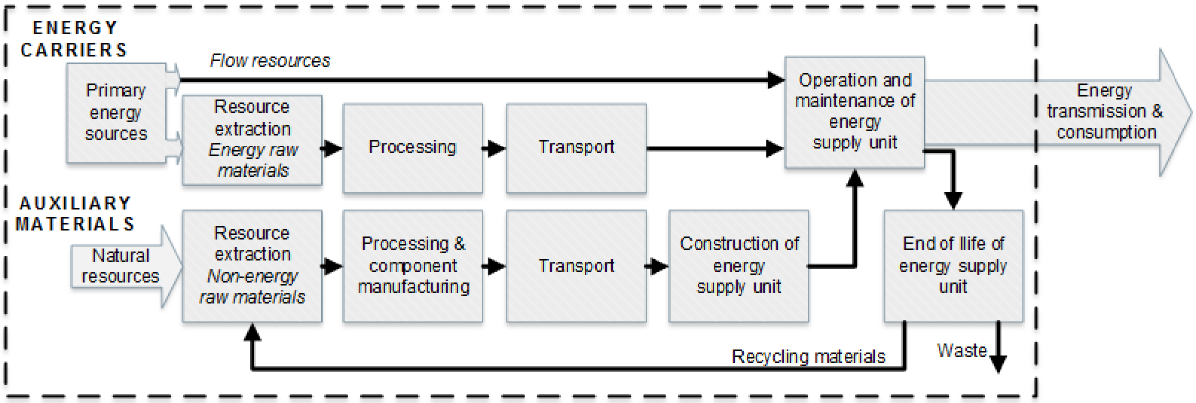


Figure 2: Life cycle of energy supply technologies

The life cycle in Figure 2 is applicable to large and small scale energy supply. The depicted process consists of two essential process lines coming together at the energy supply unit, for example a power plant. One process line focuses on energy carriers while the other one focuses on auxiliary raw materials. The latter will be in particular relevant for the case of renewable energy from flow sources, such as wind or solar irradiation, where the energy carrier line not applicable.

Cradle-to-grave approach

The reference parameter of the assessment – in an LCA methodology commonly called the functional unit – is a unit of energy (e.g. 1 kWh electricity or heat) provided at the outlet of the energy supply unit. The energy supply unit can be a centralized power plant, a decentralized individual production unit such as a solar panel, or a hybrid system between the two former categories. In the case of the centralized energy supply, the system boundary is at the connection point to the energy grid and the supplied energy is subject to further transformation and transmission processes. These processes are not considered in this SA. Neither are losses at end consumer level considered.

A cradle-to-grave approach is applied, wherein the focus lies on energy supply units and not on the provided energy itself. This means that the sourcing, transport, use and end-of-life of energy supply technologies are considered. Transmission and end-use of the provided energy, on the other hand, are out of the scope of this assessment.

The requirement on natural resources in these two lines is quite different depending on energy fuel in question. Swart et al. [49] classified natural resources into funds, flows and stocks. Stocks are depletable resources, funds can be depleted but have a defined renewal rate, and flows cannot be depleted. In the first life cycle phase, natural resources play a role as energy carriers and as materials needed for the construction of power plants. As energy carriers which originate from flow resources (e.g. wind, solar, hydro) have no need for conventional fuel extraction, the assessment will be limited to the extraction of auxiliary raw materials in these cases.

3.2 Sustainability impacts of energy supply

The analysis covered 32 sustainability studies on energy supply technologies – 29 assessment studies and three quantitative literature reviews – and focused on the identification of appropriate impact categories. Many studies of the literature sample covered the same impact categories but characterized them by using different indicators. In total, 62 distinctive indicators for the description of sustainability issues were found while the number of relevant impact categories is with 12 much smaller. This points at the challenge that one and the same impact can be assessed by using different models. For example, land use can be characterized either by using a life cycle approach accounting accumulated land use [17, 20] or by concentrating on the proportion of new development on previously undeveloped land [50]. Both approaches offer indicators for land use but the functional unit used is rather different.

The 12 impact categories were selected by summarizing the characterization approaches found in the literature sample in distinct categories while following the principles stated in section 2. Annex I shows the initially identified indicators of the literature sample and how these were summarized, included or excluded in the respective impact categories. Figure 3 visualizes the positioning of the relevant impact categories considering the three sustainability dimensions. This visualization highlights the challenge of unequivocally assigning impacts to a single dimension. This supports the notion of the triple bottom line of sustainability with the basic statement that sustainability dimensions are connected and need to be considered in a joint framework [5].

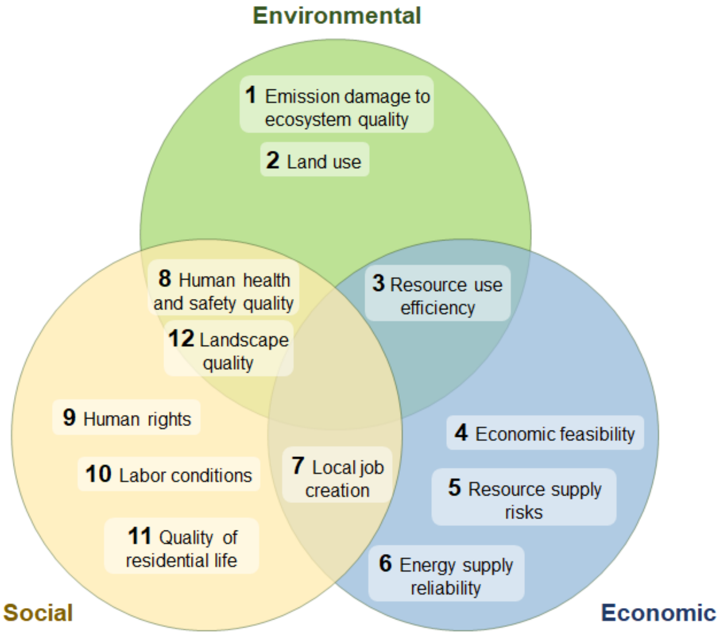


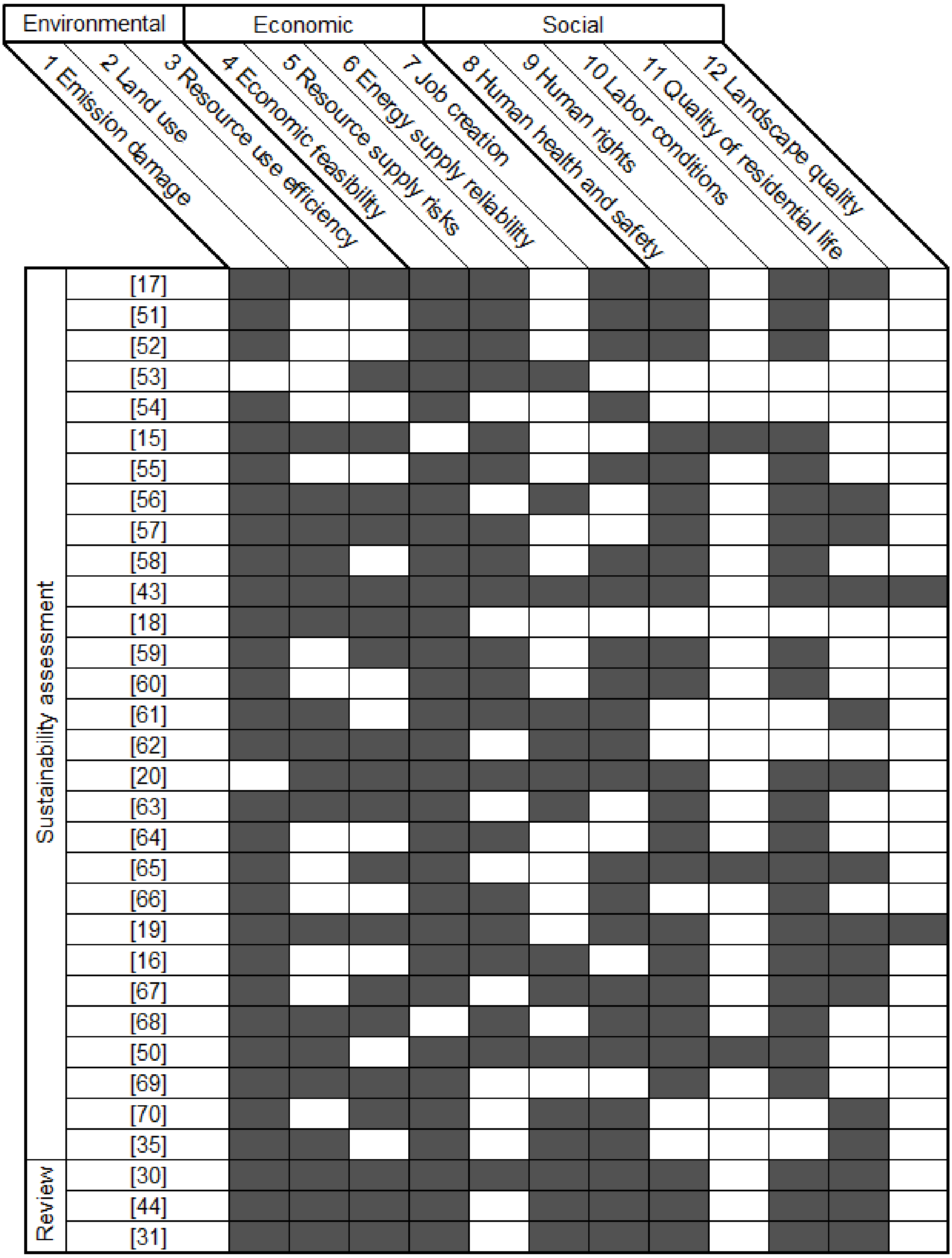
Figure 3: Impact categories of energy supply technologies in the three dimensions of sustainability

The frequency with which different impact categories were applied in the literature sample, was investigated. In the sample the high number of assessments regarding global warming potential (used by 87.5% of the sample), annualized cost and pay-back time (71.9%), and number of jobs created (62.5%) stood out. The finding that some assessment fields are used excessively in SA frameworks can be in part attributed to the high maturity of quantification methods, i.e. readily available and elaborate models, which facilitate the inclusion in assessment frameworks. The same trend was observed in the literature reviews by Martín-Gamboa et al. [30] and Wang et al. [31].

It is striking that half of the relevant impact categories are positioned in the social dimension. The explanation offered here is that the social dimension assessments lack a common endpoint. The opposite is true for the environmental dimension where various impact pathways can be subsumed under emission damage to ecosystem quality. It can be summarized to this common endpoint, although the impact can be attributed to different cause-effect chains such as global warming potential, acidification damage or eco-toxicity. A similar, commonly accepted endpoint for the presented social impact categories is not available. The described social impacts affect different parts of the population from global to local at individual points along the supply chain, which makes the definition of a common endpoint particularly challenging.

The matrix in Figure 4 shows the coverage of the 12 impact categories in each of the analyzed studies. The white areas mark gaps in the coverage of sustainability issues. First, areas are visible which are almost consistently covered by all studies, e.g. emission damage, economic feasibility, or job creation. Moreover, it is easy to spot underrepresented areas, such as the assessment of responsible supply chains regarding human rights or landscape quality.

Second, Figure 4 highlights that, although all studies are explicitly aimed at assessing sustainability, in some cases specific dimensions were disregarded. The social dimension was particularly underrepresented and disregarded in several examples of the literature sample.



		Environmental			Economic				Social				
		1 Emission damage	2 Land use	3 Resource use efficiency	4 Economic feasibility	5 Resource supply risks	6 Energy supply reliability	7 Job creation	8 Human health and safety	9 Human rights	10 Labor conditions	11 Quality of residential life	12 Landscape quality
Sustainability assessment	[17]	■	■	■	■	■		■	■		■	■	
	[51]	■			■	■		■	■		■		
	[52]	■			■	■		■	■		■		
	[53]			■	■	■	■						
	[54]	■			■			■					
	[15]	■	■	■		■			■	■	■		
	[55]	■			■	■		■	■		■		
	[56]	■	■	■	■		■		■		■	■	
	[57]	■	■	■	■	■			■		■	■	
	[58]	■	■		■	■		■	■		■		
	[43]	■	■	■	■	■	■	■	■		■	■	■
	[18]	■	■	■	■								
	[59]	■		■	■	■		■	■		■		
	[60]	■			■	■		■	■		■		
	[61]	■	■		■	■	■	■				■	
	[62]	■	■	■	■		■	■					
	[20]		■	■	■	■	■	■	■		■	■	
	[63]	■	■	■	■		■		■		■		
	[64]	■			■	■			■		■		
	[65]	■		■	■			■	■	■	■	■	
	[66]	■			■	■		■			■		
	[19]	■	■	■	■	■		■	■		■	■	■
	[16]	■			■	■	■		■		■	■	
	[67]	■		■	■		■	■	■		■	■	
	[68]	■	■	■		■		■	■		■		
	[50]	■	■		■	■	■	■	■	■	■		
	[69]	■	■	■	■				■		■		
	[70]	■		■	■		■	■				■	
	[35]	■	■		■		■	■				■	
Review	[30]	■	■	■	■	■	■	■	■		■	■	
	[44]	■	■	■	■		■	■	■		■	■	
	[31]	■	■	■	■		■	■	■		■	■	

Figure 4: Matrix of impact category coverage for studies focused on assessing the sustainability of different options for energy supply. Black cells represent that the study did consider the category.

3.3 Review of impact categories and selection of sustainability indicators

This section provides a review of assessment methods for each of the identified impact categories including proposals for concrete methods and impact indicators to be used in the SA framework. This review and a subsequent judgment of maturity of the methods are the basis for the selection of the methods for the SA framework, as presented in section 3.4.

3.3.1 Environmental impacts

Emission damage to ecosystem quality

The field of environmental assessments is dominated by (environmental) LCA. As this discipline can fall back on a development starting in the early 70s, the methodology is advanced and well developed. LCA is already commonly used for the environmental assessment of energy technologies, e.g. in the form of life cycle-based carbon footprint calculations [14]. A clear advantage is the high level of standardization of the LCA methodology. Due to the high availability of quantification methods the majority of SA frameworks for energy include a deliberation of emission damage using LCA methodology [30, 31].

One of these elaborate quantification methods is the ReCiPe method which offers quantification at midpoint and endpoint level. It is the standard method included in LCA databases for the assessment of the environmental impact and in particular emission damage [71]. For the SA framework it is proposed to include the ReCiPe method with its endpoint indicator “Potentially Disappeared Fraction of species*m^2*yr” to quantify the environmental impact of emissions.

A limitation of LCA is that it allows to objectively quantify the environmental impact but usually omits site-specific effects [19]. While site-specific emission damage is challenging to characterize, the assessment of local environmental impact could be achieved by investigating local land use, as explained in the following section.

Land use

Land occupation, land use change, and the destabilization of an ecosystem’s regulating mechanisms form a site-specific impact category. Not only the area of land lost is relevant but also the change in land quality. Impacts on land quality are diverse, reaching from changes of net productivity, soil degradation, and erosion to the loss of water purification functions [72]. Accordingly, a number of proxy indicators are in use, depending on the specific focus. Common LC impact characterization methods range from midpoint methods considering soil quality [73] or the occupation of productive land [74] to endpoint methods focusing on biodiversity loss [75]. Others differentiate the endpoint impacts in more detail, e.g. Mattila et al. [76] singled out three different impact endpoints of land use: resource depletion, soil quality and biodiversity. Koellner et al. [72] characterized impact in two pathways: biodiversity damage potential and ecosystem services. While biodiversity impact of land use received most of the attention in the past, the ecosystem services approach allows a more differentiated insight regarding the cause-effect chain of land use. This approach is further investigated.

In general, ecosystem services can be classified in provisioning, regulating and maintenance, and cultural services [77]. While provisioning services are covered by most environmental LCA and environmental impact assessment methods, there is a lack of quantified data for regulating ecosystem services and in particular cultural ecosystem services, which makes the integration and aggregation into a single unit measure challenging [78, 79]. Literature offers only few examples where ecosystem services are connected to the supply of energy, see [72, 80].

The ecosystem services approach has the clear advantage that the classification schemes for ecosystem services (e.g. Millennium Ecosystem Assessment [81] or CICES [77]) provide a systematic catalogue of relevant ecosystem processes and outputs. Accordingly, the impact of land use can be quantified by surveying the impact on provisioning and regulating ecosystem services. The ecosystem services approach allows diverse ecosystem mechanisms to be covered using a single indicator.

Although an ecosystem services approach shows potential for the systematic assessment of land use, more research is needed to allow a systematic characterization of impacts and in particular accomplish the implementation in an LCA framework [79].

Resource use efficiency

Excessive or inefficient resource use which exceeds ecosystems' natural carrying capacity poses a threat to both a healthy and sustaining environment as well as material prosperity. The high variability of resource supply chains is a challenge for the accounting of quantity and quality of resource use for the comparison of different energy technologies. A well-established approach can be found in the form of cumulative energy or cumulative exergy analysis. Both approaches account for energy flows along the life cycle and provide a comparative value of how efficient input materials are used per functional unit. An exergy analysis is e.g. proposed by Dewulf et al. [15] or Abu-Rayash and Dincer [17].

Cumulative Energy Demand (CED) and exergy analysis are essential methods for the evaluation of efficiency along the production value chain. The CED approach is based on the quantification of primary energy use and results are accordingly expressed in a physical energy unit, mostly MJ [82]. Cumulative Exergy Demand (CExD) goes beyond energetic resources. Coming from the field of thermodynamics, exergy is the term for the share of energy that is available for use. By using an exergy measure it is possible to add an indication of both quantity and quality of the available energy. CExD uses exergy to quantify the share of resources taken away from the natural environment as fuel and feedstock for industrial production and for consumption. This includes the extraction of exergy stocks and the deprivation of exergy flows (solar, wind, etc.) from the first trophic level where flows are needed for sustaining natural processes and cycles. Following this logic, also land use can be accounted for [83].

The CED approach is important for identifying and prioritizing energy savings potentials but the exergy analysis provides considerably more information about life cycle resource use. CExD is a consistent measure for the comparison of different products or systems [82, 84]. Following the recommendation of Berger et al. [85], the Cumulative Exergy Extraction from the Natural Environment (CEENE) method is the most elaborated thermodynamics-based method. It addresses shortcomings of earlier exergy methods, like double counting in bio-based fuels or considering exergy loss only for the metal-containing minerals instead of the whole ores [86]. Therefore, the CEENE method is also recommended by the UNEP Life Cycle Initiative for quantifying mineral resource use [85, 87].

3.3.2 Economic impacts

Economic feasibility

A number of indicators are used in financial accounting to determine if a project is worth implementing. Common indicators are e.g. net present value, internal rate of return and payback period [88]. These indicators are focused on the company's perspective and are limited in their ability to specify the impact on economy or society. Life Cycle Costing (LCC) and Cost Benefit Analysis (CBA) are commonly used approaches in economic or sustainability frameworks which go beyond the mentioned investment performance indicators and offer a holistic assessment of economic feasibility from a policy-makers or the societies perspective [89]. In CBA, non-financial impacts and benefits can be quantified in monetary values but the operationalization of the monetarization is a cause of prolonged discussions [90].

Different from CBA, LCC takes account of the full product life cycle [89]. Traditionally, LCC strictly accounts for monetary terms and neglects intangible impacts [91] but by now sub-categories of LCC developed focusing on the inclusion of environmental or social costs with the aim to contribute to a more holistic measure of sustainability [10, 89].

However, in the presented impact category the assessment of only the economic component, and not environmental or social costs, is sufficient. This will avoid the risk of double counting among environmental or social impact categories of the framework.

The LCC approach is recommended by Kloepffer [9] and Guinee et al. [14] as part of a life cycle based SA. The advantage over traditional accounting methods is the life cycle perspective of LCC which allows to include future cost by extending the system boundaries of cost accounting [92]. For being applicable in SA, it is necessary to consider the same life cycle inventory as for other LCAs, that is, the physical life cycle from cradle-to-grave. Uncertainties regarding costs of resources can be included in the feasibility assessment, i.e. the risk of price volatility, although overlaps with resource supply risks assessment have to be considered.

In the energy sector, life cycle cost is commonly expressed in levelized cost of energy (LCOE) per kWh produced energy. LCOE accounts for the present value of life cycle energy cost in relation to the actual energy delivered over the lifetime of the technology. It is the value at which electricity would need to be sold in order to break even [93]. A number of studies are dedicated to the calculation of this key value [57, 94, 95]. LCOE is a suitable indicator for economic feasibility but specific attention has to be given to uncertainties with regard to future cost of resources and the volatility of operation costs due to changes in the fuel prices. Moreover, the assessment of end-of-life costs is not always explicitly considered in the literature.

Resource supply risks

Potential risks for functioning resource supply are diverse, ranging from interruptions due to natural disasters to sudden price increase due to governmental intervention [96]. Dewulf et al. [97] categorized resource supply risks into four groups: (1) technical, physical and geological, (2) economic, market and strategic, (3) regulatory and social, and (4) political stability and governance factors. Schrijvers et al. [98] identified diversity of supply/import, political stability and depletion time as most widely assessed areas, both in combination and as single indicators for resource supply risks.

Indicators for supply risks play an increasingly important role for the assessment of resource criticality. Criticality assessments capture both supply risks limiting the availability of resources as well as the vulnerability of a system to a disruption [96]. In criticality assessment, a wide range of methods are used with indicators focusing on geological, technological, geopolitical, social, and environmental factors, or a combination of those [98]. The GeoPolRisk indicator, first proposed by Gemechu et al. [99], aims at complementing LCA with a risk measure of raw material usage and thereby making a step in the direction of LCSA. The indicator concentrates on supply disruption probability due to political instability of supplier countries, leaving other factors unmentioned, such as mining capacity, recycling, price volatility, or demand growth [100]. The indicator is applied as part of sustainability frameworks for the assessment at product level, see [100-102] and is well-suited to be integrated into an LCA. The compatibility with LCA is a strong argument for its application for an LCSA or SA.

Therefore, it is recommended to present the resource supply risks on product level by identifying the share of materials with high geopolitical risk of disruption using the GeoPolRisk indicator as put forward by Gemechu et al. [99]. For the comparison between energy technologies this indicator can be used to identify more or less vulnerable technologies. It has to be pointed out that GeoPolRisk indicator characterization of energy carriers is limited at the moment, therefore it will clearly be focused on the assessment of auxiliary material for the provision power supply units [85]. The risk of supply reliance on energy carriers can be covered through considering price variability in the life cycle cost assessment, in order to compensate the GeoPolRisk limitations.

Energy supply reliability

This category concerns the reliability of energy supply and the flexibility to respond to energy demand signals from the grid, e.g. to peak loads. As the system boundaries for the presented analysis exclude processes after the energy leaves the supply unit, storage and distribution solutions impacting the reliability are not considered. The aim is to purely assess the quality of energy output, that is reliability and flexibility, when entering the supply grid.

The issue of reliability and flexibility of supply is foremost found in studies concerning renewable electricity production technologies, such as wind and solar, which show flexibility constraints. Although the issue is frequently raised, there is a certain lack of operational indicators in this area [103].

One proxy method is to investigate the average capacity factor of the system which is the ratio between energy provided and the theoretical maximum considering forced and planned outages [62]. In energy generation and load models, indexes such as the Expected Energy Not Supplied (EENS) index are used for reliability analysis [104, 105]. The disadvantage of EENS is the high level of data requirements needed to accurately present energy supply and demand predictions. The level of detail EENS can provide is out of proportion for the use in an aggregated SA framework. Therefore, a simple measure is sufficient, e.g. as proposed by Maxim [20] who used qualitative description of the ability to respond to demand based on technology studies and expert opinions, aiming at a generally accepted evaluation without the need of site-specific load modeling.

Job creation

As a consequence of the shortcoming of LCC to describe impacts on the economy, the indicator of job creation is included as an additional economic indicator. Local job creation can be considered a crossdimensional topic. In the reviewed literature sample it is found just as often categorized as a societal impact.

A common indicator for this category is jobs created per MW installed power [17, 62, 106] which is also recommend for this SA framework. Unfortunately, literature is not very clear about the methods used to determine the indicator. For example, the differentiation between one-year jobs or long-term employment is not clearly made [107, 108].

The emphasis in the assessment lies here on the local impact. Only locally (at most nationally) created jobs should be considered and not job creation along the whole supply chain. The localization of impact is particularly relevant to show the potential of shifting parts of a foreign value chain to domestic markets and facilitate the local economic development.

3.3.3 Social impacts

The analyzed literature sample showed a wide variety of methodological approaches for the social dimension. Three prominent approaches can be differentiated: First, there are SLCA approaches that use indicators describing the distance to a specific performance reference point such as the European Convention on Human Rights or International Labour Organization (ILO) conventions and thereby allow the identification of hotspots along the supply chain [109]. Second, an alternative SLCA line of research uses characterization factors based on defined impact pathways, e.g. emissions leading to health impact [109, 110] or to an impact on well-being [32]. Third, tailor-made local impact assessments were identified, which focused mostly on the investigation of local attitudes of the population. As explained in the introduction, the spatial differentiation of impacts provides additional information with regard to local attitudes and related support/opposition of different energy supply technologies. For this framework, a mixture of approaches is recommended according to the best available methods for the respective impact categories.

The necessity of using different approaches in the social dimension points at the complexity of the social assessment. As there is not one overarching approach to cover global and local social endpoints from responsible supply chains to local living quality from the population viewpoint, it is necessary to cover the different categories individually.

Human health and safety quality

The category concentrates on population health and safety, based upon a causal relationship between environmental conditions and human well-being [109]. Occupational health and safety is not covered by this cause-effect chain but will be covered as part of social responsible labor conditions, see below. An assessment covering the whole life cycle is recommended. LCAs with focus on human health show great similarity to environmental LCA methods and are in fact often implemented in the course of such assessments, see e.g. [16, 58, 60].

The method of choice is the ReCiPe method [71] as it is also recommended for the assessment of emission damage in the environmental dimension. Applying the ReCiPE method in both impact categories offers the advantage of harmonized coverage of impacts of emissions. For quantifying the impact on human health, the endpoint indicator Disability Adjusted Life Years (DALYs) is used in the ReCiPe method.

Responsible supply chains with regard to human rights

Energy supply facilities and in particular low-carbon technologies as wind turbines, solar panels, and improved energy storage require specific material inputs for which the main sources are often found in countries with politically difficult conditions. Thereby, there is a risk of the energy transition contributing to severe living conditions, human right infractions, and the maintenance of weak governance situations [113, 114]. Although this is an issue of growing importance, human rights infractions and armed conflicts are not yet commonly picked up in SLCA.

In the energy sector, producers of solar and wind energy technologies run into the risk of relying on so-called conflict minerals as part of their supply chains [113]. The mining of fossil fuels is also known to spark conflicts or insurgencies funded by fossil fuel sales [115].

The UN Life Cycle Initiative provides methodological sheets for the assessment of sub-categories in SLCA. Human rights indicators are covered in several categories, e.g. Cultural Heritage, Respect of Indigenous Rights, or Prevention and Mitigation of Conflicts [116]. Moreover, databases such as the Social Hotspot Database [117] or Product Social Impact Life Cycle Assessment PSILCA [118] provide sector- and/or country-specific information regarding the risk for social infringements. These methods are based on performance reference point methods, i.e. the quantification of the risk of hotspots along the supply chain, rather than describing the actual impact. This is also owned to the lack of site-specific data and inherent lack of transparency of material flows when it comes to human rights violations [119].

Accordingly, a risk indicator will be used. The “Risk of contributing to human right infractions and conflicts” indicator describes the relative share of problematic materials along the supply chain of energy technologies. For this SA framework, the PSILCA database is recommended as it provides data for a wide range of sectors and countries and offers a good documentation of data sources and quality.

Responsible supply chains with regard to labor conditions

The assessment of labor conditions follows an SLCA approach where the supply chain activities are evaluated against the minimum requirements of fair labor conditions according to ILO conventions. Thus, hotspots and the risk of infractions are quantified using the PSILCA database for the same reasons as described for the human rights infractions assessment above.

PSILCA accounts for global issues such as child labor, forced labor or excessive working hours [118]. However, these included indicators are not adequate to assess job quality and job satisfaction in a European context. In order to consider the local impact on job quality, different, localized performance reference points need to be considered, e.g. based on the European Working Conditions Survey. Thus, the PSILCA risk indicator should be complemented with an assessment dedicated to European job satisfaction, which will result in a single indicator – “Risk of contributing to adverse labor conditions” – both considering global and European labor standards.

Quality of residential life

In well-being research, two approaches can be distinguished: the assessment of objective criteria or of subjective well-being [120, 121]. While SLCA approaches strive to base the assessment on objectively reproducible impact pathways in order to quantify the impact on human health [111, 112] or well-being as a whole [32, 122], the assessment of subjective well-being relies on people’s own judgment to specify complex situations [123].

The localization of impact sources – that is, if impact is experienced locally or far away – influences the public perception of this impact on the subjective well-being. Especially, renewable energy developments – although in general positively received by the population as a contribution to the energy transition – face the challenges of lacking public acceptance on the local level [38-40]. This discrepancy is called the “Not in My Back Yard” (NIMBY) syndrome. It points at the importance to differentiate between global and local social impact in a social assessment.

The subjective evaluation of residential life by the local population presents a suitable impact indicator as long as it is tested and corrected for the influence of NIMBY. As there is no clear cause-effect chain established yet and therefore no generic impact characterization factors, the preliminary assessment needs to be based on case study data. A rating of perceived impact on quality of residential life was investigated e.g. by Bertsch et al. [38] or Zoellner et al. [40], although not as part of an SA framework.

Landscape quality

Although landscape quality can also be considered to be part of residential life quality, in the presented framework it is recommended to consider it in a separate impact category, as it is of particular interest in the case of energy supply. Studies propose the targeted exploration of place attachment – the emotional relationship between people and a specific place, the environment or surroundings – as a defining factor for public attitude [39, 124] rather than the living environment as a whole. Others argue that public acceptance or non-acceptance of renewable energy projects is strongly associated with aesthetics and visual impacts [41, 42, 125]. Johansson and Laike [125] found that the expected impact on people’s daily life was only a minor factor for public opposition. The biggest area of concern for people was found to be the impact on the perceived unity of the environment and on landscape aesthetics and recreation.

These areas are well covered by a cultural ecosystem services approach as listed in the CICES [77]. According to this definition, cultural services are non-material outputs of ecosystems such as environmental settings, locations or situations that affect human well-being. The services cover both tangible values, such as recreational use, and intangible ones, such as aesthetics and place attachment. A change of landscapes, e.g. through power plants, means thereby a change in the supply of cultural ecosystem services. Although cultural ecosystem services are rarely considered outside of tourism and recreation research [126, 127], there is the potential to integrate the complex matter of landscape impact into the SA. The definition of a cause-effect chain in accordance with the cultural ecosystem service approach will contribute to the development of a mature assessment method.

3.4 The framework

Table 1 summarizes the preceding review and proposed selection of indicators for each impact category. Moreover, it offers a classification of each quantification method regarding its maturity.

The methods were selected according to their maturity level. The maturity was evaluated by means of three criteria: if a cause-effect chain was established, the availability of quantification factors, and the evaluation of the method by third parties and/or in the form of well-documented case studies. The clear definition of a cause-effect chain is a practice common in LCA methods, but not clearly stated in other fields. Therefore, it is distinguished between explicit and implicit cause-effect chains. An explicit cause-effect chain is e.g. put forward in the ReCiPe method defining that certain emissions into air contribute to global warming which in turn impacts environmental quality and human health. An example for an implicit cause-effect chain is the evaluation of responsible supply chains with regards to human rights. Here it is implied that society as a whole has the responsibility to avoid human rights infractions and that by accepting a high risk of infractions the society is impacted negatively.

Table 1: Selected impact categories for sustainability assessment of energy supply technologies

Impact categories		Description	Quantification method	Evaluation of maturity				Indicator
				Cause-effect chain	Character-ization factors	Validated	Maturity rating	
Environmental	1. **Emission damage to ecosystem quality**	Air and water pollution pathways along the energy supply life cycle	ReCiPe see [71]	Yes / explicit Emissions lead to ecosystem damage [71]	Yes	Interim recommended by [128]	3 / 3	Loss of species over space and time
	2. **Land use - provisioning & regulating ecosystem services**	Accumulated land occupation over the entire life cycle of the unit considering also the quality of land used by concentrating on provisioning and regulating ecosystem services impact	Accounting of ecosystem services based on CICES [77]	Yes / explicit Land use change leads to biodiversity ecosystem service damage potential [72]	Not available	Yes	1 / 3	Tbd*
	3. **Resource use efficiency**	Efficiency with which resources are extracted, processed and used along the life cycle in order to produce useful energy	Cumulative Exergy Extraction from the Natural Environment (CEENE) [83]	Yes / implicit Excessive exergy extraction needs to be avoided due to a limited carrying capacity of ecosystems	Yes	Recommended by [85]	3 / 3	MJexergy
Economic	4. **Economic feasibility**	Average cost of producing energy over the life time of the unit; it takes into account all investments, operation and maintenance, fuel and decommissioning	Accounting of life cycle cost [57, 94, 95]	Yes / implicit High spending and inefficient use of financial resources impacts prosperity	– **	Need to be adapted to include future cost variability and end-of life costs required	2 / 3	Levelized Cost of Energy
	5. **Resource supply risks**	Risk of changing accessibility of energy fuels and required raw materials due to import country concentrations and price volatility	Product-specific application of GeoPolRisk indicators [99]	Yes / implicit Material requirements coming with high GeoPolRisk are a risk to prosperity	Yes	Recommended by [85]	3 / 3	Share of material inputs with high GeoPolRisk
	6. **Energy supply reliability**	Ability to respond to peak demand and to contribute to overall grid stability	Qualitative rating based on literature and expert opinions	Not defined	Not available	Yes	0 / 3	Tbd*
	7. **Local job creation**	Direct full time employment created locally at the site or in the region of power plants	Accounting of jobs created based on benchmark values	Yes / implicit High local job creation is aspired as contribution to prosperity	– **	Assessed by [129, 130]	3 / 3	Direct local employment opportunities created

Impact categories		Description	Quantification method	Evaluation of maturity				Indicator
				Cause-effect chain	Character-ization factors	Validated	Maturity rating	
Social	**8. Human health and safety quality**	Emissions with impact on human health, including radiation as well as risks of accidents along the life cycle	Various methods depending on impact pathway as recommended by [128]	Yes / explicit Emissions lead to reduced life expectancy and fatalities	Yes	Recommended methods by [128]	3 / 3	Disability-adjusted life years
	9. Responsible supply chains with regards to human rights	Risk of human rights infraction and conditions funding of conflict parties in connection with resource sourcing along the supply chain	PSILCA see [118]	Yes / implicit Responsibility of the society to avoid infractions	Partially	Yes Risk of conflict minerals is underrepresented	2 / 3	Risk of contributing to human right infractions and conflicts
	10. Responsible supply chains with regard to labor conditions	Infractions on fair labor conditions considering differences between global and local minimum standards	PSILCA see [118]	Yes / implicit Responsibility of the society to avoid infractions	Partially	Yes Needs to be adapted with reference values for European job satisfaction	2 / 3	Risk of contributing to adverse labor conditions
	11. Quality of residential life	Perceived impact on areas of quality of residential life as part of overall subjective well-being	Local survey of impacted population following the example of [38] and [40]	Not defined	Not available	Yes	0 / 3	Tbd*
	12. Landscape quality as cultural ecosystem service	Perceived impact on the intrinsic value of intact landscape and of recreational opportunities as part of overall subjective well-being	Local survey of impacted population using cultural ecosystem services partially following [41, 125, 131]	Not defined	Not available	Yes	0 / 3	Tbd*

* To be defined depending on cause-effect chain and characterization method

**Not applicable for accounting methods

As shown in Table 1, the level of maturity varies among the proposed quantification methods with ratings from 0 to 3 points. A rating of 3 out of 3 means that the proposed method is well-established and can be used without significant alterations. A rating of 0 or 1 point highlights methods which are put forward by the authors due to a lack of adequate assessment approaches. These need to be tested as part of the SA framework.

In the categories emission damage, resource use efficiency, resource supply risks, job creation and human health it is possible to rely on well-established quantification methods. The evaluation of the level of maturity shows that these methods are recommended for the characterization of the respective impact categories by external experts. It should be considered that in these fields research is ongoing and methods can and should be improved in the future.

The quantification methods with a medium level of maturity of 2 out of 3 points show certain shortcomings. Although characterization factors are available, these need to be adapted to the requirements for assessing energy supply technologies. These specific adaptations have not been evaluated yet, hence the medium maturity level. For example, the assessment of labor conditions can be based on characterization factors provided by the PSILCA database which very well covers global impacts. However, as reference standards used in PSILCA – such as child labor and forced labor – fail to be applicable to the European standards, adaptation is needed in order to consider European minimum standards as reference points for the assessment of the local dimension at the power plant site.

New assessment methods with a low maturity level are proposed in cases where an assessment is crucial for the complete SA framework but existing methods are not sufficient. For the cases of land use, energy supply reliability, quality of residential life, and landscape quality the authors are proposing original and tailor-made indicators, which will be first applied and tested as part of the SA framework. For example, in the case of land use, it is proposed to investigate an ecosystem services approach. The methodology should be advanced to not only be applied for specific locations but also to include life cycle effects. Another example are novel social indicators that can be derived from research on public attitude and perception where case studies for specific energy production sites are regularly conducted. To make results usable as general social indicators, the work has to move away from isolated observations and needs to offer comparable scores for different technology options. Researchers already investigated the comparison of the perceived quality of life impact [38, 40], although not as part of an SA framework.

The impact categories as described in Table 1 are placed at the relevant stages of the life cycle of energy supply. This shows that the life cycle approach is an integral part of the impact assessment in different categories while at the same time there is a visible difference between global and local impact assessment categories.

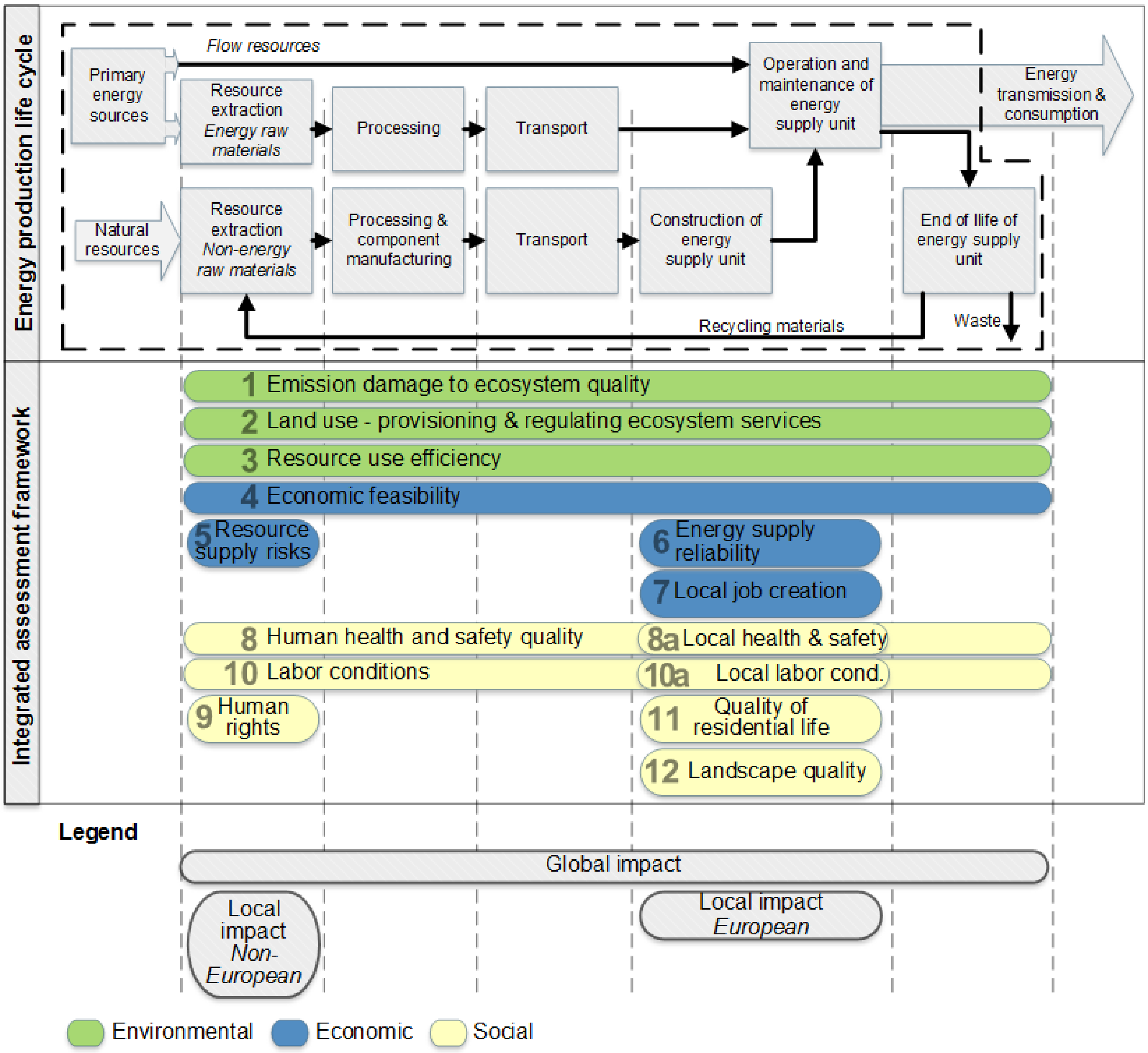


Figure 5: Sustainability assessment framework alongside the energy supply life cycle

Figure 5 shows the energy supply life cycle in combination with the integrated assessment framework consisting of 12 impact categories. Using this illustration, it is possible to differentiate three types of spatial coverage: life cycle impact, local impact at the point of resource extraction which takes places mostly in non-European countries, and local impact at the point of the energy supply unit's operation which is due to the focus of the framework in European countries. The differentiation between non-European and European local impact clarifies the points of reference used in the impact assessment, e.g. labor standards. It does not mean that the local impact is assessed at the level of whole Europe.

Half of the identified impact categories are considered relevant along the complete life cycle while the other half concerns specific parts of the supply chain, either with an international dimension (resource extraction) or a local one (energy supply facilities). The figure shows that for the environmental assessment the full life cycle impact is considered, which contributes to a fair comparison of products as upstream impacts are accounted for. The local dimension plays a significant role in the economic and social dimension with the majority related to the operation of energy facilities. In the social dimension, the focus lies on a comprehensive assessment of the impact on local well-being of the population at the site of the construction and operation of the energy supply unit. The strong relevance of the local dimension for social impact assessment confirms that it is important to differentiate between life cycle and local perspectives in order to capture the full range of impacts on sustainability.

Rather than presenting the SA results in a dashboard of 12 indicators, the results should be aggregated into areas of concern in order to facilitate the decision-making process. The sustainability score aggregation is the last necessary step in the integration of different methods.

3.5 Sustainability score aggregation

A challenge of the multidimensionality of the SA framework is to present results in a comprehensive and yet clear way. Kalbar et al. [132] pointed out that the increasing complexity of SAs leads to more complex decision situations. Not only is there a high number of indicators, they also have different measurement units and different structures, e.g. emissions with exponential impact influence, costs where absolute maxima need to be observed or relative Likert scores. The aggregation at this point serves the purpose of simplification. On the one hand, simplification through expressing impacts in a common unit, e.g. in USD of incurred costs, on the other hand, a simplification of the decision-making process by processing several impacts to a limited number of scores [133]. For the latter option the aggregation is a purely mathematical procedure and not based on a cause-effect chain.

In SA frameworks found in literature, aggregation is applied at different stages. It can be considered in the choice of indicators as e.g. done by Maxim [20] who used widely accepted aggregated indicators and weighted those indicators using expert judgment. Hadian and Madani [18] used a footprint approach to assess impacts which provided them with results in the same unit, making aggregation simple and transparent. Alternatively, aggregation can be considered in order to move from a dashboard of various indicators to a single sustainability score [17, 62] or a selection of aggregated indexes according to areas of protection [36, 134].

Despite the risks of misinterpretation there is a demand for single score results in order to make SA results accessible for decision-makers [135]. In any case, the aggregation and in particular weighting of several indicators always bears the risk of being subjective [136, 137].

The assessment using the presented framework will result in 12 specific indicators which might be difficult to process by a non-expert audience. Normalization, weighting and final aggregation of the indicators aim at producing a reduced set of scores to present the results. These steps are all possible causes for a loss of information and objectivity, and therefore monitored and evaluated closely [48].

Hammond et al. [138] depicted the relation of data, indicators and indexes as an "information pyramid" where primary data are the base of the pyramid and presented in the form of field-specific indicators which in turn can be aggregated to indexes. The number of indexes should be limited as this level is presented to decision-makers and the public [138]. Following the approach of the information pyramid, the different information levels of the presented framework are shown in Figure 6. The figure shows from left to right the computation and aggregation of information. A dedicated decision-making level is defined, building the bridge between expert presentation of specific impacts and a simple presentation of a single aggregated sustainability index. At this intermediate level several areas of concern can be compared by decision-makers or the public.

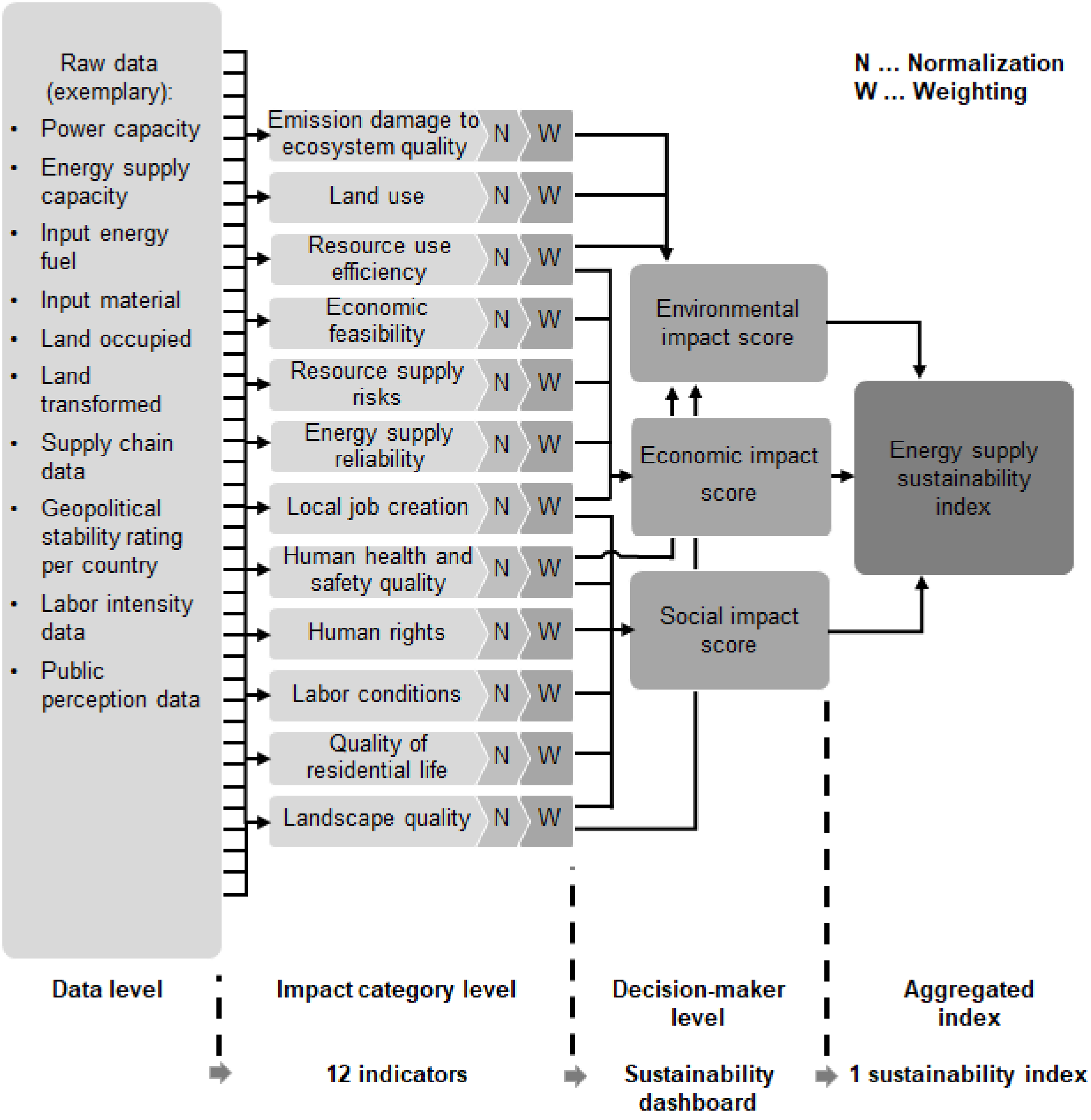


Figure 6: Aggregation of information in the SA framework

The challenge of the aggregation step is to find the balance between presenting simple sustainability areas and overloading decision-makers with information. In this framework the balance is achieved by using both a sustainability dashboard with 3 aggregated indicators for environmental, economic, and social impact respectively, and a total sustainability index in parallel.

The aggregation of a number of indicators always implies weighting, in particular when there are different numbers of indicators per aggregated category or when overlapping categories can be assigned to more than one sustainability dimension, e.g. human health both as environmental and social indicator. There is no single answer as to which categories should be weighted more or less but unintended weighting originating from the sole quantity of indicators needs to be avoided.

In general, aggregation can be done purely mathematically e.g. by an additive or geometric aggregation approach or using multi-criteria decision-making techniques [137, 139]. The decisive difference between these approaches is that they imply different levels of substitutability amongst sustainability dimensions. While additive aggregation allows compensation of weak performance in certain categories through strong performance in others, geometric is less sensitive to this and (partial) non-compensatory decision-making techniques allow no trade-offs [140]. Another risk is that actual impacts are broken down to comparable functional units and transferred into scores which makes the assessment of accumulating effects, such as water usage to the point of depletion, difficult [141]. Techniques such as Analytical Hierarchy Process or outranking techniques like PROMETHEE and ELECTRE are commonly applied in sustainable energy planning [139, 142]. It is proposed to test out different weighting and aggregation scenarios and to use sensitivity analysis to understand the impact on the overall assessment in different scenarios.

4 Discussion and conclusion

The presented review confirmed that literature offers a wide variety of SA approaches. SA is used as an umbrella term for a multidimensional assessment but apart from that commonality there is no universally agreed-upon approach. This has the consequence that the assessment of energy supply technologies often omits certain aspects of sustainability, especially the social dimension, which leads in the long run to uncertainty for project developers and policy makers. In order to address this issue, a novel framework is presented here. The framework provides the basis for a reliable and complete assessment for sustainability of energy supply technologies and energy mix options.

The analysis of SA frameworks in literature showed that while there are areas which are excessively covered, e.g. emission damage, there are also “blind spots”. These “blind spots” refer to impact categories which are mostly disregarded in SAs, such as the assessment of responsible supply chains with regard to human rights and to landscape quality. This does not mean that these areas are never considered in the context of energy supply but that the step from localized case studies to an integrated SA was rarely done. The availability of well-established quantification methods, as is the case for the assessment of emission damage or accounting of resource use efficiency, encourages the consideration of these impact categories for any assessment framework. Further development of quantification methods and according indicators will contribute to the better representation of all impacts in future assessments. The need to further develop assessment methods in order to equally cover the areas of sustainability was also pointed out by Martín-Gamboa et al. [30] as well as Schaubroeck and Rugani [32].

The social assessment was found to be generally neglected and in need of expansion. This result is in agreement with analyses in previous SAs [15, 17, 19, 43]. Unique in the presented framework is the integration of social impacts as perceived by the population. The importance of public acceptance was considered before [16, 20, 67] and also commonly surveyed in specific local impact assessments [38, 40], but to the best of our knowledge a systematic characterization method for perceived impact on residential life and landscape quality has not yet been proposed.

Guinee et al. [14] advocated the integration of models of various disciplines for a LCSA framework. The presented framework goes one step further and the authors advocate for a side-by-side use of life cycle, local and risk assessment methods. Rather than implementing the proposed assessments in parallel, they are integrated in an SA framework. Aggregation to a comprised collection of sub-indicators is needed to present decision-makers with comparable and easily assessable scores.

The proposed framework is ready for the application in the form of a case study. Concrete case studies could contribute to the further development and validation of assessment methods with low maturity. In particular, in areas where the method is not commonly applied in the energy field and the level of maturity was found to be low, more effort is expected to affirm the choice of indicators and assessment methods. In addition, the case study application would allow the study of sensitivities between the impact categories. In future applications it will also be necessary to consider weighting of the presented impact categories which was not discussed at this stage.

A complete SA is still a challenge but the presented framework is one step towards a systematized discussion on the sustainability impact of the energy sector. The framework for the SA of energy supply was constructed in steps, addressing in turn shortcomings of existing frameworks. First, the life cycle of energy supply technologies was delineated and system boundaries were defined. A comprehensive literature analysis led to the identification of relevant impact categories suitable for describing sustainability impacts. Second, a literature review was conducted regarding quantification methods and concrete indicators. This resulted in the proposal of indicators taking into account their different levels of maturity. Moreover, the spatial coverage of the assessment methods was discussed and global and local impacts distinguished. Finally, the selected assessment methods were ready for the integration in a comprehensive framework and presented either in a dashboard of aggregated sub-indicators or in a single sustainability index.

As energy is an integral part of our society, the real challenge lies with minimizing the impact that its supply has on the environment and the well-being of society. Adequately, quantifying the impact of a society's energy supply options is the necessary first step for responsible decision-making. Not knowing how to assess the sustainability of energy supply technologies is not an option.

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Annex I Analysis and selection of impact categories

The following Figure A.1 shows the sustainability criteria identified in the literature sample summarized in impact categories. The criteria and indicators found in literature were summarized in impact categories each describing a distinctive root cause. The scale of the bar chart shows the count for how often this category was found in the sample.

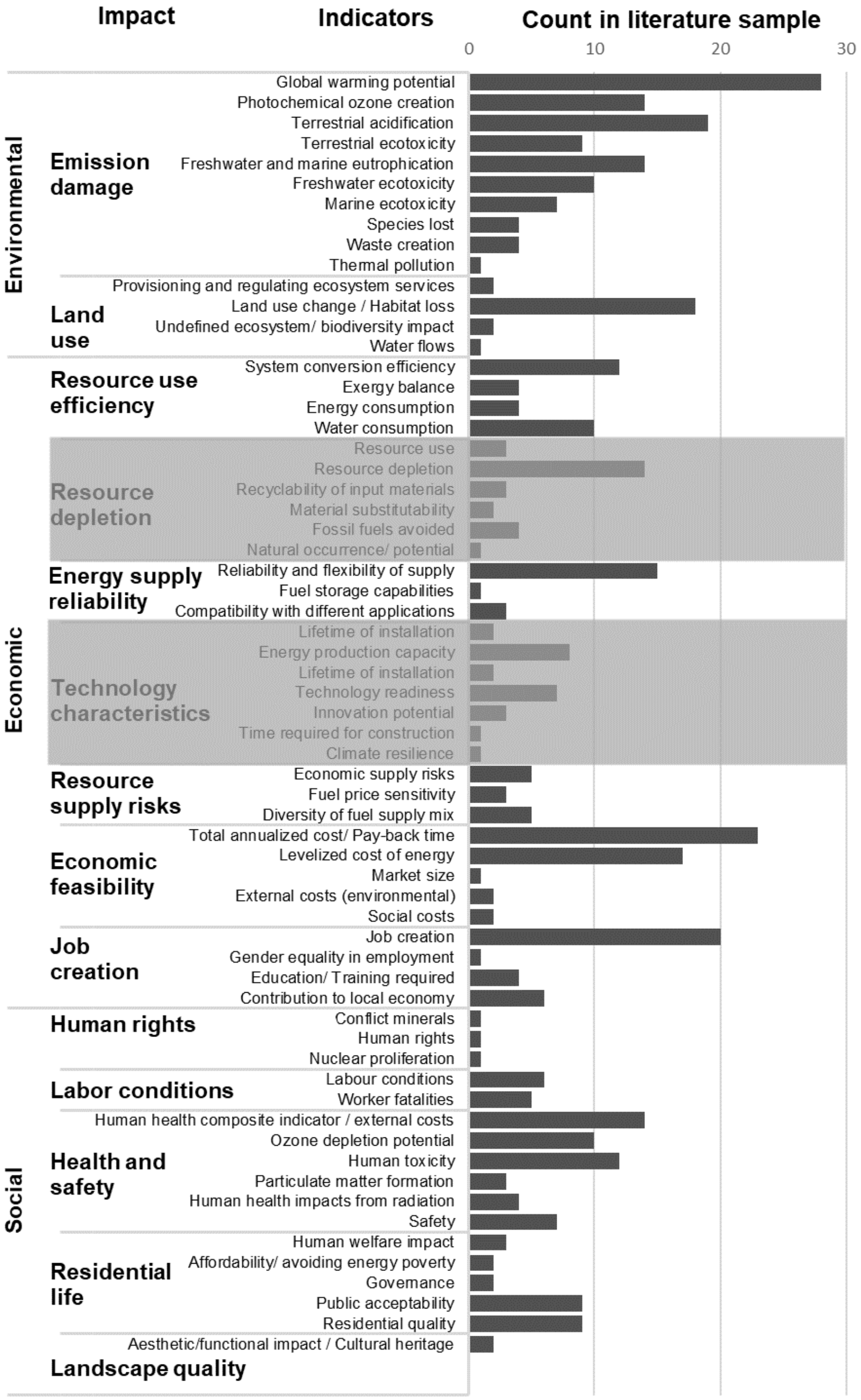

Figure A.1: Categorization of sustainability indicators found in the literature sample

The categorization in distinct impact categories was an iterative process in which connected and mutually dependent criteria where summarized in joint categories. The process had the aim to reduce categories as much as possible and comply with the independence principle as described in section 2. This methodology allowed to concentrate on concrete impacts and break down the multifaceted influence of overarching topics such as the status of laws and policies. E.g. the impact of regulations regarding emissions or their absence will be displayed in the environmental categories, supporting or hindering tax and tariff systems in the economic assessment, the omission of labor protection laws in the social assessment.

From the 14 impact categories identified, in the end only 12 were found to be applicable for the SA framework. From the criteria found in literature the categories “resource depletion” and “technology characteristics” were excluded.

The category “technology characteristics”, which contains indicators regarding the technological specifics including technology readiness, production capacity and efficiency, was excluded as the characteristics not adequately describe sustainability concerns. Moreover, technology characteristics cannot be cleanly separated from other impact categories and thereby do not meet the independence principles as described in section 2 of this study. The category is highly related with the assessment of economic feasibility or resource use efficiency.

The category “resource depletion” was excluded. The assessment of the long-term depletion of geological resources is commonly used in LCA. However, physical scarcity is – due to the long depletion horizons – often not considered in criticality studies [97, 98]. It is argued that the risk of materials supply disruptions is adequately presented by considering geopolitical and price risks summarized in the impact category resource supply risks. In the short to medium-term for energy supply projects, economic availability of resources will be more significant than geological availability.

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