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Proposal for a sustainability framework for energy technologies

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Contents

Abstract

The European Green Deal is a flagship initiative of the European Commission aimed at achieving a sustainable future through a clean energy transition. This report proposes a sustainability assessment framework (SAF) for evaluating energy technologies, inspired by the Safe and Sustainable by Design (SSbD) framework. It supports the Clean Energy Technology Observatory (CETO) in monitoring research and innovation activities for clean energy technologies. The background concepts underlying the SAF are discussed, including sustainability principles, life cycle assessment, sustainable innovation, and energy-specific concepts. The proposed SAF includes three dimensions: supply security, environmental sustainability, and social sustainability. Energy security encompasses economic aspects, such as stable energy supply, accessibility of resources, and trade considerations. Environmental sustainability is based on the Product Environmental Footprint methodology and aligned with the SSbD framework. The social sustainability dimension considers impacts on workers, local communities, value chain actors and society, according to the Social Life Cycle Assessment methodology. The framework has a hierarchical structure placing energy security first, and recognizing its interconnections with environmental and social objectives. The framework supports the European Union's priority on energy security in the context of achieving clean energy transition and becoming the first climate-neutral continent by 2050.

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1 Introduction

A clean energy transition is one of the building blocks of the European Green Deal, the European Commission (EC) flagship initiative aiming to transform the EU's economy for a more sustainable future (EC - European Commission, 2019b). In particular, the EU Green Deal aims to make the EU's economy climate-neutral by 2050, with a particular focus on reducing greenhouse gas emissions and promoting clean energy.

In this context, relevant policies and strategies related to energy include the Renewable Energy Directive (RED III) (EC - European Commission, 2021e), which sets binding targets for EU member states to increase the share of renewable energy in the overall energy mix. The previous recast of Renewable Energy Directive (RED II) also requires Member States to provide a framework to facilitate the development of energy communities, even among the low-income and vulnerable households, as a way to reduce energy poverty (European Union, 2018). In addition, the Energy Efficiency Directive focuses on improving energy efficiency across various sectors and the Clean Energy Package includes several legislative initiatives to drive the energy transition (EU - European Union, 2023). The latter package aims to create a more competitive, flexible, and consumer-oriented energy system and covers areas such as energy market design, electricity market rules, renewable energy community empowerment, and consumer rights.

As part of the European Green Deal, the European Climate Pact[1] invites all citizens to actively participate in climate action. The Pact builds on a series of packages and visions promoting the energy transformation. First, it builds on the vision "of an Energy Union with citizens at its core, where citizens take ownership of the energy transition". It aims at empowering citizens to make more informed consumption choices, use energy more efficiently and make optimal investment decisions.

The legislative package Clean Energy for All Europeans strengthened with the Recommendation on Energy Poverty (EC - European Commission, 2020a), includes the policy priority of protecting vulnerable citizens and tackling energy poverty. In particular, the Recommendation provides specific guidance on how to measure, define and tackle energy poverty based on the available EU-level support.

The RePower EU plan (EC - European Commission, 2022c), launched in response to the global energy market disruption caused by Russia's invasion of Ukraine, reinforced the need to accelerate on the energy transition while promoting clean energy production. The plan also aims at enhancing efficiency throughout the European Union, implementing a range of energy-saving measures and promoting energy-conscious practices. Moreover, diversifying its energy mix and decreasing reliance on fossil fuels, the EU lessened its vulnerability to geopolitical disruptions.

The EU is also working on developing a sustainable finance framework, to redirect private capital towards sustainable investments through the EU Taxonomy, which establishes criteria for determining environmentally sustainable economic activities (European Union, 2020). The Corporate Sustainability Reporting Directive (CSRD) entered into force in 2023 (European Union, 2022) modernises and strengthens the rules concerning the social and environmental information that companies have to report. Companies subject to the CSRD will have to report according to European Sustainability Reporting Standards (ESRS) which are currently in publication.

This report proposes a sustainability assessment framework (SAF) for the evaluation of energy technologies. It is partially based on the framework on Safe and Sustainable by Design (Caldeira et al., 2022) developed by the JRC, especially for what concern the structure, the definition of concepts, sustainability dimensions, life cycle based approach, hierarchical principle and the selection of aspects to assess. Compared to the SSbD, however, this proposal does not include the safety assessment, which is used for the evaluation of hazard assessment linked to chemicals and materials, as well as the human health impacts and safety aspects in their processing and application phase. Instead, the aspect of security and access to energy is explored in the case of energy technology sustainability assessment.

The proposal for a SAF aims to support the Clean Energy Technology Observatory (CETO)[2], a joint initiative between the Joint Research Centre, DG Research and Innovation and DG Energy. Started in 2022, CETO monitors the EU research and innovation activities on the clean energy technologies needed to achieve the European Green Deal's objectives. In particular, this framework aims at providing a structure and a guidance for the

[1] https://climate-pact.europa.eu/index_en

[2] https://setis.ec.europa.eu/publications/clean-energy-technology-observatory-ceto_en

sustainability assessment of energy technologies, taking into account and streamlining the analysis performed in the technology reports, especially for what concerns the selection of energy-relevant sustainability aspects.

The report includes a description of the background concepts underpinning the SAF (chapter 2), it then defines sustainability dimensions and a hierarchical approach for the assessment (chapter 3); it describes the elements of the framework (chapter 4) and provides guidance on the assessment of the three relevant sustainability dimensions: security, environmental and social sustainability (chapter 5). Chapter 6 discusses the changes applied compared to the CETO analysis and the challenges towards the full implementation of the framework. The final chapter (7) provides some conclusions on the added value of the proposal, its limitations and next steps for an enhanced methodological guidance.

2 Background concepts underpinning the sustainability assessment framework for energy technologies

In this section we describe some of the relevant concepts supporting the development of the SAF. They include general concepts in the sustainability field, applicable to all kind of sectors and systems, and then we focus on energy-specific concepts, which contribute to shape the framework and identify the relevant dimensions.

2.1 Sustainability and Sustainable Development Goals

The concept of sustainability emerged in the context of a growing awareness of an imminent ecological crisis. The concern about the use of natural resources in relation to the population growth dates back to the 18th century, when political economists such as Thomas Robert Malthus drew attention to the use of natural resources in this context (Purvis et al., 2019). The modern concept of sustainability, however, originated in the 1970s, being popularly attributed to the Club of Rome's report "Limits to Growth" (Meadows et al., 1972). One of the arguments of the popular essay was that the modern growth-based economy was unsustainable on a finite planet.

The idea that economic growth could be compatible with environmental limits and social fairness and justice led to the concept of sustainable development. It was defined in the Brundtland Report of the World Commission on Environment and Development, Our Common Future, as the humanity's ability of meeting "the needs of the present generations without compromising the ability of future generations to meet their own needs" (WCED, 1987). While this definition leaves space for different interpretations, it was pivotal in shaping the most common representation of the sustainability concept, i.e. the composition and interactions between three pillars: economy, environment and society. The relationships among these three dimensions are generally assumed to be compatible and mutually supportive (Littig & Griessler, 2005), though it is still unclear how the integration of these elements should be operationalized. Besides the environmental, social and economic considerations, the integration of additional pillars related to institutional, cultural, and technological issues has also been proposed (e.g. O'Connor, 2006; Vos, 2007). Partnership and peace were recognised as critical components of sustainability (UN General Assembly, 2015). Furthermore, awareness of the interplay between all the sustainability pillars and related goals and targets has increased.

The Brundtland Report definition also underpins the definition of sustainability considered in the ISO Guide 82:2019 providing guidelines for addressing sustainability in standards where "sustainability refers to a state of the global system, encompassing the environmental, social and economic subsystems, in which the needs of the present are met without compromising the ability of future generations to meet their needs." (ISO, 2019).

The need to operate within a safe space respecting Earth's ecological limit was translated into the so-called Planetary Boundaries (PB) framework developed by Rockström et al. (2009). This framework defines the preconditions for sustainable development by identifying and quantifying planetary boundaries that must not be transgressed by human activities thus avoiding unacceptable and irreversible environmental changes. Assessing a system in term of contribution to transgressing planetary boundaries, means to perform an Absolute Environmental Sustainability Assessment. The PB framework defines nine planetary boundaries: climate change, biosphere integrity, stratospheric ozone depletion, ocean acidification, biochemical flows, land-system change, freshwater use, atmospheric aerosol loading, and novel entities (previously called 'chemical pollution' (Rockström et al., 2009). From these PB, functional diversity (as part of Biosphere integrity), and atmospheric aerosol loading are not yet quantified as per the 2015 PB update (Steffen et al., 2015).

Acknowledging the interdependence of the socio-economic and environmental issues, the concept of Safe and Just Operating Space (SJOS) for humanity have been proposed (Raworth, 2017). Following the idea behind the Planetary Boundaries, which implies environmental limits that cannot be transgressed, the concept was extended to social categories and boundaries. The "doughnut economy" concept allows to visualize the SJOS area, which corresponds to a situation where resources are used and allow to fulfil human needs, while remaining within the planetary boundaries (Figure 1).

Figure 1. Doughnut economy representation

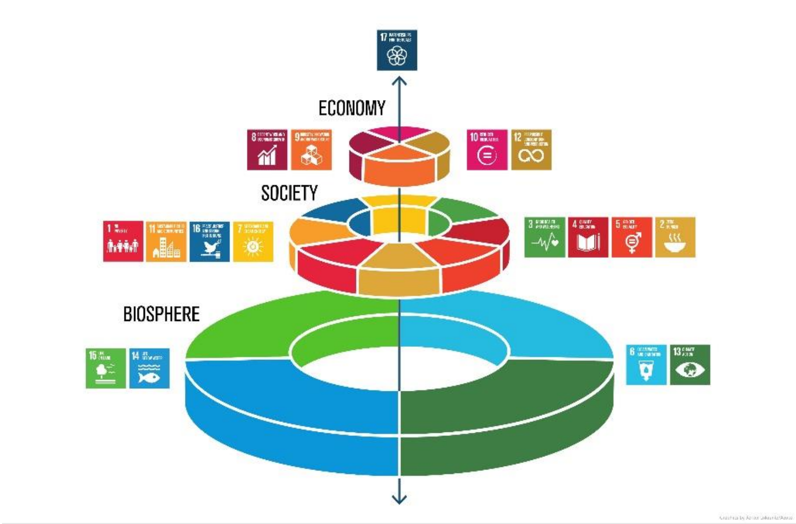
Source: Raworth, K. (2017)

Hence, the concept of sustainability has evolved over time, leading to the development of the so-called sustainability science, which is translating sustainability principles into practical solutions.

The sustainability principles have been enunciated also in terms of specific goals for humankind, the United Nations' Sustainable Development Goals (SDGs). The 17 SDGs, including 169 targets and 231 indicators, are defined in the Agenda 2030 (UN General Assembly, 2015) and set out a vision for a future global society. The 2030 Agenda for Sustainable Development covers the different dimensions of sustainability, providing principles and reference for policy at different levels (local, national and regional level) and for business and corporate decision makers. The European Union has committed to play a pivotal role in SDGs achievements (EC - European Commission, 2016) and to align its development policy with the SDGs (EC - European Commission, 2019a).

In the sustainability science debate, there are proposals to present the SDGs giving emphasis to the role of environment and ecosystems as building blocks for socio-economic development (Figure 2). This is in line with the so-called “strong sustainability” approach, where the conservation of the natural capital is the main objective and where the increase in economic and social capital should not happen at the expense of natural capital.

Figure 2. Presentation of the economy and society related SDGs as dependent upon the biosphere and its integrity



Source: Azote Images for Stockholm Resilience Centre

Sustainability assessment aims to operationalise the concept of sustainability in the analysis of concrete problems and in decision-making situations. Reflecting the heterogeneity of the theoretical concept, sustainability assessment is not a strictly defined methodology, but rather a field of science and practice that covers a range of possible tools and processes.

The various definitions of sustainability assessment (SA) proposed in literature converge in some fundamental features, such as complexity, transdisciplinary and support to decision-making. Sala et al. (2015) proposes a conceptual SAF, which is composed of a set of principles and a sustainability assessment procedure. According to the authors, the principles underpinning a SAF are:

- Guiding vision
- Essential considerations
- Adequate scope
- Framework and indicators
- Transparency
- Effective communication
- Continuity and capacity
- Broad participation of stakeholders.

The latter principle is particularly important, as it is peculiar and may distinguish SA from other integrated impact assessment methods, extending the coverage of the assessment, rather than to combining the parts. In this respect, Hacking & Guthrie (2008) outline how the "integrated assessment is a necessary but not sufficient condition for SA", which has also been defined as a form of strategic assessment, i.e. having a broad and forward-looking focus and perspective.

2.2 Life Cycle Assessment

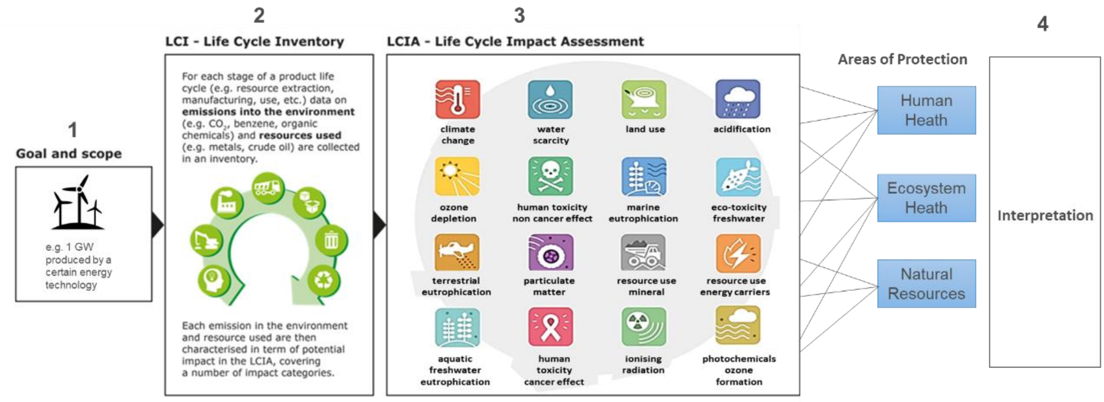
Assessing sustainability requires integrated approaches, able to model complex systems and to capitalise the best knowledge on impact assessment. Moreover, they should allow comparison between different options, be reproducible and transparent, highlighting trade-offs. Among the available approaches to sustainability assessment, Life Cycle Thinking (LCT) and the life cycle-based approaches applying LCT can play a pivotal role in comparing options and solutions in terms of sustainability (Sala et al., 2013). Life cycle thinking is a basic concept referring to the need of assessing burden and benefits associated to products/sectors/projects adopting a holistic perspective, from raw material extraction to end of life. LCT can be applied to assess the environmental, social, and economic pillars using Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA), and Life Cycle Costing (LCC) methodologies. Life Cycle Sustainability Assessment (LCSA) combines the three methodologies to provide a holistic assessment of the implications of a product life cycle. The three methodologies have various levels of availability and maturity, which in turn influence their level of implementation (Valdivia et al., 2021). LCA is the most established and mature methodology, having implemented characterisation models with justified impact pathways. A compendium on LCA providing guidance on how to apply LCA is provided by (Hauschild & Wenzel, 1998). S-LCA and LCC are less developed, especially concerning the impact assessment phase.

The importance of employing a life cycle perspective in assessing sustainability of production and consumption systems has been increasingly acknowledged in the EU policies since the early 1990s (Sala et al., 2021). The European Green Deal (EC - European Commission, 2019b), for instance, includes several policy initiatives which explicitly cite and mention life cycle (LC) thinking and methods. In the Chemical Strategy for Sustainability (EC - European Commission, 2020b) a life cycle perspective is required in the identification and minimisation of potential negative impacts linked to chemicals and materials.

Figure 3 shows the main elements of LCA, an internationally standardised tool (ISO, 2006) for the integrated environmental assessment of products (goods and services). As for the other LC-based methodologies (i.e., Social Life Cycle Assessment and Life Cycle Costing) four main phases are included in the methodology:

1. Goal and scope: describing the reason for executing the study, a definition of the studied product and its life cycle and the defining of system boundaries;
2. Inventory: listing all emissions released into the environment and resources extracted from the environment along the whole life cycle of the product under investigation;
3. Impact assessment: results or indicators of potential environmental and human health impacts are translated, with the help of an impact assessment method, into environmental impacts;
4. Interpretation: necessary for identifying, quantifying, checking and evaluating information from the results of the inventory and/or the Life Cycle Impact Assessment.

Figure 3. Main elements of the Life Cycle Assessment methodology



Source: based on Caldeira et al. 2022

2.3 Sustainable Innovation and Responsible Research and Innovation

Sustainable Innovation includes those innovations that can reconcile economic, social and environmental goals in order to achieve a "win-win-win" situation (Afeltra et al., 2023) and Responsible Research and Innovation (RRI).

Innovation can take many forms, for example (Iakovleva et al., 2021):

— product innovation: change in products/services offered by a company
— process innovation: change in the way products/services are offered or presented to the consumer
— innovation of position: change in the context in which the products/services are introduced in the market
— paradigm innovation: change in the basic mental models that guide the actions of the company.

There is growing literature referring to RRI (Yaghmaei & Poel, 2021), which is framed as a way to steer and manage innovation development, and to connect the basic concerns of business with the global challenges of society, i.e., the challenge for companies in a increasingly competitive world to innovate in order to generate economic benefits, but also to generate sustainable social value. The definition of RRI includes the concept that responsible innovation refers to a new or significantly improved product, service, or business model whose implementation at the market solves or alleviates an environmental or a social problem' (Halme & Korpela, 2014). Hence, principles of RRI include anticipation of societal needs and reflection of concerns (Owen et al., 2020), which calls for new innovation policies. RRI has led to the development of a possible framework of implementation, including for SMEs (Gonzales-Gemio et al., 2020).

2.4 Specific concepts related to the energy sector

Concepts are categories for the organization of ideas and building blocks of theory around which measures can be developed in order to allow the quantification of relevant aspects (Bryman, 2016). In this section we describe the most relevant concepts underpinning the SAF for energy technologies proposed in this report.

2.4.1 Clean and low-carbon energy

As a consequence of the signature of The Paris Agreement, 194 countries submitted Nationally Determined Contributions for achieving their objectives in terms of targets, policies and measures for reducing national emissions and on adapting to climate change impacts (UNFCCC, 2022b). In this context of reducing global emissions, the COVID-19 crisis resulted in a slight reduction of global CO_2 emissions in 2020, but in 2021 there was a return to pre-pandemic levels. In the Sixth Assessment Report (AR6) "Climate change widespread, rapid, and intensifying", the Intergovernmental Panel on Climate Change (IPCC) concluded that climate is warming up faster than what was foreseen, and immediate action should be taken (Myhre et al., 2013).

There is a common understanding that climate change should be managed, and that the timeframe for doing so is closing. There is a broad set of ways in which the economy can be decarbonised, which should be combined. Technological development can partially contribute to tackling climate change: in order to reduce the global greenhouse gas (GHG) emissions, we have been replacing fossil fuels with sustainable renewable energy sources. Open questions include which renewable technologies should be used, to what extent, how much energy we will actually need in the future. Moreover, technological development is insufficient: growing consumption continues to go well beyond planetary limits (Club of Rome, 2022) (Club Of Rome, 2022). Increasing energy efficiency is also part of the solution, but behavioural and social changes are likely necessary.

Technology innovation and deployment, and the availability of resources, economic growth, changes in society, not to mention unpredictable events like the pandemics, extreme weather events or geopolitical upheavals, will affect how humans produce, transform and consume energy and the degree to which the energy system is environmentally sustainable. The global energy market has been affected by Russia's invasion of Ukraine causing a shift on gas supply and an acceleration of the clean energy transition driven by the REPowerEU plan (EC - European Commission, 2022c) and the amended Fit for 55 (EC - European Commission, 2021d).

In this context, the EU Taxonomy Climate Delegated Act (European Union, 2020) aims at supporting sustainable investment by making it clearer which economic activities most contribute to meeting the EU's environmental objectives. It defines an actual list of environmentally sustainable activities through technical screening criteria. The goal of the EU Taxonomy is to prevent greenwashing and to help investors identify economic activities in line with environmental and climate objectives. Shifting towards renewable energy is essential for achieving climate neutrality, and it is also necessary to have stable sources to accelerate the transition towards net-zero greenhouse gas emissions.

An in-depth review of a range of energy scenarios is needed to better understand the role that selected technologies could play in future energy systems, how they interact with each other, what is needed to integrate them into existing systems and how they will be affected by social changes. Also, a comparative assessment of energy scenarios is useful, because it may identify the basic set of technologies dominating the majority of energy scenario projections (Tarvydas, 2022).

International co-operation on energy will also need to be enhanced and redesigned. With the centrality of energy to the global development and climate agenda undisputed, it is important to further increase the international co-operation helping to steer the energy transition. The speed at which energy sectors respond to geopolitical developments makes it imperative that co-operative modalities, instruments and approaches remain stable and secure. For their own good, and for that of the developing world, the G20 countries – that account for the bulk of global emissions - must act in concert, raising their climate ambitions and fulfilling their pledges. For the developing world, collaboration is crucial if countries are to leapfrog systems already nearing obsolescence in the developed world and thereby avoid misplaced investments.

2.4.2 Renewable energy

Renewable energy is energy derived from natural sources – such as sunlight and wind - that are replenished at a higher rate than they are consumed.

Fossil fuels – such as coal, oil and gas - on the other hand, are non-renewable resources that take hundreds of millions of years to form. Fossil fuels cause harmful greenhouse gas emissions when burned, such as carbon dioxide. Generating electricity from renewable energy sources can lower emissions, in comparison to burning fossil fuels. A cleaner and more resilient future energy system with net-zero emissions will require a wide range of technologies, some of which are still at an early stage of development. For these new technologies, innovation is an uncertain and competitive process.

Successful technology concepts eventually pass through four stages: prototype, demonstration, early adoption and maturity. Feedback between the stages means that technology options are always evolving. Size, consumer value and synergies with other technologies are all attributes that determine the speed with which technologies pass through the stages. The process of innovation involves a wide range of participants: governments, researchers, investors, entrepreneurs, corporations and civil society all play important roles in generating ideas for new or improved technologies and in improving and financing them right through to market entry and deployment. Innovation systems are complex and rest on four pillars: resource push, knowledge management, market pull and socio-political support (IEA - International Energy Agency, 2020).

As an example, the first demonstrations of photovoltaic (PV) cells were made in the 1950s in the United States by Bell Labs, which was granted the right to spend a certain share of AT&T and Western Electric's operating budget on risky and basic R&D as part of its government-regulated telecommunications license. US dominance of the technology persisted through the 1970s under the supervision of the National Aeronautics and Space Administration (NASA), which had sizeable public R&D funds, and which began using PV in satellites and shuttles. The oil shocks of the 1970s spurred Japan and the US to increase their public funding for PV research in a quest for more secure energy sources. In the US, companies were spun off from government-regulated laboratories and found niche business opportunities for PV. Throughout the 1980s and 1990s, PV for electricity production was uncompetitive except for off-grid customers with a willingness to pay a high price for small amounts of electricity. Suppliers in the US, then Japan and Germany were, however, able to scale-up as a result of government procurement and incentive policies in these countries. As the potential became more apparent to researchers in more countries, R&D funding increased, the number of patents accelerated and costs fell. Of particular significance in helping to create a market were government feed-in tariff programmes, first in Germany in the 1990s, then in Italy, Spain, the United States, China and India by the 2010s. These programmes, backed by rising deployment targets, targeted grid connected systems and provided the guaranteed scale-up needed for global supply chains. At this point, patenting peaked and the market consolidated around a dominant design. Even though the development of solar PV to this point took around 60 years, progress would almost certainly have been slower if these countries – and others not mentioned here – had not shared the responsibility for these innovation stages (IEA - International Energy Agency, 2020).

Moreover, a diversified and interconnected energy system requires the modernisation and expansion of infrastructure. Transmission and distribution systems will need to accommodate the highly localised, decentralised nature of many renewable sources, along with the various trade routes and intermittence involved. With regard to the interconnectors required to trade electricity and shipping routes for hydrogen and derivatives, planning must consider a staggering array of global dynamics, proactively linking countries to promote diverse and resilient energy systems. Public acceptance, which is critical for any large-scale undertaking, can be promoted through transparency in planning and implementation, and by providing opportunities for communities to voice their perspectives.

2.4.3 Energy efficiency, labelling and eco-design

To accelerate the transition to a circular economy model, the European Commission designed a future oriented agenda in its Circular Economy Action Plan for a cleaner and more competitive Europe (EC - European Commission, 2020c).

The proposal for a new Ecodesign for Sustainable Products Regulation, published on 30 March 2022, is the cornerstone of the Commission's approach to more environmentally sustainable and circular products. The proposal builds on the existing Ecodesign Directive, which covers energy-related products (EC - European Commission, 2022f). The proposal establishes a framework to set eco-design requirements for specific product groups to significantly increase their circularity, energy performance and other environmental sustainability standards. It will enable the setting of performance and information requirements for almost all categories of physical goods placed on the EU market (with some notable exceptions, such as food and feed, as defined in Regulation EC/178/2002). For groups of products that share sufficient common characteristics, the framework also allows to set common rules.

The framework will allow for the setting of a wide range of requirements, including on

— product durability, reusability, upgradability and reparability
— presence of substances that inhibit circularity
— energy and resource efficiency
— recycled content
— remanufacturing and recycling
— carbon and environmental footprints
— information requirements, including a Digital Product Passport.

The new "Digital Product Passport" will provide information about products' environmental sustainability. It aims to help consumers and businesses make informed choices when purchasing products, facilitate repairs and recycling and improve transparency about products' life cycle impacts on the environment. The product passport should also help public authorities to better perform checks and controls (EC - European Commission, 2022f).

By 2030, the new sustainable products framework can lead to 132 mtoe of primary energy savings, which corresponds roughly to 150 billion cubic meters of natural gas, almost equivalent to EU's import of Russian gas (*Ibidem*).

The current legislation on Ecodesign requires that priorities for implementation are established through regularly updated rolling working plans that take stock of progress made and include indicative priorities for new energy-related product groups to be considered.

The Ecodesign and energy labelling working plan 2022-2024 builds on work done since the adoption of the first Ecodesign Directive, but also covers the work required under the Energy Labelling Framework Regulation (EU/2017/1369) and takes stock of the progress made with the European Product Registry for Energy Labelling (EPREL). The plan also covers similar work on tyre labelling that has a specific legal basis.

The working plan 2022-2024 covers new energy-related products and updates and increases the ambition for products that are already regulated, as a transitionary measure until the new regulation enters into force. It addresses consumer electronics, such as smartphones, tablets and solar panels, a fast-growing waste stream (EC - European Commission, 2022b).

2.4.4 The social dimension of energy: energy access, energy poverty, energy sufficiency, energy justice

Energy is not merely a technical or economic concept, but deeply embedded with social, cultural, and behavioural aspects. The social dimension of energy refers to the impact and interaction between energy systems and society and therefore taking into account how energy production, distribution, and consumption affect individuals, communities, and societies as a whole.

At its core, the social dimension of energy refers to how energy choices and practices shape people's lives, behaviours, and well-being. This encompasses various aspects such as energy access and sufficiency, affordability, energy justice, social acceptance of energy technologies, behavioural change, and the social implications of (just) energy transitions.

Energy access refers to the availability, affordability and reliability of modern energy services for individuals and communities. It encompasses the provision of electricity, clean cooking solutions, heating, cooling, and mechanical power, which are crucial for meeting basic human needs and driving socioeconomic development (IEA - International Energy Agency, 2017).

Access to energy is essential for improving living standards, education, healthcare, and economic opportunities. The access to safe and efficient cooking technologies and fuels, which should replace traditional biomass (such as wood, charcoal, and dung) and inefficient cook stoves, is crucial for reducing indoor air pollution, improving health outcomes (especially for women and children), and mitigating environmental degradation. Access to affordable and sustainable electricity, heating and cooling systems is vital for human well-being, particularly in regions with extreme climates. Access to energy for productive activities plays a crucial role in poverty reduction, job creation, and fostering economic growth in rural and urban areas. Additionally, reliable energy access ensures a continuous and consistent supply of energy, reducing disruptions and enabling the functioning of the economic system.

Energy access is therefore fundamental for achieving various social, economic, and environmental development goals. Efforts to expand energy access, particularly in developing countries, remote areas and for marginalized populations, are crucial to tackling energy poverty, promoting energy justice, and advancing sustainable development.

Energy poverty refers to the lack or limited access to modern energy services, such as electricity and clean cooking facilities, which are essential for meeting basic human needs (Sovacool, 2012). It is a multidimensional concept that encompasses both the lack of energy availability and the inability to afford and effectively utilize energy services. Energy poverty affects billions of people globally, particularly in developing countries. In developed countries, energy poverty is usually linked to the affordability of energy services (such as heating, cooling, cooking and lighting) and is usually measured through expenditure-based (comparing energy costs against a threshold), consensual-indicators (self-reported assessment of housing conditions), and direct measurement (comparing the level of energy services to a certain benchmark) (DellaValle & Czako, 2022).

In developed countries, sustainable consumption has also been related to the concept of energy sufficiency. In general, sufficiency perspectives draw attention to the point at which further consumption levels do not drive increasing levels of well-being. In particular, several studies have found strong correlations between energy consumption and/or carbon emissions and living standards at lower consumption levels (developing countries), and decoupling at higher levels (industrialized countries). In particular, there is a point when the Human Development Index (used as a proxy for human well-being) reaches a saturation level (plateau) at increasing energy consumption levels (Steinberger & Roberts, 2010). Following this evidence, many scholars suggested to define energy sufficiency as a policy objective and a societal goal, defining thresholds of per capita energy consumption that allow achieving more equitable collective well-being while preserving the Earth's ecological integrity (Burke, 2020).

The energy sufficiency concept has been applied at EU level in terms of energy saving objectives. Indeed, driven by the energy crises that followed the Russian invasion to Ukraine, the EU has set energy savings objectives, with the aim of decreasing the reliance on fossil fuel imports from Russia. The target of decreasing gas consumption by at least 15% was exceeded and the gas demand dropped by 18% between August 2022 and March 2023[3].

Energy justice is a concept related to the social and ethical dimensions of energy systems, in particular to a fair distribution of energy benefits and burdens among individuals, socio-economic groups and communities. It recognizes that energy decisions can have significant impacts on marginalized groups, vulnerable populations, and the environment. Energy justice encompasses various aspects, including accessibility, affordability, reliability, safety, and participation in decision-making processes (Jenkins et al., 2016). Among other definitions, Sovacool et al. (2017) describes energy justice as a "global energy system that fairly disseminates both the benefits and costs of energy services, and one that has representative and impartial energy decision-making". They also define a framework for energy justice which includes 10 principles, which include, e.g., availability, sustainability, affordability, intergenerational equity and transparency (Table 1).

Linked to energy justice, climate justice is a framework that connects social inequalities and climate change, in particular looking at the distributional effects of climate change. In particular, it is noted that developed nations are the biggest producers of the emissions that induce climate change, while its effects disproportionately burden the poorest and disadvantaged (often in developing countries) (Burke, 2020).

Building on the concept of just transition, the EU has addressed the social and economic effects of the transition towards a climate neutral economy, focusing on the regions, industries and workers who will face the greatest challenges. This is the case of regions whose economy heavily relies on carbon intensive industries and production of fossil fuels. A dedicated fund was created to support vulnerable people and citizens which might be affected by the transition, e.g. because of job loss. Also companies and regions should be supported in facilitating economic diversification, investing in renewables, improving in energy infrastructures, etc. (EC 2021).

[3] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en

Table 1. Principles of the energy justice conceptual framework proposed by Sovacool et al. (2017)

	Principle	Description
1	Availability	People deserve sufficient energy resources of high quality (suitable to meet their end uses)
2	Affordability	All people, including the poor, should pay no more than 10% of their income for energy services
3	Due process	Countries should respect due process and human rights in their production and use of energy
4	Transparency and accountability	All people should have access to high quality information about energy and the environment and fair, transparent, and accountable forms of energy decision-making
5	Sustainability	Energy resources should be depleted with consideration for savings, community development, and precaution
6	Intra-generational equity	All people have a right to fairly access energy services
7	Intergenerational equity	Future generations have a right to enjoy a good life undisturbed by the damage our energy systems inflict on the world today
8	Responsibility	All actors have a responsibility to protect the natural environment and minimize energy-related environmental threats
9	Resistance	Energy injustices must be actively, deliberately opposed
10	Intersectionality	Expanding the idea of recognitional justice to encapsulate new and evolving identities in modern societies, as well as acknowledging how the realization of energy justice is linked to other forms of justice e.g. socio-economic, political and environmental

3 Definitions and sustainability dimensions in the proposed framework

In this section, the definitions adopted in the framework are presented. These are partially based on the SSbD framework developed by (Caldeira et al., 2022), but adapted to the sustainability assessment of energy technologies. Annex 1 gives an overview of the definitions of the terms used.

3.1 Definitions

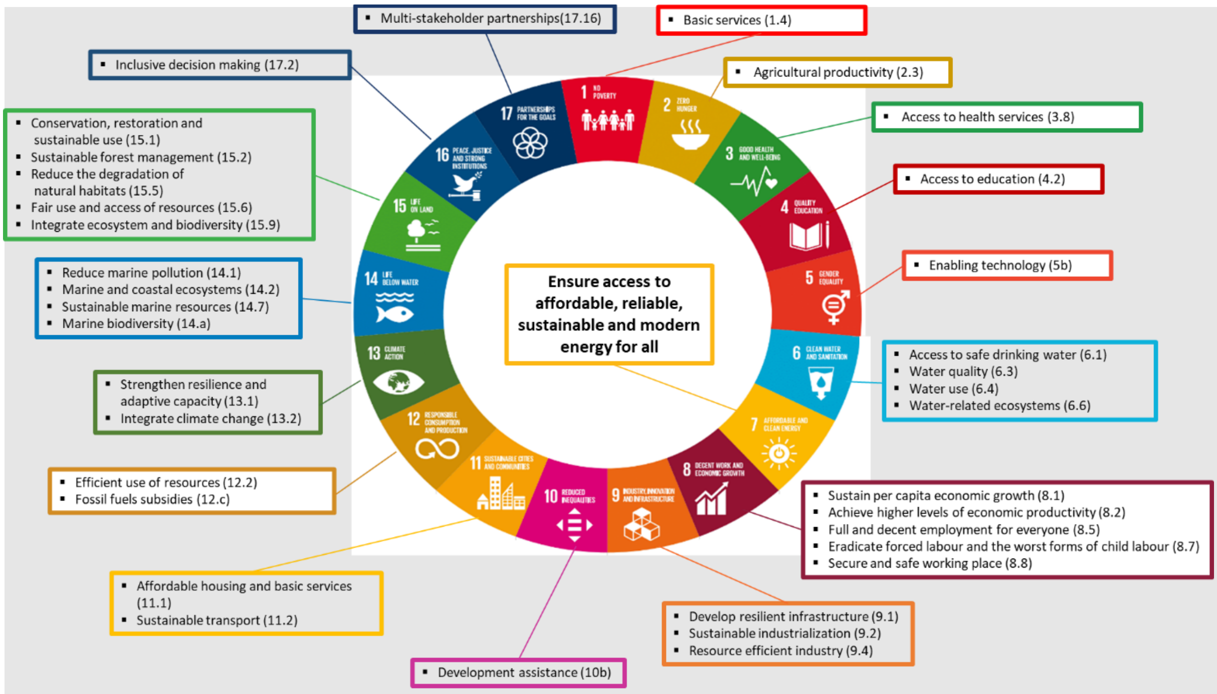
The concept of sustainability can generally be formulated as the ability of a product/service/technology "to deliver its function without exceeding environmental and ecological boundaries along its entire life cycle, while providing welfare, socio-economic benefits and reducing externalities" (Caldeira et al. 2022).

Sustainable energy can be defined in multiple ways. It refers to the production, distribution, and consumption of energy in a manner that meets present needs without compromising the ability of future generations to meet their own energy needs (Hollaway, 2013). Sustainable energy is sometimes identified with the renewability of the energy sources, for instance Lund (20120) defines sustainable energy as those sources that are not expected to be depleted in a time frame relevant to the human race and that therefore contribute to the sustainability of all species (Lund, 2010). It should be noted, however, that renewable energy sources are not necessarily exploited in a sustainable way but there are many other factors influencing the overall sustainability of energy systems.

Taking a broader perspective, the International Renewable Energy Agency (IRENA) defines sustainable energy as "energy that is accessible, cleaner and more efficient, affordable, and reliable, while contributing to economic growth, social well-being, and a stable environment." (IRENA, 2022). This definition emphasizes the attributes of accessibility, cleanliness, efficiency, affordability, and reliability, as well as the broader benefits of sustainable energy for society and the environment. Similarly, Grigoroudis et al. (2021) relate energy sustainability to the provision of adequate, reliable, and affordable energy, in conformity with social and environmental requirements.

Several other definitions capture the essence of sustainable energy. One widely recognized definition is provided by the United Nations Sustainable Development Goal (SDG) 7, which aims to ensure "access to affordable, reliable, sustainable, and modern energy for all." (UN General Assembly, 2015). This definition emphasizes the importance of affordability, reliability, and modernity while highlighting the need for sustainability. It is also evident that energy is an enabler for many other SDGs, e.g. those related to, e.g., industry, housing, poverty, etc. In some cases, trade-offs can emerge between the goal of ensuring energy access and those related to environmental preservation. Figure 4 illustrates the relevant goals and targets related to sustainable energy.

Figure 4. SDG 7 and other goals and targets related to secure and sustainable energy



Source: own elaboration

UNECE (2020) recognises the key role that energy plays in economic and social development, as well as its environmental impact and in the project "Pathways to Sustainable Energy"", sustainable energy is structured in three pillars that embrace the most relevant SDGs (Error! Reference source not found.):

— Energy Security: 'Securing the energy needed for economic development'

— Energy and Quality of Life: "Provision of affordable energy that is available to all at all times"

— Energy and Environment: "Limit the impact of energy system on climate, ecosystems and health"

Figure 5. Energy for Sustainable Development, as conceptualized in UNECE 2020

Source: UNECE 2020

In summary, sustainable energy should be affordable and reliable, provided by modern energy services that are environmentally friendly, socially inclusive, and economically viable. It encompasses the use of renewable energy sources, energy efficiency measures, and the consideration of long-term environmental and social impacts. Achieving sustainable energy is crucial for addressing energy security, combating climate change, promoting economic development, and ensuring a better future for generations to come.
In the next section the dimensions for a secure and sustainable energy are defined.

3.2 Sustainability dimensions and hierarchical approach

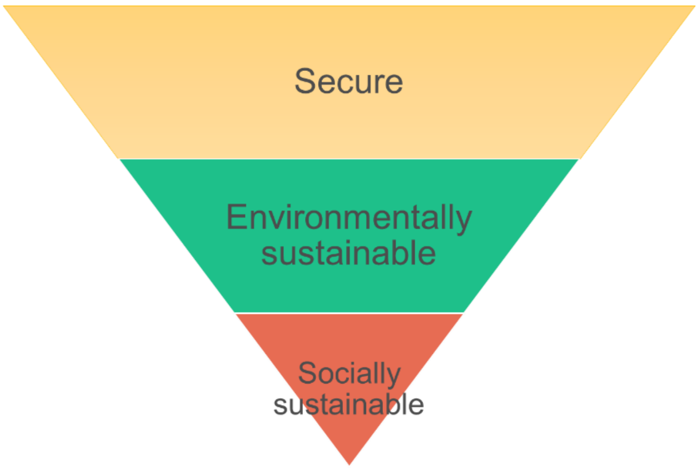
Based on the SDG 7 and UNECE framework on energy for sustainable development, the following dimensions are defined as part of the framework proposed in this report, following the structure shown in Figure 6:

— Supply security

— Environmental sustainability

— Social sustainability

Figure 6. Hierarchical principles underpinning the sustainability assessment framework for energy technologies



Source: own elaboration

Energy security is a transversal concept, which primarily addresses the economic aspects related to a stable energy supply within a national or regional context. This encompasses the accessibility of energy resources, including trade considerations and related energy prices. Numerous significant factors, including social, economic, environmental, and technological elements, play a crucial role in this field. While some nations perceive energy security as achieving self-sufficiency in energy sources, others view it within a regional framework, emphasizing interconnectivity and trade. Availability of energy resources can also play a role in case of exhaustible resources, as depletion can be accelerated by increasing energy demands due to growing global population and economic development. Similarly, biophysical and economic availability of minerals used to build energy infrastructures can hinder the energy supply, especially in the case of some renewable technologies have high demands of Critical Raw Materials.

Other threats to energy security include social and political aspects, like geopolitics, terrorism, opposition from local communities or conflicts. Energy security can also be threatened by environmental factors like natural disasters or climate change preventing policies, which can phase out some energy sources due to their high carbon intensity.

Historically, the EU has been highly dependent on imports of both energy and raw materials. The recent geopolitical events of the Russia-Ukraine war lead to a change of perspective and energy security became a top priority in the EU policy. As described in the RePower EU Communication (EC - European Commission, 2022c), published in response to the hardships and global energy market disruption caused by Russia's invasion of Ukraine, energy security can be achieved through the following measures: diversifying energy supplies, securing affordable energy supplies, producing clean energy and saving energy (*Ibidem*). In order to pursue these objectives, for instance facilitating the production of renewable energy technologies, the Net Zero Industry Act (EC - European Commission, 2023) aims at creating a predictable and simplified regulatory environment, which aims at promoting investments in the production capacity of products that are key in meeting the EU's climate neutrality goals.

As mentioned, energy security includes also environmental and social objectives, especially for what concerns the clean and renewable energy production, the access to affordable energy and the role of energy as enabler for social services like health, education, housing, etc., as shown in Figure 4 on the relation of SDG 7 with other Goals. For these reasons, energy security can be considered as the first step in the hierarchical structure of the framework illustrated in Figure 6. Nevertheless, trade-offs can also emerge between the security dimension and other environmental and social aspects. For instance, ensuring affordable access to energy can create environmental impacts affecting local communities where energy projects are developed.

The environmental sustainability dimension of energy concerns the need of ensuring that increasing energy demand is met, while providing a healthy environment with clean air, and protecting from climate change. Energy emissions contribute 60% of total greenhouse gas emissions (UNECE, 2020) so reducing the carbon footprint across the energy supply chain is vital in order to support climate change mitigation efforts. Beyond climate change and air pollution measures, other relevant environmental impacts to be taken into account include the competition for natural resources like water and land, the pollution of air caused by energy generation and consumption, all the environmental impacts due to mining activities, needed to supply minerals and metals for energy infrastructures, batteries, etc.

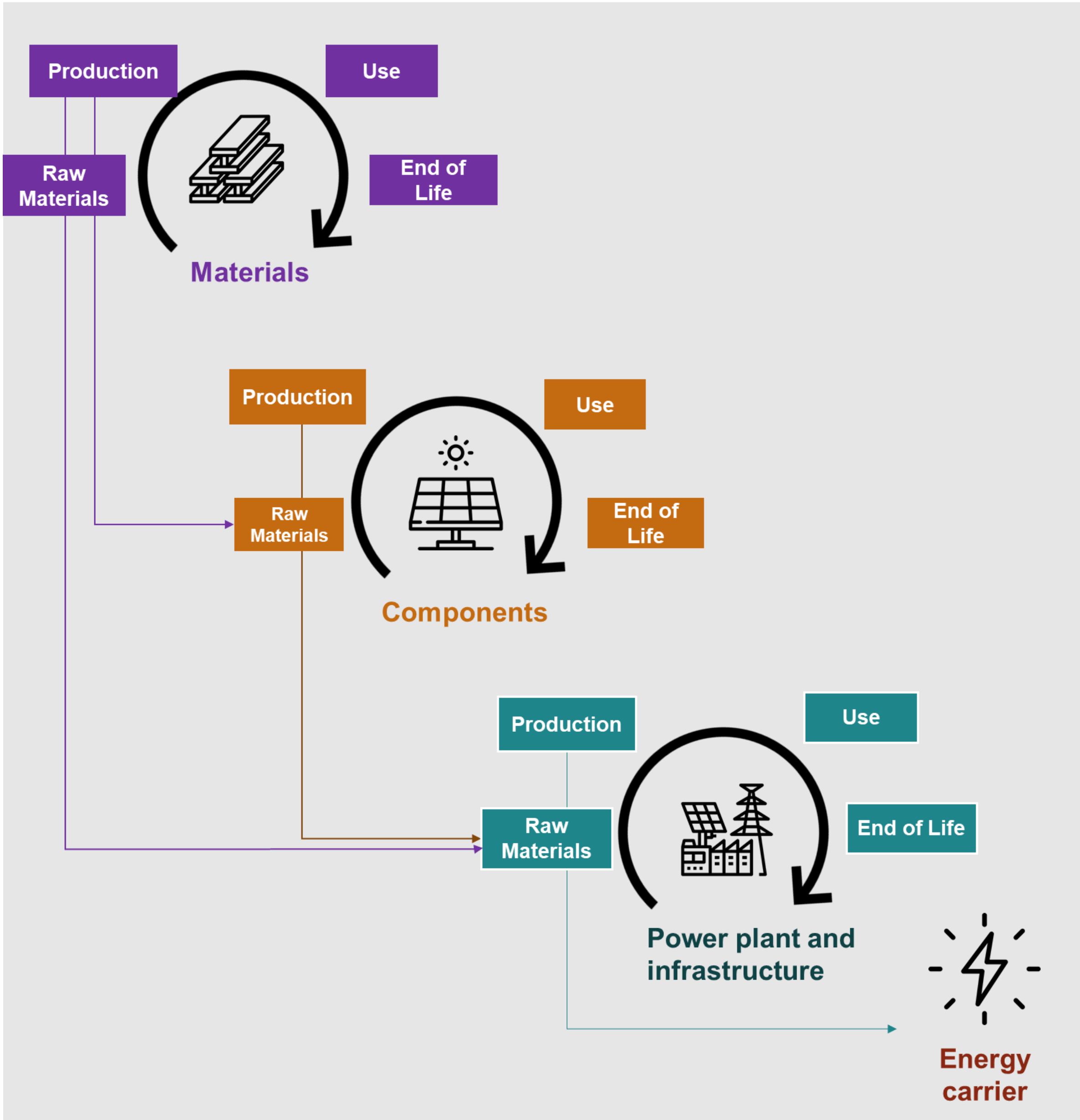
The social sustainability dimension of the framework includes additional social considerations that are not captured in the security dimension (i.e. related to access and affordability) and that can affect all types of stakeholders. This comprises the impacts on local communities where an energy project is developed, including rural development, but also impacts occurring in supply chains involved in the production of materials and infrastructure. For instance, poor working conditions and human rights abuses in the sectors involved in the energy supply chain. Notably, also positive impacts should be taken into account as the contribution to employment and development.

4 Structure of the framework: a stepwise approach

4.1 Elements of the framework

The SAF proposed here can be used for the evaluation and comparison of energy technologies. Aligned with the Safe and Sustainable by Design framework for chemicals and materials (Caldeira et al., 2022; EC - European Commission, 2022a), the framework builds on the assessment of the entire life cycle of an energy technology, thus considering the production of materials, components, power plant and infrastructure needed to supply an energy unit. Figure 7 provides an illustration of the various steps for a generic technology, but life cycles can differ considerably, depending on the energy source and technology.

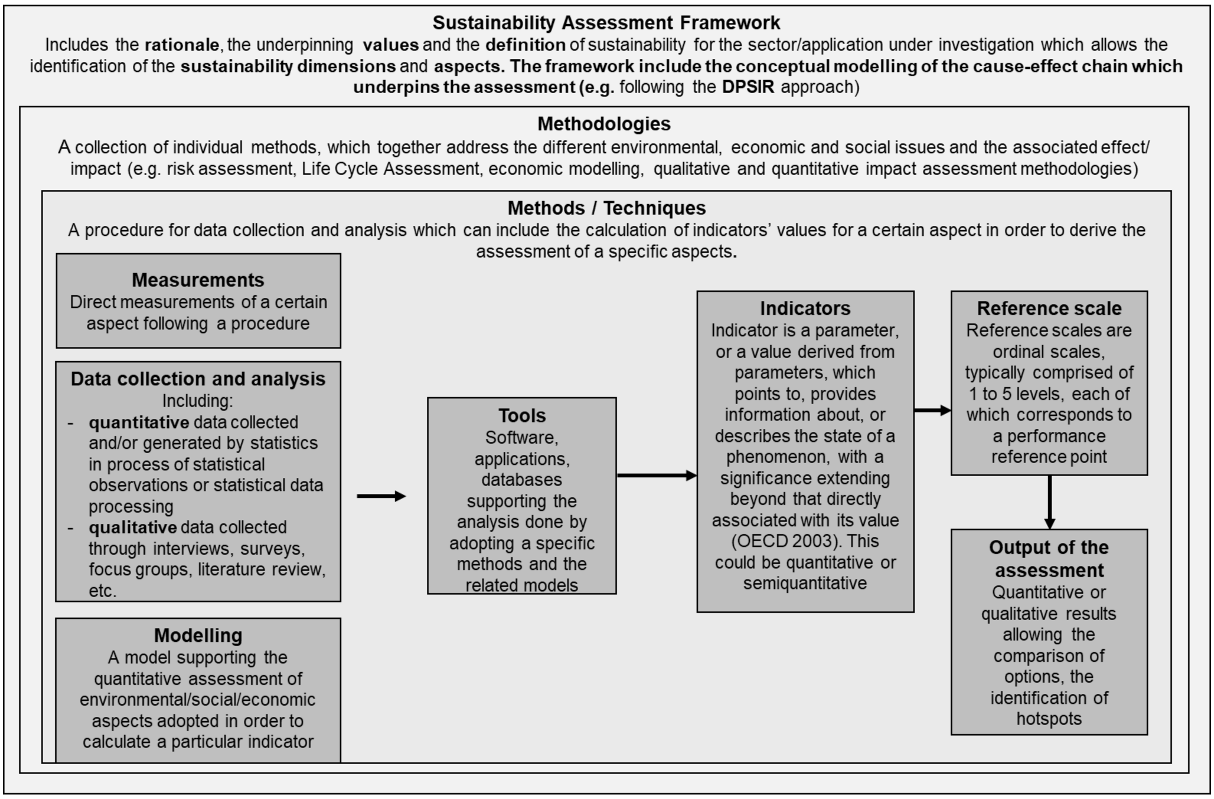
Figure 7. Simplified representation of the life cycle of an energy technology. The life cycle stages are connected via logistics (transport and distribution stages)



Source: own elaboration

The framework proposes a rationale and structure for the identification and integration of sustainability dimensions, aspects, methodologies, methods, models, indicators and tools, to evaluate the sustainability of energy technologies and their contribution to energy security. The definitions of the terminology used is defined in Error! Reference source not found. adapted from Sala et al. (2013) and Caldeira et al. (2022).

Figure 8. Structure for a sustainability assessment framework and its elements



Source: own elaboration

4.2 Conceptual modelling of the cause-effect chain

Within the framework, a conceptual modelling of the key cause-effect chain should underpin the assessment. The Driver-Pressure-State-Impact-Response (DPSIR) approach (EEA - European Environmental Agency, 1999) can support in the identification of this rationale. Indeed, it assumes a chain of causal links starting with 'Driving forces' (economic sectors, human activities) through 'pressures' (generated by the processes (emissions, waste) to 'states' (physical, chemical and biological) and 'impacts' on ecosystems, human health and functions, eventually leading to 'responses' by different private and public stakeholders[4] (prioritisation, target setting, indicators). The aspects to be considered within the identified sustainability dimensions (namely security, environmental and social aspects) can be classified according to the following categories:

— Drivers which can produce pressures on a system. These include socio-economic issues like demographic changes, consumption activities, etc. but also resource-related aspects, i.e. those aspects that relate to and characterise the energy production process and could be considered specific for the technology.

— Pressure aspects which reflect a pressure along the supply chain on the environment, human health (due to the resource-related aspects) such as emissions to water, soil or air, operational costs, working hours etc.).

— State aspects which can refer to biophysical conditions but also legislative frameworks.

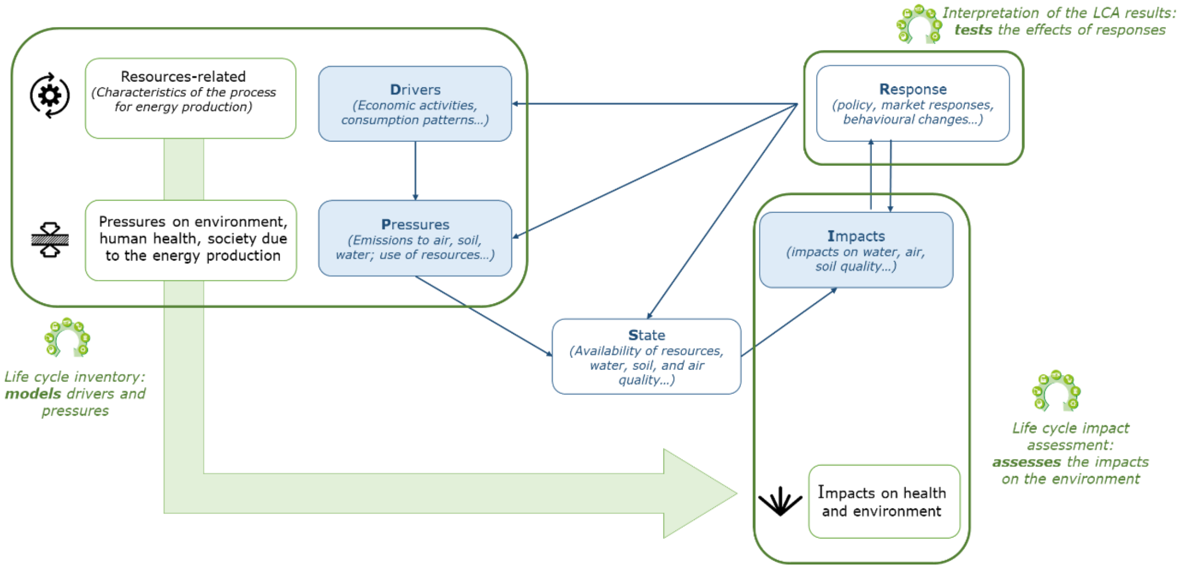
[4] Exact meaning in Annex "Definitions"

— Impact aspects which reflect the effect caused by the pressure aspects, in the respective dimensions: security, environmental, social, and economic. In the case of social impacts, impacts on human well-being is the final outcome of the process. However, the categories and indicators used to assess the social part are related to pressures and state.

— Response-related aspects which relate to reactions from different stakeholders.

The DPSIR allows designing a structure for which indicators follow a cause-effect chain, especially in the case of environmental aspects. Figure 9 illustrates the relation between the elements of the DPSIR framework and of the phases of the Life Cycle Assessment methodology. The first category relates to the 'Drivers' in the sense that decisions taken regarding for example the type of feedstock to use, and specific technological and processing-related choices, will determine the pressures on the environment, human health and on society. Therefore, 'Pressures' in the DPSIR are related to the 'pressure aspect'. Finally, as indicated in Figure 9, both 'Drivers' and 'Pressures' will be reflected in the 'Impacts'.

Figure 9. Classification of aspects in resource-related aspects, pressures, and impacts (green boxes) in relation to the DPSIR framework (blue boxes). The figure illustrates as well the relation with the Life Cycle Assessment steps (Inventory analysis, Impact Assessment, and Interpretation).



4.3 Design principles

The SAF can be applied also at a research and development stage, applying some design principles that can support the integration of sustainability principles in the development of new energy technologies.

The proposed design principles (Table 2) build on those developed in Caldeira et al. (2022) as well as policy related ambitions (e.g. transition to a circular economy (EC - European Commission, 2020c), to a bio-economy (EC - European Commission, 2018), to zero pollution (EC - European Commission, 2021c) etc..

Among the principles, some are related to environmental sustainability and resources, aiming to minimise the use of natural resources and the emission of substances into the environment. This can be achieved by several strategies which include, for example, increasing the resource efficiency, the process efficiency (e.g. via process intensification or applying lean thinking), applying the waste hierarchy, using innovative business models for innovation, exploring opportunities for industrial symbiosis etc. (Corona et al., 2019).

Table 2. List of design principles and associated definitions, and example of indicators that can be used in the technology design phase

Principle (based on SSbD framework)	Definition	Examples of indicators related to the principle
Material efficiency	Reduce the use of raw materials and the generation of waste.	- Net mass of materials consumed - Material Intensity index*

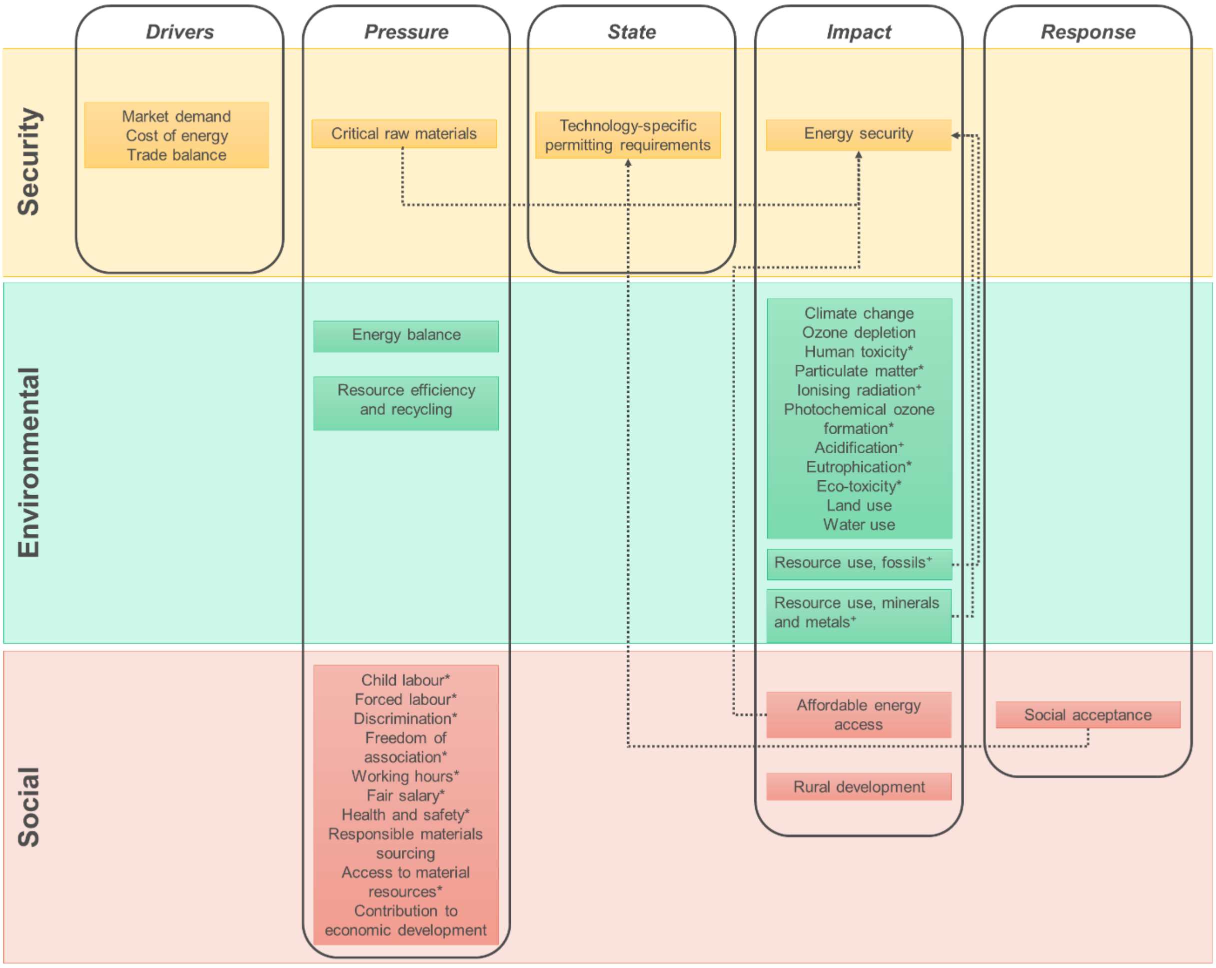
Principle (based on SSbD framework)	Definition	Examples of indicators related to the principle
		- Water consumption - Recycling efficiency/recovery rate - Total amount of waste - Amount of waste to landfill - Critical Raw Material presence
Minimize the use of hazardous chemicals/materials in the production of components	Preserve functionality of products/technologies while reducing or completely avoid using hazardous chemicals/materials where possible.	- Biodegradability of manufactured material - Classification of raw materials as Substance of Very High Concern (SVHC)
Design for energy efficiency	Minimize the overall energy used to produce a product/technology in the manufacturing process and/or along the supply chain.	-- Energy consumption - Energy efficiency
Use renewable sources	Target resource conservation, either via resource closed loops or using renewable material/ secondary material and energy sources.	- Renewable or fossil feedstock - Recycled content - Share of Renewable Energy
Prevent and avoid hazardous emissions	Apply technologies to minimise and/or to avoid hazardous emissions or pollutants in the environment.	- Biological oxygen demand - Chemical oxygen demand - Total organic carbon - Non-Aqueous Liquid Discharge - Wastewater to treatment - Amount of hazardous waste
Reduce exposure to hazardous substances	Eliminate exposure to chemical hazards from processes as much as possible. Substances which require a high degree of risk management should not be used and the best technology should be used to avoid exposure along all the life cycle stages.	- Biodegradability of manufactured chemical/material - Classification of raw chemicals/materials as SVHC
Design for circularity	Design a technology in a way that, once it has fulfilled its function, it breaks down into products that do not pose risk to the environment/humans. Design to ease reuse, waste collection, sorting and recycling/upcycling.	- Recyclable? - Durability - Disassembly/reparability design
Consider the whole life cycle	Apply the other design principles thinking through the entire life cycle, from supply-chain of raw materials to the end-of-life in the final product/technology	- Recyclable? - Disassembly/reparability design - Durability - Value-based resource efficiency indicator - Material Circularity Indicator

* Ratio between the kg of raw materials used per kg of material produced.

5 Security and sustainability assessment

The overall structure of the framework is shown in Figure 10. All the security and sustainability aspects are organized following the classification of the DPSIR framework described in section 4.2. The figure also shows the security, environmental and social aspects in the relation to the previous Clean Energy Technologies Observatory (CETO) framework. A more detailed description of the available methods and data sources for each aspect is available in Annex 2.

Figure 10. Overall structure of the sustainability assessment framework for energy technologies with security, environmental and social aspects organized based on DPSIR approach. Arrows indicate that specific social and environmental aspects can influence energy security



*: aspects present in CETO with a different name or in an aggregated form e.g. working conditions, air quality; +: new aspects, not included in CETO

Source: own elaboration

5.1 Security assessment

Assessing energy security within the context of an energy technology sustainability assessment, as in the case of CETO, involves considering the potential risks and vulnerabilities associated with the specific technologies being evaluated. Aspects to be considered to assess energy security of energy technologies are described in Table 3.

Table 3. Sustainability aspects included in the pillar "security"

DPSIR stage	Aspect	Description
Driver	Market demand	At global level, the quantity of energy required by consumers and industries can increase due to population and economic growth. For the EU, urbanization, increasing levels of industrialization and changing comfort preferences can be drivers of increased energy demand. More extreme climate conditions might also play a role, as they can result in increasing/decreasing energy demand, for heating and cooling.
Driver	Cost of energy	Increasing energy demand and limited resource availability can result in higher cost, which can threat the affordable access to energy. Increasing cost of energy can also be driven by changes in the supply side, due to a variety of events, e.g. natural disasters impacting energy infrastructures or conflicts and geopolitical controversies where resources are used as political weapons, as in the case of the Russian invasion of Ukraine.
Driver	Trade balance	High reliance on imports can result in higher vulnerability and risk of supply. Diversification of trade partners and level of governance of energy supplying countries are key factors to take into account in order to manage the energy supply risk.
Pressure	Use of Critical Raw Materials (CRMs)	CRMs are materials with relatively higher economic importance for the EU economy and higher supply risk, due to the high concentration of supply from countries with weak governance. The limited substitutability of these materials can also increase materials' criticality which in turn leads to a risk of supply disruption and can be reflected in higher prices in the market. Given the high requirements of CRM for some renewable technologies (e.g. batteries, wind turbines, etc.) (Carrara et al., 2023) shortages of these materials or unstable markets can affect the supply of clean energy technologies.
Driver	Trade balance	High reliance on imports can result in higher vulnerability and risk of supply. Diversification of trade partners and level of governance of energy supplying countries are key factors to take into account in order to manage the energy supply risk.
Pressure	Use of Critical Raw Materials (CRMs)	CRMs are materials with relatively higher economic importance for the EU economy and higher supply risk, due to the high concentration of supply from countries with weak governance. The limited substitutability of these materials can also increase materials' criticality which in turn leads to a risk of supply disruption and can be reflected in higher prices in the market. Given the high requirements of CRM for some renewable technologies (e.g. batteries, wind turbines, etc.) (Carrara et al., 2023) shortages of these materials or unstable markets can affect the supply of clean energy technologies.
State	Technology-specific permitting requirements	The permitting requirements influence the speed of permitting procedures, which varies from one Member State to another. Delays on the permitting procedures can have serious impact on investors and result in the installation of outdated technologies, with negative impacts on competitiveness and energy security. Increasing public

DPSIR stage	Aspect	Description
		involvement and acceptance of renewable energy projects is also important in order to avoid negative perception and opposition to energy projects from local communities.
Impact	Biophysical availability	The biophysical availability of energy resources (e.g. fossil fuels) and minerals and metals used for the supply of energy infrastructure can also affect the energy security. In the LCA methodology, the use of exhaustible resources is assessed considering the available reserve in order to assess the impact on resource depletion (Section 5.2).
Impact	Affordable energy access	It refers to the ability of individuals, households, and communities to obtain reliable and sufficient energy services at a cost that is affordable relative to their income levels. It encompasses the affordability of both the energy sources themselves (such as electricity, natural gas, or cooking fuels) and the appliances or technologies required to utilize those energy sources. This aspect is discussed in the section 2.4.4 and part of the social assessment (5.3).
Response	Public acceptance	Public acceptance of energy projects is also an important precondition to ensure stable energy supply. Opposition from local population can slow down project development. (This aspect is discussed in the social assessment section 5.3). Public consultation and stakeholder engagement during the permitting process can provide information to the public, affected communities, and interested parties, allowing them to express concerns, provide feedback, and participate in decision-making processes. On the other side, the length and complexity of the permitting requirements can influence the energy supply and slow down the response to energy market shocks.

5.2 Environmental sustainability assessment

The environmental sustainability assessment of energy technologies cover the environmental impacts along the entire value chain, from extraction of raw materials up to waste management through a holistic approach integrating the minimisation of the environmental impacts, and maximization of circularity and functionality throughout their entire lifecycle. Life cycle assessment is proposed to assess the environmental impacts of energy technologies.

To assess the environmental sustainability of an energy technology a function-based LCA including the entire life cycle must be conducted. Aspects related to system boundary conditions and their context need to be considered for comparison. LCA studies should be conducted following the same modelling principles to ensure its harmonisation and allow comparison of results. Below there is a brief overview of LCA guidelines as well as current limitations. In any case, LCA results must be presented stating clearly the assumptions and data sources used.

5.2.1 LCA guidance in the context of energy technologies

Clean energy technologies must be assessed in a robust, consistent and quality assured manner in the context of sustainability. This includes in relation to both direct impact considerations, but equally assessments must analyse entire value chains/life cycles associated with different technologies.

To ensure consistency and comparability in LCA studies that are used in the energy technology, context specific guidance should be developed.

At this stage, it is recommended to refer to existing EC guidelines, i.e. the Product Environmental Footprint (PEF) method (EC - European Commission, 2021b), which is the European Commission recommended method to assess the life cycle environmental performance of products on the market (EC - European Commission, 2021b). The method builds on the ISO 14040 and 14044 (ISO, 2006, 2020) standards and it provides further guidance and requirements to ensure the replicability and comparability of LCA results, at the level of data (format and nomenclature), modelling principles for inventories, impact assessment methods and related characterisation factors, normalisation, and weighting. Moreover, it provides general rules for multi-functional process (i.e., processes that produce more than one valuable output).

It is also common practice in LCA frameworks to develop specific rules for categories of similar products in order to provide further guidance related to the specificity related to the life cycle of those products (e.g. primary data required, specific allocation rules for multi-functional processes, secondary data to be used). In the context of the PEF, these rules are called Product Environmental Footprint Category Rules (PEFCR).

The LCA of energy technologies may entail specific challenges, such as the low technology readiness levels (TRL) of the technologies. When the maturity level of a technology is low (e.g., TRL <5), it is usually difficult to perform a proper LCA due to low representativeness of primary data (e.g., data from lab scale pilot differ from real industrial plant data). To overcome this issue, there is a growing interest in Prospective LCA, which develops approaches and guidance on extrapolation of meaningful inventory data for LCA from lab/pilot processes to industrial scale. On this topic several studies have been recently published (e.g. Arvidsson et al., 2018; Cucurachi et al., 2018; van der Hulst et al., 2020).

Another relevant aspect addressed by prospective LCA is how to model product systems considering the evolution of the industrial context and emerging technologies (e.g., the shift of energy systems toward higher share of renewables or reduction of environmental impacts).

5.2.2 Indicators and other considerations

Environmental sustainability embraces a variety of different aspects (see e.g. the taxonomy of impacts proposed by (Bare & Gloria, 2008). Some aspects are widely modelled, such as the impact categories considered in the Environmental Footprint Impact assessment method with the respective indicators. This method is recommended by the European Commission to assess the life cycle environmental performance of products (EC - European Commission, 2021b) and could be considered as a minimum set of impacts to be addressed when conducting an LCA study. Other aspects are not yet fully covered by current LCA practices and might need to be addressed on a case-by-case basis, addressing possible indicators and ranges.

Regarding the Environmental Footprint the method considers in total 16 impact categories that are related to several policy objectives such as carbon footprint, protection of human health and of biodiversity. It is important to note that in the real world the different environmental aspects are interlinked as, for example, pollution and climate change are key drivers of impacts on biodiversity loss and human health.

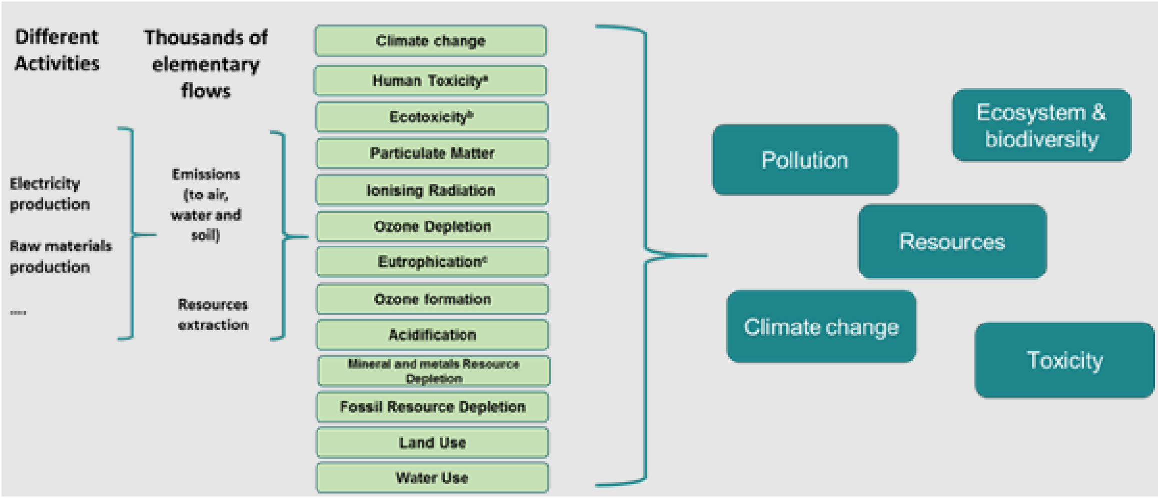
The 16 impact categories relate to the objective of minimising the environmental footprint in particular on climate change, resource use, ecosystems and biodiversity.

Among the 16 impact categories, 13 of them provide a broad view on the environmental performance of the energy technologies, while three are related to toxicity that it is differentiated in human toxicity (cancer and non-cancer) and ecotoxicity impact categories. The focus of the assessment is rather on indirect impacts via different compartments and in the overall toxicity footprint rather than a specific focus on direct exposure.

The 16 impact categories (Table 4) can be expressed also as a single score. However, we suggest retaining the 16 individual indicators for reporting to better illustrate the trade-offs among them and the main hotspots.

We propose to cluster the different impacts categories in 4 groups: toxicity, climate change, pollution, and resources, as presented in Table 5, reflecting LCA levels that relate to different policy objectives and scopes. Currently, there is not an impact category in the EF method directly addressing biodiversity loss. Nevertheless, the EF method account for the main drivers for biodiversity loss such as Climate Change or Land Use. Hence, EF results could be considered a proxy of biodiversity footprint by means of the underpinning drivers of loss. Moreover, in operational LCA frameworks, "functional diversity" and related "ecosystem services" assessment methods are currently not included, and underlying models for several impact categories not yet fully operational. For instance, ecotoxicity in EF focuses on freshwater organisms only, whereas a complete ecotoxicity assessment should address terrestrial, marine, soil, and sediment organisms as well (Figure 11).

Figure 11. Environmental Footprint (EF) impact categories



[a] two impact categories: cancer and non-cancer; [b] freshwater; [c] three impact categories: terrestrial, freshwater, and marine eutrophication

Source: Caldeira et al. (2022)

Acknowledging that the existing environmental impacts go beyond those covered in the EF method (Bare & Gloria, 2008), the addition of other impact categories is optional, and related criteria could be proposed and included. Also, several life cycle impact assessment (LCIA) methods to assess impacts on biodiversity exist (eg. IMPACTworld (Bulle et al., 2019), LC-IMPACT (Verones et al., 2020) or ReCipe2016 (Huijbregts et al., 2017) that are being assessed to be used in the context of the EF method.

Specific category rules for the application of the EF method have been developed. Box 1 describes those available for the photovoltaic technology.

Table 4. Recommended models for the Environmental Footprint method including indicator, units and models[5]

LCA Assessment level	Impact category	Indicator	Unit	Recommended default LCIA model
Toxicity	Human toxicity, cancer effects	Comparative Toxic Unit for humans (CTU_h)	CTUh	based on USEtox2.1 model (Fantke et al., 2017) adapted as in (Saouter et al., 2018)
	Human toxicity, non-cancer effects	Comparative Toxic Unit for humans (CTU_h)	CTUh	based on USEtox2.1 model (Fantke et al. 2017), adapted as in Saouter et al., 2018)
	Ecotoxicity freshwater	Comparative Toxic Unit for ecosystems (CTU_e)	CTUe	based on USEtox2.1 model (Fantke et al. 2017), adapted as in Saouter et al., 2018)
Climate Change	Climate change	Global warming potential (GWP100)	kg CO_2 eq	Bern model - Global warming potentials (GWP) over a 100-year time horizon (based on (IPCC, 2013)
Pollution	Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11eq	EDIP model based on the ODPs of the World Meteorological Organisation (WMO) over an infinite time horizon ((WMO, 2014)+ integrations)

[5] LCIA models are subjects to further refinements. To access the most updated list of models and indicators, the reader is invited to consult the list published in the European platform on life cycle assessment (https://eplca.jrc.ec.europa.eu/)

LCA Assessment level	Impact category	Indicator	Unit	Recommended default LCIA model
	Particulate matter/Respiratory inorganics	Human health effects associated with exposure to $PM_{2.5}$	Disease incidences[6]	PM model (Fantke et al., 2016) in (UNEP, 2016)
	Ionising radiation, human health	Human exposure to ^{235}U	kBq ^{235}U	Human health effect model as developed by Dreicer et al., 1995 (Frischknecht et al, 2000)
	Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS (Van Zelm et al., 2008) as applied in ReCiPe 2008
	Acidification	Accumulated Exceedance (AE)	mol H+ eq	Accumulated Exceedance (Posch et al., 2008; Seppälä, et al., 2006)
	Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)
	Eutrophication, aquatic freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Struijs, et al. 2009)as implemented in ReCiPe 2008
	Eutrophication, aquatic marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe 2008
	Land use	Soil quality index**[7] aggregating: Biotic production, Erosion resistance, Mechanical filtration and Groundwater replenishment	Dimensionless*	Soil quality index based on LANCA model (De Laurentiis et al., 2019) and on the LANCA CF version 2.5 (Horn and Maier, 2018)
Resources	Water use	User deprivation potential (deprivation weighted water consumption)	m^3 water eq of deprived water	Available WAter REmaining (AWARE) model (Boulay et al., 2018; UNEP, 2016)
	Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	CML (Guinée et al., 2002) and (Van Oers et al. 2002)
	Resource use, energy carriers	Abiotic resource depletion – fossil fuels (ADP-fossil)[8]	MJ	CML (Guinée et al., 2002) and (Van Oers et al. 2002)

*dimensionless index[9] resulting from the aggregation of the individual indicators for soil covering: biotic production (kg biotic production/ (m^2*a)); Erosion resistance (kg soil/ (m^2*a)); mechanical filtration (m^3 water/ (m^2*a)); and groundwater replenishment (m^3 groundwater/ (m^2*a)).;

[6] The name of the unit is changed from "Deaths" in the original source (UNEP, 2016) to "Disease incidences"

[7] This index is the result of the aggregation, performed by JRC, of the 4 indicators provided by LANCA model for assessing impacts due to land use as reported in De Laurentiis et al, (2019).

[8] In the ILCD flow list, and for the current recommendation, Uranium is included in the list of energy carriers, and it is measured in MJ.

[9] This refers to both land occupation and transformation

Box 1. Product Environmental Footprint Category Rules

The Product Environmental Footprint (PEF) Guide provides detailed and comprehensive technical guidance on how to conduct a PEF study. PEF studies may be used for a variety of purposes, including in-house management and participation in voluntary or mandatory programmes. For some specific clean energy technologies (such as photovoltaics) there are Product Environmental Footprint Category Rules (PEFCR) available. The EC Recommendations 2279/2021 states that if a PEFCR exists, this should be used for calculating the environmental footprint of a product belonging to that product category.

For photovoltaic modules, the Technical secretariat who developed it was composed of manufacturers of photovoltaic (PV) modules, energy research centres, LCA consultants, and PV industry associations who were part of stakeholder consultations, overall representing more than 50% of the EU market player for this product group at the time of the study. Also, the PV PEFCR has been prepared taking into account relevant schemes at the time of the study, including several established international standards and guidelines such as IEA PVPS Task 12 Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity (2015b); Product Category Rules within the International EPD System IES (PCR CPC 171 & 173 2013); Product Category Rules within the European Standards on Environmental Product Declaration of construction works (EN 15804 2013).

The PV PEFCR is valid for products in scope sold in the European Union + EFTA.

The product category corresponds to the production of photovoltaic modules used in photovoltaic power systems for electricity generation. The product analysed is a photovoltaic module. “Photovoltaic module” is used as general term for panels (framed modules) and laminates (unframed modules).

PV technology has developed strongly in a relatively short time. Many different technologies for panel production exist today. They differ in material consumption, efficiency, life expectancy and costs but also in their environmental performance. The PV PEFCR includes five subcategories representing the following PV technologies:

- Cadmium-Telluride photovoltaic modules (CdTe)
- Copper-Indium-Gallium-Selenide photovoltaic modules (CIS / CIGS)
- Micromorphous Silicon photovoltaic modules (micro-Si)
- Multicrystalline Silicon photovoltaic modules (multi-Si)
- Monocrystalline Silicon photovoltaic modules (mono-Si)

The functional unit (FU) is 1 kWh (kilowatt hour) of DC electricity generated by a photovoltaic module.

The product system of the electricity production with a photovoltaic module consists of five life cycle stages: raw material acquisition and pre-processing, distribution and storage, production of the main product, use and end of life. The manufacturing of PV modules shall cover raw material extraction to wafer, cell and module production in case of crystalline silicon modules, the supply chain of semiconductors (micromorphous silicon, cadmium sulphide, cadmium telluride, gallium and other materials used in thin film technologies) in case of thin film PV modules and the supply chain of carrier and connection materials (such as glass, silver, junction box and frame in case of PV panels). The product system shall also include the mounting system required to fix the PV modules on a slanted roof because its production depends on the conversion efficiency of the module. The electric installation shall also be taken into account. The inverter and the AC cabling shall not be part of the product system. The transport of the PV modules, the mounting system and the electric installation to the place of installation of the PV system shall be included in a separate life cycle stage. The production of the main product shall comprise the assembly of the PV system. The use phase shall include electricity production and panel/system maintenance (cleaning). The end of life shall cover the transport of the PV modules to a recycling facility or to a landfill, the dismantling of the modules and the recycling / landfilling process itself.

5.2.3 Description of the Environmental Footprint 3.1 Impact Categories

Climate change

This indicator refers to the increase in the average global temperatures as result of greenhouse gas (GHG) emissions. The greatest contributor is generally the combustion of fossil fuels such as coal, oil, and natural gas. The global warming potential of all GHG emissions is measured in kilogram of carbon dioxide equivalent (kg CO_2 eq), namely all GHG are calculated in relation to the amount of the global warming potential of 1 kg of CO_2.

Ozone depletion

The stratospheric ozone (O_3) layer protects us from hazardous ultraviolet radiation (UV-B). Its depletion increases skin cancer cases in humans and damage to plants. The potential impacts of all relevant substances for ozone depletion are converted to their equivalent of kilograms of trichlorofluoromethane (also called Freon-11 and R-11), hence the unit of measurement is in kilogram of CFC-11 equivalent (kg CFC-11 eq).

Human toxicity, cancer effects

This indicator refers to potential impacts, via the environment, on human health caused by absorbing substances from the air, water and soil. Direct effects of products on human health are currently not measured. The unit of measurement is Comparative Toxic Unit for humans (CTUh). This is based on a model called USEtox.

Human toxicity, non-cancer effects

This indicator refers to potential impacts, via the environment, on human health caused by absorbing substances from the air, water, and soil. Direct effects of products on human health are currently not measured. The unit of measurement is Comparative Toxic Unit for humans (CTUh). This is based on a model called USEtox.

Particulate matter

This indicator measures the adverse impacts on human health caused by emissions of Particulate Matter (PM) and its precursors (e.g. NO_x, SO_2). Usually, the smaller the particles, the more dangerous they are, as they can go deeper into the lungs. The potential impact of is measured as the change in mortality due to PM emissions, expressed as disease incidence per kg of $PM_{2.5}$ emitted.

Ionising radiation

The exposure to ionising radiation (radioactivity) can have impacts on human health. The Environmental Footprint only considers emissions under normal operating conditions (no accidents in nuclear plants are considered). The potential impact on human health of different ionising radiations is converted to the equivalent of kilobequerels of Uranium 235 (kg ^{235}U eq).

Photochemical ozone formation

Ozone (O3) on the ground (in the troposphere) is harmful: it attacks organic compounds in animals and plants, it increases the frequency of respiratory problems when photochemical smog ("summer smog") is present in cities. The potential impact of substances contributing to photochemical ozone formation is converted into the equivalent of kilograms of Non-Methane Volatile Organic Compounds (e.g. alcohols, aromatics, etc.; kg NMVOC eq).

Acidification

Acidification has contributed to a decline of coniferous forests and an increase in fish mortality. Acidification can be caused by emissions to the air and deposition of emissions in water and soil. The most significant sources are combustion processes in electricity, heat production, and transport. The more sulphur the fuels contain the greater their contribution to acidification. The potential impact of substances contributing to acidification is converted to the equivalent of moles of hydrogen (general name for a cationic form of atomic hydrogen, mol H+ eq).

Eutrophication, terrestrial

Eutrophication arises when substances containing nitrogen (N) or phosphorus (P) are released to ecosystems. These nutrients cause a growth of algae or specific plants and thus limit growth in the original ecosystem. The potential impact of substances contributing to terrestrial eutrophication is converted to the equivalent of moles of nitrogen (mol N eq).

Eutrophication, freshwater

Eutrophication impacts ecosystems due to substances containing nitrogen (N) or phosphorus (P), which promotes growth of algae or specific plants. If algae grow too rapidly, it can leave water without enough oxygen for fish to survive. Nitrogen emissions into the aquatic environment are often caused by fertilisers used in agriculture, but also by combustion processes. The most significant sources of phosphorus emissions are sewage treatment plants for urban and industrial effluents and leaching from agricultural land. The potential impact of substances contributing to freshwater eutrophication is converted to the equivalent of kilograms of phosphorus (kg P eq).

Eutrophication, marine

Eutrophication in ecosystems happens when substances containing nitrogen (N) or phosphorus (P) are released to the ecosystem. As a rule, the availability of one of these nutrients will be a limiting factor for growth in the ecosystem, and if this nutrient is added, the growth of algae or specific plants will increase. For the marine environment this is mainly due to an increase of nitrogen (N). Nitrogen emissions are caused largely by the agricultural use of fertilisers, but also by combustion processes. The potential impact of substances contributing to marine eutrophication is converted to the equivalent of kilograms of nitrogen (kg N eq).

Ecotoxicity, freshwater

This indicator refers to potential toxic impacts on an ecosystem, which may damage individual species as well as the functioning of the ecosystem. Some substances tend to accumulate in living organisms. The unit of measurement is Comparative Toxic Unit for ecosystems (CTUe). This is based on a model called USEtox.

Land use

Use and transformation of land for agriculture, roads, housing, mining or other purposes. The impacts can vary and include loss of species, of the organic matter content of soil, or loss of the soil itself (erosion). This is a composite indicator measuring impacts on four soil properties (biotic production, erosion resistance, groundwater regeneration and mechanical filtration), expressed in points (Pts)

Water use

The abstraction of water from lakes, rivers or groundwater can contribute to the ‘depletion’ of available water. The impact category considers the availability or scarcity of water in the regions where the activity takes place, if this information is known. The potential impact is expressed in cubic metres (m^3) of water use related to the local scarcity of water.

Resource use, fossils

The earth contains a finite amount of non-renewable resources, such as fossil fuels like coal, oil and gas. The basic idea behind this impact category is that extracting resources today will force future generations to extract less or different resources. For example, the depletion of fossil fuels may lead to the non-availability of fossil fuels for future generations. The amount of materials contributing to resource use, fossils, are converted into MJ.

Resource use, minerals and metals

This impact category has the same underlying basic idea as the impact category resource use, fossils (namely, extracting a high concentration of resources today will force future generations to extract lower concentration or lower value resources). The amount of materials contributing to resource depletion are converted into equivalents of kilograms of antimony (kg Sb eq).

5.2.4 Resource efficiency, recycling and circularity

Important aspects to consider in the evaluation of energy technologies are the resource efficiency, recycling and circularity of material system. In the framework several indicators for circularity are suggested to be considered in the design phase. LCA is able to address also aspects for the circular economy such as the recycling of the material at the end-of-life, the energy recover from the waste treatment, and the use of recycling feedstock. These aspects are defined in the goal and scope when setting the system boundaries. LCA allows for a deeper analysis of the benefits of the circular economy, since it quantifies impacts across different environmental impact categories, rather than attribute an absolute value to a single circularity metric. In this direction the Circular Footprint Formula (CFF) has been developed in the PEF method to quantify these impacts, and allocate the burdens of the waste production and recycling treatment along the different life cycles. Indeed, the recycling process has two functions: on the one hand, the production of a recycled material (also as secondary raw material), and on the other hand, the waste treatment. Therefore, the impacts (and benefits) can be shared between the life cycle producing and treating the waste, hence using the recycled material production as service.

The CFF includes the effect of change in performances delivered by the recycled material compared to the virgin one and a parameter to allocate the burdens across the system that is producing the waste and the one using the recycled material, taking into the account the specific market situation of the secondary material.

5.2.5 Energy balance

It is also important to assess the energy balance considering indicators such as the Energy Pay Back Time (EPBT) that, in the context of LCA, is defined as the amount of time it takes for an energy system to generate the amount of energy equivalent to the amount that took to produce the system. EPBT strongly depends on geographical deployment distribution, in terms of environmental factors and associated grid mix efficiencies.

As an example, EPBT of PV technologies is defined as:

$$\text{Energy Pay Back Time} = (E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL}) / ((E_{agen}/ n_G) - E_{O\&M})$$

where Emat is the primary energy demand to produce materials comprising PV system; Emanuf is the primary energy demand to manufacture PV system; Etrans is the primary energy demand to transport materials used during the life cycle; Einst is the primary energy demand to install the system; EEOL is the primary energy demand for end-of-life management; Eagen is the annual electricity generation; EO&M is the annual primary energy demand for operation and maintenance; and n_G is the life-cycle grid efficiency of the electricity grid of the country or region where the analysed PV system is deployed (calculated as the ratio of the yearly electricity output of the entire grid to the total PE harvested from the environment for the operation of the grid in the same year) (Leccisi et al., 2016), the average primary energy to electricity conversion efficiency at the demand side.

Another useful energy metric is the Energy Return on Energy Invested (EROI), which is calculated as the ratio of the energy delivered to society to the sum of energy carriers diverted from other societal uses. It is defined as:

$$EROI = \text{Gross Energy Output} / \sum \text{Energy Investments}$$

Specifically, for a PV system:

$$EROI_{el} = Out_{el}/Inv$$

When Out_{el} is the total energy output over the PV system’s lifetime, in units of electricity; Inv is the additional PE indirectly “invested” in order to produce, deploy, maintain, and decommission the PV system.

And also:

$$EROI_{PE\text{-}eq} = Out_{PE\text{-}eq}/Inv = (Out_{el}/n_G)/Inv$$

where $Out_{PE\text{-}eq}$ is the energy delivered to society in units of equivalent PE; n_G is the life cycle energy efficiency of the electricity grid of the country or region where the analysed PV system is deployed (calculated as the ratio of the yearly electricity output of the entire grid to the total PE harvested from the environment for the operation of the grid in the same year).

5.3 Social sustainability assessment

The social dimension of sustainability assessment is less developed than the environmental one, especially from the operational point of view. Conceptually, a universal definition of social sustainability does not exist, and some scholars argue that social sustainability is rather a dynamic concept that can change over time and depending on the context of its application. Such conceptual imprecision and the flexibility in the interpretation can be seen both as a strength (because it facilitates communication among different actors and disciplines) and as a weakness (as it needs to be defined every time the term is used) (Boström, 2012). Many studies address the theoretical and conceptual definition of social sustainability, trying to respond to the question of what social sustainability is, what should be measured and what are the main themes to be addressed.

A variety of aspects can be considered relevant within the social sustainability umbrella. Equity/equality, human wellbeing, human rights and livelihood are recurrent concepts mentioned in social assessment studies. In addition, some features characterise social sustainability, such as (Mancini et al., 2018):

- importance of the local context and the local governance,
- attention to local needs and values,
- integration of different perspectives (e.g. through the consideration of different stakeholders and community engagement),
- need for an integrated vision of sustainability and the importance of integrating governance into sustainability,
- consideration of positive impacts benefits coming from economic activities (e.g. creation of employment, provision of infrastructure in local communities, etc.).

The above-mentioned features can imply methodological challenges in performing an impact assessment. In particular, the social assessment is characterised by the presence of qualitative information and behavioural aspects which can make quantification and comparison of alternatives more difficult.

The Life Cycle Initiative published the Guidelines for Social Life Cycle Assessment of Products and Organisations in 2020, which provide a set of stakeholder categories and impact subcategories that should be considered in the social impact assessment. While other approaches are possible, this publication can be considered a milestone towards the better definition and implementation of social sustainability assessment (UNEP, 2020b).

5.3.1 Social assessment frameworks and methodologies

Depending on the scope of the analysis, various methodologies can be used to assess social impacts. These methodologies are based on common general guidance, which set common principles to be protected and issues of concerns to be analysed. Among them, the SDGs framework is provides a reference list of objectives and targets to be pursued for achieving a sustainable development (Section 2). Several Goals focus on social aspects, e.g. poverty eradication (Goal 1), food security (Goal 2), health (Goal 3), education (Goal 4), gender equality (Goal 5), decent work (Goal 8), reduce inequalities (Goal 10), peace and justice (Goal 16). Other goals, while referring to environmental or technological aspects, have a clear link with social aspects, like those related to water and sanitation (Goal 6) and access to energy (Goal 7), sustainable cities and communities (Goal 11).

Figure 12 provides an overview of methodologies that can be applied at project, organisation or product level, and developed by international organisation or academia; industry or business associations; NGOs or multi-stakeholder partnerships. While the list is not comprehensive, it shows a variety of methods and approaches that can be undertaken when performing a social assessment.

Given the importance of undertaking a life cycle perspective when assessing sustainability, as discussed in Section 2, the following section will briefly illustrate some features of the S-LCA methodology.

Figure 12. Overview of the main social assessment methodologies (non-exhaustive list), by level of assessment and type of stakeholder applying the methodology.

<table>
<tr><th colspan="5">General Guidelines</th></tr>
<tr><td colspan="5"></td></tr>
<tr><td colspan="5">• International Labour Organisation (ILO) Declaration on Fundamental Principles and Rights at Work
• ISO 26000 (International Organisation for Standardization)
• UN Guiding Principles on Business and Human Rights
• European Commission Guidelines on Non-Financial Reporting
• International Integrated Reporting Council (IIRC)
• OECD guidelines for Multinational Enterprises</td></tr>
<tr><td colspan="2" rowspan="2"></td><th colspan="3">Assessment methodologies (by level of assessment)</th></tr>
<tr><th>Project/ intervention</th><th>Organisation</th><th>Product</th></tr>
<tr><th rowspan="3">Assessment methodologies (by stakeholder)</th><th>International organisations/ Academia</th><td>• Social Impact Assessment (SIA)
• Social Return on Investment (SROI)
• International Finance Corporation (IFC) Performance Standards</td><td>• Social Organisational Life Cycle assessment (SO-LCA)
• Due diligence
• Social Footprint
• Social Handprint</td><td>• Social Life Cycle Assessment (S-LCA)
• Social Footprint
• Social Handprint</td></tr>
<tr><th>Industry</th><td>• Social and Human Capital Protocol</td><td>• Social and Human Capital Protocol</td><td>• Handbook for Product Social Impact Assessment (PSIA)
• WBCSD Social Life Cycle Metrics for Chemical Products</td></tr>
<tr><th>NGO / Multi-stakeholder</th><td>• Human Rights Impact Assessment (HRIA)</td><td>• Global Reporting Initiative (GRI)</td><td>• Thesis Index (Sustainability Consortium)</td></tr>
</table>

5.3.2 Social Life Cycle Assessment methodology

Similarly to LCA, the Social Life Cycle Assessment (S-LCA) methodology consists of four phases:

- goal and scope
- inventory
- impact assessment
- interpretation

In the goal and scope phase, relevant stakeholders and impact categories must be selected. The consideration of various stakeholder categories is a feature characterising the S-LCA and it is not needed in the environmental LCA. This allows taking into consideration all the stakeholders that might be affected (in a positive or negative way) by a certain production and consumption system.

The UNEP S-LCA Guidelines recommend considering six stakeholder categories in the assessment of social impacts: workers, local communities, consumers, (other) value chain actors, society and children. Forty social aspects (defined in S-LCA as impact subcategories) can be considered (the most relevant ones for the assessment should be selected) (UNEP, 2020b) (Figure 13). A materiality assessment[10] can support the selection of stakeholder categories and impact subcategories.

[10] See definition in Annex 1

Figure 13. List of stakeholder categories and impact subcategories defined by the S-LCA Guidelines

WORKERS	LOCAL COMMUNITY	VALUE CHAIN ACTORS	CONSUMERS	SOCIETY	CHILDREN
Child labour	Access to material resources	Fair competition	Health and Safety	Contribution to economic development	Education provided in the local community
Forced labour	Access to immaterial resources	Promoting social responsibility	Transparency	Public commitment to sustainability issues	Health issues for children as consumers
Fair salary	Respect of indigenous rights	Supplier relationships	End of life responsibility	Prevention and mitigation of armed conflicts	Children concerns regarding marketing practices
Working hours	Safe and healthy living conditions	Respect of intellectual property rights	Feedback mechanism	Technology development	
Equal opportunities / discrimination	Local employment	Wealth distribution		Corruption	
Health and Safety	Delocalization and migration			Ethical treatment of animals	
Social benefits / social security	Cultural heritage			Poverty alleviation	
Freedom of association and collective bargaining	Community engagement				
Employment relationship	Secure living conditions				
Sexual harrassment					
Smallholders including farmers					

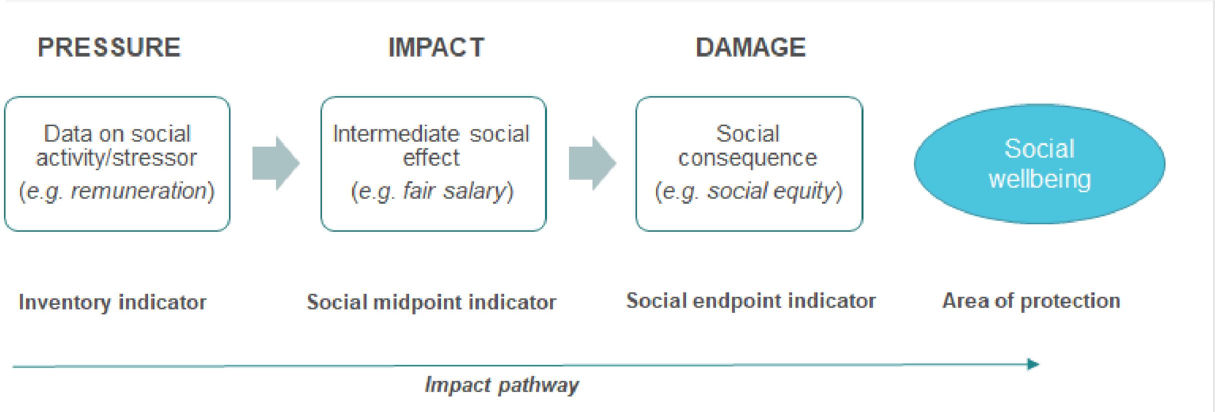
Source: own elaboration based on UNEP 2020

During the inventory phase, data is collected in relation to the selected impact categories. This process can include qualitative information, gathered through interviews, questionnaires, focus groups and other social research techniques. Triangulation of data, i.e. collecting the same information from different sources can be necessary in order to reduce uncertainty and consider different and/or conflicting perspectives.
The impact assessment can be performed using two main approaches:

— The impact pathway approach follows the same reasoning used in LCA – it aims at assessing changes due to a certain pressure at an intermediate step of the cause-effect chain (i.e. midpoint) or at the final step of the cause-effect chain (endpoint level), therefore considering the final consequences of a certain activity (Figure 14). In S-LCA usually only one area of protection is used, i.e. social wellbeing. This approach uses causal or correlation/regression-based relationships between the product system/organisations' activities and the resulting potential social impacts in a process called characterisation.

— The reference scale approach translates the performance of system/organisations' activity into an evaluation of potential impacts. This is done through reference scales (Table 5), defined during the inventory phase, which set, for each indicator, various levels of social performance or social risk. The reference scales then combine the indicator value with performance reference points (PRP) corresponding to different levels of performance compared to thresholds, targets or objectives. Legislation, standards, international conventions and other normative tools can be used as sources to extract these critical levels and define what can be considered a satisfactory or a deficient performance. This approach does not consider the propagation of effects and longer-term consequences but is limited to the evaluation of inventory indicators.

Figure 14. Impact pathway approach



Source: UNEP (2020)

Table 5. Example of reference scale

Level	Performance Reference Point
+1	Salary above decent wage level
0	Salary corresponding to decent wage level for a specific geographical location
-1	Salary below decent wage level

Source: Goedkoop et al 2020

5.3.3 Selection of relevant social aspects

In order to define a relevant and workable set of social aspects that should be prioritized when performing a sustainability assessment of an energy technology, the following steps are performed:

1. Selection of relevant social frameworks used in policy and corporate context
2. Review of the social aspects included in the frameworks under consideration, taking the S-LCA methodology as a reference list
3. Identification of a limited set of important social aspects that are included in most of the frameworks
4. Inclusion of important energy-specific social aspects included in the CETO framework which are not represented in the list selected at point 3.

Concerning point 1 above, the relevant frameworks identified to guide the selection of social aspects are the following (see Annex 2 for details):

a. UNEP Guidelines for Social Life Cycle Assessment of Products and Organisations (UNEP, 2020a)
b. Clean Energy Technology Observatory (CETO) framework (Tarvydas, 2022)
c. European Commission Better Regulation toolbox (EC - European Commission, 2021a)
d. OECD Guidelines for Multinational Enterprises on Responsible Business Conduct (OECD, 2011)(OECD, 2023)
e. Product Social Impact Assessment Handbook (Goedkoop et al., 2020)
f. The Corporate Sustainability Reporting Directive (EC - European Commission, 2022e)
g. Final Report on Social Taxonomy (EU Platform on Sustainable Finance, 2022)
h. Proposal for a Directive on Corporate Sustainability Due Diligence (EC - European Commission, 2022d)

Starting from the 40 impact subcategories related to seven stakeholder categories identified in the UNEP Guidelines, we identified the number of frameworks covering each subcategory (Annex 2) and selected those included at least in seven frameworks out of eight. In addition, four social aspects included in the CETO framework have been added given their relevance in the context of energy projects development, namely: social acceptance, affordable access to energy, contribution to economic development, rural development. Table 6 provides the list of the prioritized subcategories, with a brief description of the aim partially based on (UNEP, 2021).

Table 6. Recommended list of aspects for the social sustainability assessment

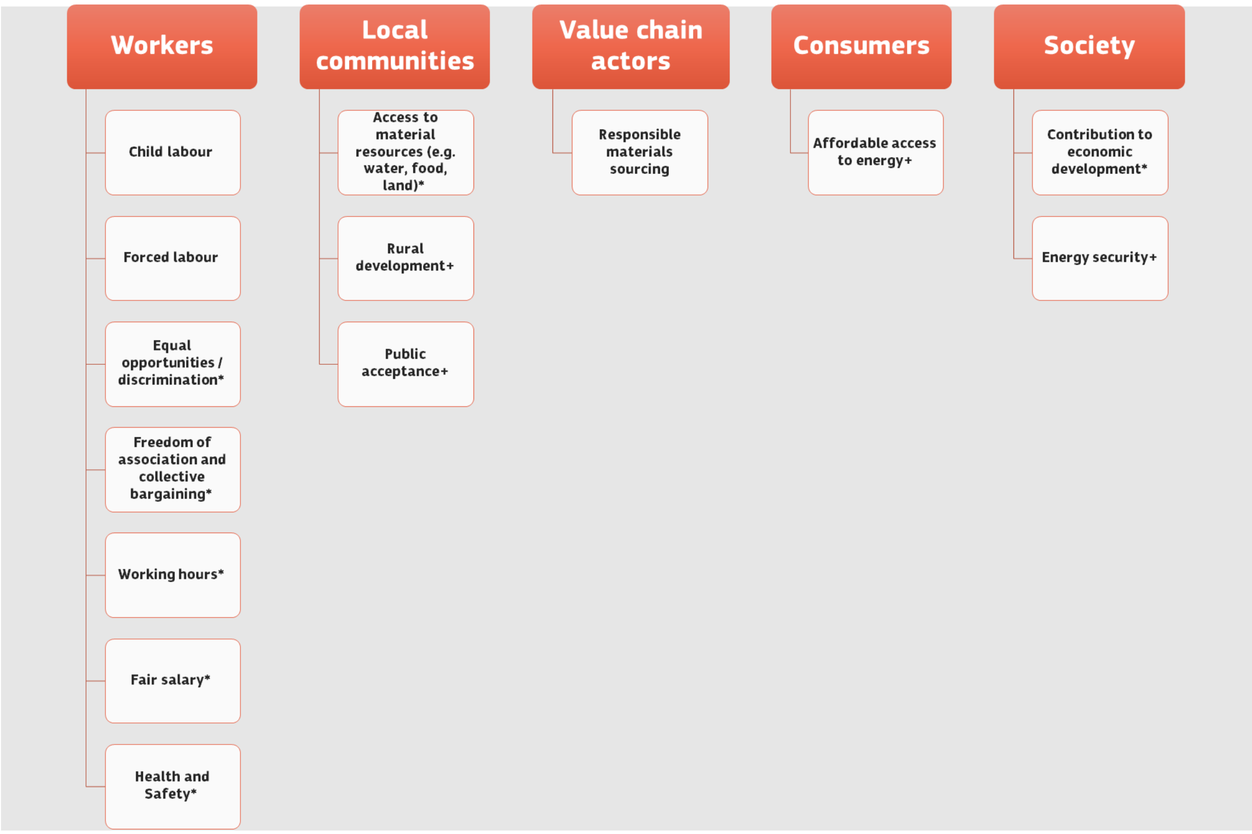
Stakeholders category	Social subcategories	N° of frameworks including the aspect	Aim of the impact subcategory	Relation with CETO categories
Workers	Child labour	8	It aims to verify if organizations in the supply chain are employing children (as defined in the ILO conventions) or if sector/locations involved in the supply chain are at risk of child labour. It will be looked upon if the conditions are favourable for the occurrence of child labour, and the existence and quality of prevention and mitigating measures taken by the organization.	Not present in previous CETO framework
Workers	Forced labour	8	It aims to verify that forced or compulsory labour is not used in the organization and if sector/locations involved in the supply chain are at risk of child labour.	Not present in previous CETO framework
Workers	Equal opportunities / discrimination	8	It aims to assess equal opportunity management practices and the presence of discrimination in the opportunities offered to the workers by the organizations and in the working conditions (Including any distinction, exclusion, or preference made on the basis of race, colour, sex, religion, political opinion, national extraction, or social origin, which has the effect of nullifying or impairing equality of opportunity or treatment in employment or occupation).	Part of “working conditions”
Workers	Freedom of association and collective bargaining	8	It aims to verify the compliance of the organization with freedom of association and collective bargaining standards. In particular 1) whether the workers are free to form and join association(s) of their choosing even when it could damage the economic interest of the organization, 2) whether the workers have the right to organize unions, to engage in collective bargaining, and to strike.	Part of “working conditions”
Workers	Working hours	8	It aims to verify if the number of hours effectively worked is in accordance with the ILO standards	Part of “working conditions”

Stakeholders category	Social subcategories	N° of frameworks including the aspect	Aim of the impact subcategory	Relation with CETO categories
			and when overtime occurs, compensation in terms of money or free time is planned and provided to the workers.	
Workers	Fair salary	7	It aims to assess whether practices concerning wages are in compliance with established standards and if the wage provided is meeting legal requirements, whether it is above, meeting, or below industry average and whether it can be considered as a living wage.	Part of "working conditions"
Workers	Health and safety	7	It assesses both the rate of incidents and the status of prevention measures and management practices. An incident is defined as a work-related event in which an injury or ill health (regardless of severity) or fatality occurred or could have occurred.	Part of "working conditions"
Value chain actors	Responsible materials sourcing[2]	7	It aims at considering potential impacts or unintended consequences of procurement and purchasing decision, especially for what concern the responsible sourcing of materials.	Present as such
Local community	Access to material resources (incl. water, land, food)	7	This subcategory assesses the extent to which organizations respect, work to protect, to provide or to improve community access to local material resources (i.e. water, land, mineral, and biological resources) and infrastructure (i.e. roads, sanitation facilities, schools, etc.). It can also include food security issues e.g. the in case of land competition between energy projects and agricultural land use.	Partially covered by the aspects food security and energy security
Local community	Public acceptance	n.a.	The aim is to assess if there might be opposition from local communities towards a certain technology, e.g. based on existing conflicts and protest movements. As it relates to perception, level of information and feelings, it is not necessarily linked to specific impacts but it can give information on the enabling conditions, risk of bottlenecks in the development and permitting phase, and the quality of the decision making process in a certain sector (in terms of inclusiveness, and community involvement).	Present as such

Stakeholders category	Social subcategories	N° of frameworks including the aspect	Aim of the impact subcategory	Relation with CETO categories
Local community	Rural development	n.a.	This aspect aims at considering specific impacts on rural areas, determined by the development of an energy project. It can include a variety of aspects, for instance the income and employment in rural areas (e.g. changes in agricultural productivity and yields), education and skills (e.g. vocational training and skill development); entrepreneurship and local economy (e.g. local economy diversification and provision of energy for income-generating activities).	Present as such
Consumers	Affordable access to energy	n.a.	This aspect aims at considering both the access to energy, (e.g. the percentage of population without access to electricity; duration and frequency of energy shortages or blackouts) and the affordability for households in terms of expenditure for energy compared to the income.	Present as such
Society	Contribution to economic development	n.a.	This subcategory assesses to what extent the organization/product or service contributes to the economic development of the society. It can be measured at different geographical levels. It can be assessed in terms of contribution to GDP but also jobs creation, education and training provided, investment level, etc.	Present as “contribution to GDP

Figure 15 resumes the social subcategories selected for the assessment of the social sustainability of energy technologies, in relation to the addressed stakeholders’ categories.

Figure 15. List of selected social aspect, per stakeholder category



Notes: (*) subcategories that were present in CETO, but with different names or grouped in a single category (+) additional categories from CETO

Source: own elaboration

6 Discussion on the implementation of the framework

The proposed framework is partially based on the list of aspects evaluated in the CETO technology reports, but reviews and complements it with insights from existing life cycle based sustainability assessment methodologies.

For the environmental part, which is the most developed both from the methodological point of view and in terms of implementation, the proposal aims at standardizing the assessment towards the rules of the Product Environmental Footprint. It entails that some aspects assessed in CETO in an aggregated form (e.g. ecosystem and biodiversity impact) are split in the corresponding impact categories used in the PEF methodology, i.e. eutrophication, acidification, ecotoxicity, etc. Reference to specific assessment methods and guidance is given in chapter 5.2.

For the social dimension, the Social Life Cycle Assessment was used as a reference methodology for defining a structure of relevant stakeholders and social aspects. This entailed the disaggregation of the aspect "working conditions" in multiple categories (e.g. fair salary, discrimination, health and safety, etc.) which should be assessed separately, applying the indicators suggested in Annex 5 and in (UNEP, 2021). The aspect of food security was included in the broader category "access to material resources", which aims at assessing competition for land, food, water and other types of resources in local communities. This broader scope allows to take into account the relevant issues of concern, depending on the energy technology. For instance, while access to food can be relevant in the case of biofuels, the access to clean water can be a relevant aspect to take into account for other energy technologies.

Some social sustainability aspects included in the proposed framework are not included in the S-LCA methodology but have been retained given their relevance for the evaluation of energy technology sustainability: social acceptance, rural development, affordable energy access. These are complex aspects that are not easily assessed with specific single indicators. In the case of rural development, a set of indicators can be more suitable to understand the impact of a specific energy technology in a rural territory. For social acceptance, more complex analysis and on-site investigation should be used in order to assess this aspect case by case. A descriptive and qualitative approach based on literature review and insights from case studies can be useful in these cases.

The S-LCA methodology provides a useful structure of stakeholders and categories, but its application at technology level presents some difficulties as the suggested social aspects cannot be assessed at a general level. As described in Caldeira et al. (2023), a possible approach to undertake a social assessment at sector or technology level is to analyse the supply chain of a certain technology and identify social hotspots in terms of high risk country-sectors combinations along the supply chain. While the granularity of the assessment is very low, this approach has the advantage to rely on mostly publicly available data, and to provide a wide perspective on potential social risks for different stakeholders, allowing for the comparison of possible scenarios.

The security dimension replaced the economic dimension that was part of the CETO assessment. While this dimension includes many economic and market-related aspects, this change allows a broader perspective on the policy priority underpinning the framework, and it may capture some interlinkages between environmental and social aspects, which can affect or influence energy security.

While the life cycle-based methodologies do not offer specific and standardized methodologies that can be applied for this dimension, in the case of Critical Raw Materials, approaches to include their consideration in a life cycle sustainability assessment are discussed in, e.g. Bachmann et al. (2021). For other aspects concerning energy security, a descriptive approach is suggested and further research is needed in order to identify the best methods.

6.1 Limitations of the study

The proposed framework analyses the relevant concepts related to energy sustainability and proposes a set of aspects to be addressed in the analysis of energy technologies. It then identifies the available sustainability assessment methods and indicators that can be applied for an integrated assessment.

Given the different levels of methodological development, not all aspects can be assessed/quantified in comparable manner, and therefore it is not possible to apply a multi-criteria decision tool to compare alternatives, as in the case of the SSbD framework for chemicals and materials. Compared to that framework, which relies on well-established methodologies for safety assessment, in the case of energy the pillar of security lacks a standardized approach for its assessment. However, methods based on supply risk could be developed for the analysis of energy technologies, building on the criticality assessment performed for materials.

In the case of the social sustainability assessment, data required to perform a Social LCA should be specific and take into account the context where the production process takes place or a technology is deployed. Performing an assessment at the level of technology implies that average values of social performance can be used, and therefore only social hotspots can be identified, based on the assumed country of origin of the various components in the energy technology supply chain.

The proposed framework is an attempt of considering the sustainability of energy technology in a comprehensive way, and therefore it combines economic, social and environmental aspects. The proposed indicators and methods, however, have different levels of application, and in some cases their use for the assessment of a technology is not straightforward, or it may require some elaborations. For instance, the environmental aspects taken into account in the Environmental Footprint are applicable primarily at product level but can be also used to evaluate the environmental performance of a company (organization level) or a technology. Applications at macro scale (i.e. sector and country level) are also possible even though this is not the most common application for LCA studies. Most social aspects are instead applicable at company or supply chain level (looking at corporate performance and relations with local communities). Product assessment or macro-scale hotspot screening are also possible, using country-sector specific data from S-LCA databases. However, some aspects like social acceptance and rural development require a subnational investigation and context-specific data and insights. Generalizing these aspects at technology level can be challenging but a review of literature can provide information linked to the deployment of certain technologies. For what concerns the security pillar, it is possible to assess the amount of critical raw materials, used in a product, in a technology and in a supply chain. Other aspects that can affect energy security like cost of energy and trade balance are generally assessed at country/regional.

Table 7 provides an overview of the main levels of application for the assessment of the aspects included in the framework, showing gaps where certain aspects are not easily applicable at the level of technology, but may require different consideration.

Table 7. Level of application for the assessment of the aspects included in the proposed sustainability assessment framework for energy technologies

		Level of application					
		Company/ supply chain	Product or component	Technology	Sector	Country	Region / municipalities
Security	Critical Raw Materials	x	x	x			
	Market demand					x	
	Cost of energy	x					
	Trade balance					x	
	Technology-specific permitting requirements			x		x	
	Energy security					x	
Environmental	Resource efficiency and recycling	x	x	x	x	x	
	Energy balance	x	x	x	x	x	
	Climate change	x	x	x	x	x	
	Ozone depletion	x	x	x	x	x	
	Human toxicity	x	x	x	x	x	
	Particulate matter	x	x	x	x	x	
	Ionising radiation	x	x	x	x	x	

		Level of application					
		Company/ supply chain	Product or component	Technology	Sector	Country	Region / municipalities
	Photochemical ozone formation	x	x	x	x	x	
	Acidification	x	x	x	x	x	
	Eutrophication	x	x	x	x	x	
	Eco-toxicity	x	x	x	x	x	
	Land use	x	x	x	x	x	
	Water use	x	x	x	x	x	
	Resource use, fossils	x	x	x	x	x	
	Resource use, minerals	x	x	x	x	x	
Social	Social acceptance	x					x
	Affordable energy access					x	x
	Child labour	x	x		x	x	
	Forced labour	x	x		x	x	
	Discrimination	x	x		x	x	
	Freedom of association	x	x		x	x	
	Working hours	x	x		x	x	
	Fair salary	x	x		x	x	
	Health and safety	x	x		x	x	
	Responsible materials sourcing	x	x		x	x	
	Access to material resources	x					x
	Rural development					x	x
	Contribution to economic development	x			x		

7 Conclusions

The sustainability assessment framework for energy technologies proposed in this report is a conceptual framework to guide and help researchers and practitioners in the assessment of energy technologies. In particular, it provides a general approach and considerations to evaluate the sustainability of energy technologies, allowing a comparison of alternatives. From the methodological point of view, it is aligned with the framework on Safe and Sustainable by Design chemicals and materials developed by JRC and tested on case studies (Caldeira et al., 2023; Caldeira et al., 2022). However, the safety dimension is not represented here and, instead, energy security aspects are taken into account. The proposal also builds on the analysis of the Technology Reports published by the Clean Energy Technology Observatory (CETO), in particular for what concerns the identification of relevant aspects to assess.

The proposed framework underpins on background concepts related to sustainability as well as energy-specific concepts. It then defines three main dimensions as part of the framework: energy security, environmental sustainability and social sustainability. It provides guidance on the aspects to consider in each dimension and the methodologies that can be used for their assessment.

For the security dimension, a description of relevant aspects to be taken into account and a structure based on a cause-effect chain are suggested. The assessment of this pillar is not well defined in the context of a sustainability framework. However, the criticality assessment of materials, based on supply risk deriving from import dependency, concentration of supply, low governance of producing countries, etc., could be a basis for the development of energy security assessment. The environmental dimension is based on the standardized LCA methodology, while for the social dimension a selection of social categories was performed in order to prioritize a short list of social aspects (impact subcategories) affecting the various stakeholders. Guidance on the assessment of each aspect is then provided, based on the Social LCA methodology. For some aspects, a descriptive approach based on literature review is recommended.

Given the current status of development, the proposed framework does not allow for the full quantitative assessment of all the dimensions and aspects, and for their integration in a multi-criteria decision making tool. However, it provides a rationale and a structure for relevant sustainability aspects to be taken into account in the assessment of energy technologies, based on current policy priorities. Moreover, it provides methodological guidance for the assessment of most aspects, based on the available life cycle assessment methodologies. Further research is needed in order improve assessment methods for complex socio-economic aspects, like eg. social acceptance, rural development and affordable access to energy and to better investigate their interaction and influence on energy security.

References

Afeltra, G., Alerasoul, S. A., & Strozzi, F. (2023). The evolution of sustainable innovation: from the past to the future. *European Journal of Innovation Management*, *26*(2), 386–421.

Arvidsson, R., Tillman, A., Sandén, B. A., Janssen, M., Nordelöf, A., Kushnir, D., & Molander, S. (2018). Environmental assessment of emerging technologies: recommendations for prospective LCA. *Journal of Industrial Ecology*, *22*(6), 1286–1294.

Bachmann, T. M., Hackenhaar, I. C., Horn, R., Charter, M., Gehring, F., Graf, R., Huysveld, S., & AF Alvarenga, R. (2021). *D1. 4 Critical evaluation of material criticality and product-related circularity approaches*.

Bare, J. C., & Gloria, T. P. (2008). Environmental impact assessment taxonomy providing comprehensive coverage of midpoints, endpoints, damages, and areas of protection. *Journal of Cleaner Production*, *16*(10), 1021–1035. https://doi.org/10.1016/j.jclepro.2007.06.001

Bianchi, M., Bachmann, T. M., van der Kamp, J., Riemer, M., Riva, F., Préat, N., & Taelman, S. E. (2021). *Critical evaluation of economic approaches. Orienting Project Deliverable 1.3*.

Boström, M. (2012). A missing pillar? Challenges in theorizing and practicing social sustainability: introduction to the special issue. *Sustainability: Science, Practice and Policy*, *8*(1), 3–14. https://doi.org/10.1080/15487733.2012.11908080

Boulay, A. M., Bare, J., Benini, L., Berger, M., Lathuillière, M.J. Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A. V., Ridoutt, B., Oki, T., Worbe, S., & Pfister, S. (2018). The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). *International Journal of Life Cycle Assessment*, *23*(2), 368–378. https://doi.org/10.1007/s11367-017-1333-8

Bryman, A. (2016). *Social research methods*. Oxford university press.

Bulle, C., Margni, M., Patouillard, L., Boulay, A.-M., Bourgault, G., De Bruille, V., Cao, V., Hauschild, M., Henderson, A., & Humbert, S. (2019). IMPACT World+: a globally regionalized life cycle impact assessment method. *The International Journal of Life Cycle Assessment*, *24*, 1653–1674.

Burke, M. J. (2020). Energy-sufficiency for a just transition: a systematic review. *Energies*, *13*(10), 2444.

Caldeira, C., Farcal, L., Garmendia Aguirre, I., Mancini, L., Tosches, D., Amelio, A., Rasmussen, K., Rauscher, H., Riego Sintes, J., & Sala, S. (2022). *Safe and sustainable by design chemicals and materials - Framework for the definition of criteria and evaluation procedure for chemicals and materials*. *KJ-NA-31100-EN-N (online),KJ-NA-31100-EN-C (print)*. https://doi.org/10.2760/487955 (online),10.2760/404991 (print)

Caldeira, C., Garmendia Aguirre, I., Tosches, D., Mancini, L., Abbate, E., Farcal, L., Lipsa, D., Rasmussen, K., H, R., J, R. S., & S, S. (2023). *Safe and Sustainable by Design chemicals and materials - Application of the SSbD framework to case studies*. *KJ-NA-31-528-EN-N (online),KJ-NA-31-528-EN-C (print)*. https://doi.org/10.2760/329423 (online),10.2760/769211 (print)

Carrara, S., Bobba, S., Blagoeva, D., Alves Dias, P., Cavalli, A., Georgitzikis, K., Grohol, M., Itul, A. et al. (2023). *Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU ? A foresight study*. Publications Office of the European Union. https://doi.org/10.2760/386650 (online).

Club of Rome. (2022). *Annual Report*. https://www.clubofrome.org/wp-content/uploads/2023/01/2022-CoR_Annual_Report.pdf

Corona, B., Shen, L., Reike, D., Carreón, J. R., & Worrell, E. (2019). Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. *Resources, Conservation and Recycling*, *151*, 104498.

Cucurachi, S., van der Giesen, C., & Guinée, J. (2018). Ex-ante LCA of emerging technologies. *Procedia CIRP*, *69*, 463–468.

De Laurentiis, V., Secchi, M., Bos, U., Horn, R., Laurent, A., & Sala, S. (2019). Soil quality index: Exploring options for a comprehensive assessment of land use impacts in LCA. *Journal of Cleaner Production, 215, Pp.63-74.*, *215*, 63–74. https://doi.org/10.1016/j.jclepro.2018.12.238

DellaValle, N., & Czako, V. (2022). Empowering energy citizenship among the energy poor. *Energy Research &*

Social Science, *89*, 102654. https://doi.org/https://doi.org/10.1016/j.erss.2022.102654

EC - European Commission. (2016). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Next steps for a sustainable European future European action for sustainability. COM(2016) 739 final*.

EC - European Commission. (2018). *A sustainable Bioeconomy for Europe. Strengthening the connection between economy, society and the environment. Updated Bioeconomy Strategy*. https://doi.org/10.2777/478385

EC - European Commission. (2019a). *Commission Staff Working Document 2019 EU report on Policy Coherence for Development, SWD(2019)20*.

EC - European Commission. (2019b). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. COM (2019) 640 final*.

EC - European Commission. (2020a). *Commission Recommendation (EU) 2020/1563 of 14 October 2020 on energy poverty*.

EC - European Commission. (2020b). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Chemicals Strategy for Sustainability Towards a Toxic-Free Environment COM (2020) 667*.

EC - European Commission. (2020c). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Circular Economy Action Plan. For a cleaner and more competitive Europe. COM/2020/98 final*. https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf

EC - European Commission. (2021a). *Better Regulation Guidelines. SWD(2021) 305 final*.

EC - European Commission. (2021b). *Commission Recommendation of 16.12.2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. C(2021) 9332 final*.

EC - European Commission. (2021c). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Pathway to a Healthy Planet for All EU Action Plan: "Towards Zero Pollution for Air, Water and Soil" CO*.

EC - European Commission. (2021d). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions "Fit for 55": delivering the EU's 2030 Climate Target on the way to climate neutrality. COM(2021) 550 fi*.

EC - European Commission. (2021e). *Proposal for a Directive of the European Parliament and of the Council amending Directive (EU) 2018/2001 (...) as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652*.

EC - European Commission. (2022a). *Commission Recommendation of 8.12.2022 establishing a European assessment framework for 'safe and sustainable by design' chemicals and materials. C(2022) 8854 final*.

EC - European Commission. (2022b). *Communication from the Commission on Ecodesign and Energy Labelling Working Plan 2022-2024*.

EC - European Commission. (2022c). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions REPowerEU Plan. COM(2022) 230 final*.

EC - European Commission. (2022d). *Proposal for a DDirective of the European Parliament and of the Council on Corporate Sustainability Due Diligence and amending Directive (EU) 2019/1937. COM/2022/71 final*.

EC - European Commission. (2022e). *Proposal for a Directive of the Eureopean Parliament and of the Council on Corporate Sustainability Due Diligence and amending Directive (EU) 2019/1937 COM(2022) 71 final*.

EC - European Commission. (2022f). *Proposal of the European Parliament and of the Council on establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC COM(2022) 142 final*.

EC - European Commission. (2023). *Proposal for a regulation of the European Parliament and of the Council on* *establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act). COM(2023) 161 final*.

EEA - European Environmental Agency. (1999). *Environmental indicators: Typology and overview*. https://www.eea.europa.eu/publications/TEC25

EU - European Union. (2023). *Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast) (Text with EEA relevance)*.

EU Platform on Sustainable Finance. (2022). *Final Report on Social Taxonomy*. https://ec.europa.eu/info/sites/default/files/business_economy_euro/banking_and_finance/documents/280222-sustainable-finance-platform-finance-report-social-taxonomy.pdf

European Union. (2018). *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance.)*.

European Union. (2020). *Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088 (Text with EEA relevance)*.

European Union. (2022). *Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting*.

Fantke, P., Bijster, M., Guignard, C., Hauschild, M., Huijbregts, M., Jolliet, O., Kounina, A., Magaud, V., Margni, M., McKone, T. E., Posthma, L., Rosenbaum, R. K., van de Meent, D., & van Zelm, R. (2017). *USEtox®2.0 Documentation (Version 1), http://usetox.org.* https://doi.org/10.11581/DTU:00000011

Fantke, P., Evans, J., Hodas, N., Apte, J., Jantunen, M., Jolliet, O., & McKone, T. E. (2016). *Health impacts of fine particulate matter. In: Frischknecht, R., Jolliet, O. (Eds.), Global Guidance for Life Cycle Impact Assessment Indicators: Volume 1. UNEP/SETAC Life Cycle Initiative, Paris*. 76–99.

Frischknecht, R., Braunschweig, A., Hofstetter, P., & Suter, P. (2000). Human health damages due to ionising radiation in life cycle impact assessment. *Environmental Impact Assessment Review*. https://doi.org/10.1016/S0195-9255(99)00042-6

Gemechu, E. D., Helbig, C., Sonnemann, G., Thorenz, A., & Tuma, A. (2016). Import-based indicator for the geopolitical supply risk of raw materials in life cycle sustainability assessments. *Journal of Industrial Ecology*, *20*(1), 154–165.

Goedkoop, M. J., de Beer, I. M., Harmens, R., Indrane, D., Saling, P., Morris, D., Florea, A., Hettinger, A. L., Indrane, D., Visser, D., Morao, A., Musoke-Flores, E., Alvarado, C., Rawat, I., Schenker, U., Head, M., Collotta, M., Andro, T., Viot, J., & Whatelet, A. (2020). Product Social Impact Assessment Handbook 2020. In *Amersfoort, The Netherlands: The Roundtalble for Product Social Metrics*.

Gonzales-Gemio, C., Cruz-Cázares, C., & Parmentier, M. J. (2020). Responsible innovation in smes: A systematic literature review for a conceptual model. *Sustainability*, *12*(24), 10232.

Grigoroudis, E., Kouikoglou, V. S., Phillis, Y. A., & Kanellos, F. D. (2021). Energy sustainability: a definition and assessment model. *Operational Research*, *21*, 1845–1885.

Guinée, J. B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H. A., de Bruijn, H., van Duin, R., & Huijbregts, M. A. J. (2002). *Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards. Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Series: Eco-efficiency in industry and science. Kluwer Academic Publishers. Dordrecht*. Kluwer Academic Publishers. https://doi.org/10.1007/BF02978897

Hacking, T., & Guthrie, P. (2008). A framework for clarifying the meaning of Triple Bottom-Line, Integrated, and Sustainability Assessment. *Environmental Impact Assessment Review*, *28*(2–3), 73–89. http://linkinghub.elsevier.com/retrieve/pii/S0195925507000297

Halme, M., & Korpela, M. (2014). Responsible innovation toward sustainable development in small and medium-sized enterprises: A resource perspective. *Business Strategy and the Environment*, *23*(8), 547–566.

Hauschild, M. Z., & Wenzel, H. (1998). *Environmental Assessment of Products. Vol. 2 – Scientific background*.

Chapman {&} Hall.

Hollaway, L. C. (2013). 19 - Sustainable energy production: Key material requirements. In J. B. T.-A. F.-R. P. C. for S. A. (Second E. Bai (Ed.), *Woodhead Publishing Series in Civil and Structural Engineering* (pp. 675–701). Woodhead Publishing. https://doi.org/https://doi.org/10.1016/B978-0-12-820346-0.00012-5

Horn, R., & Maier, S. (2018). *LANCA®- Characterization Factors for Life Cycle Impact Assessment, Version 2.5 November 2018*.

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & Van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment*, *22*, 138–147.

Iakovleva, T., Oftedal, E., & Bessant, J. (2021). Changing role of users—innovating responsibly in digital health. *Sustainability*, *13*(4), 1616.

IEA - International Energy Agency. (2017). *Energy Access Outlook 2019: From Poverty to Prosperity*. https://www.climateaction.org/images/uploads/documents/EnergyAccessOutlook.pdf?

IEA - International Energy Agency. (2020). *Energy technology perspective. Special report on clean energy innovation*.

IRENA, I. R. E. A. (2022). *World energy transitions outlook*. eBook Partnership.

ISO. (2006). *Environmental Management - Life Cycle Assessment - Requirements and Guidelines, ISO 14044*. ISO.

ISO. (2019). *ISO GUIDE 82:2019(E): Guidelines for addressing sustainability in standards*.

ISO. (2020). *ISO 14040:2006/A2:2020 Environmental management — Life cycle assessment — Principles and framework — Amendment 2*.

Jenkins, K., McCauley, D., Heffron, R., Stephan, H., & Rehner, R. (2016). Energy justice: A conceptual review. *Energy Research & Social Science*, *11*, 174–182.

Leccisi, E., Raugei, M., & Fthenakis, V. (2016). The energy and environmental performance of ground-mounted photovoltaic systems—a timely update. *Energies*, *9*(8), 622.

Littig, B., & Griessler, E. (2005). Social sustainability: a catchword between political pragmatism and social theory. *International Journal of Sustainable Development*, *8*(1/2), 65. https://doi.org/10.1504/IJSD.2005.007375

Lund, H. (2010). *Chapter 1 - Introduction* (H. B. T.-R. E. S. Lund (ed.); pp. 1–12). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-375028-0.00001-7

Mancini, L., Eynard, U., Eisfeldt, F., Ciroth, A., Blengini, G. A., & Pennington, D. W. (2018). *Social Assessment Of Raw Materials Supply Chains: A Life-Cycle-Based Analysis*. Publications Office of the European Union. https://doi.org/10.2760/470881

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens, W. W. I. I. I. (1972). *The Limits to Growth*. Universe Books.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., & Zhang, H. (2013). Anthropogenic and Natural Radiative Forcing. In S. K. A. Stocker, T.F.D. Qin, G.-K. Plattner, M. Tignor & V. B. and P. M. M. J. Boschung, A. Nauels, Y. Xia (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

O'Connor, M. (2006). The "Four Spheres" framework for sustainability. *Ecological Complexity*, *3*(4), 285–292. https://doi.org/10.1016/j.ecocom.2007.02.002

OECD. (2011). *OECD Guidelines for Multinational Enterprises 2011 Edition*.

OECD. (2016). *Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas. Third Edition*.

OECD. (2023). *OECD Guidelines for Multinational Enterprises on Responsible Business Conduct*. http://mneguidelines.oecd.org/mneguidelines/

Owen, R., Macnaghten, P., & Stilgoe, J. (2020). Responsible research and innovation: From science in society to science for society, with society. In *Emerging Technologies* (pp. 117–126). Routledge.

Posch, M., Seppälä, J., Hettelingh, J. P., Johansson, M., M., M., & Jolliet, O. (2008). The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. *International Journal of Life Cycle Assessment*, *13*, 477–486. https://doi.org/10.1007/s11367-008-0025-9

Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins. *Sustainability Science*, *14*(3), 681–695. https://doi.org/10.1007/s11625-018-0627-5

Raworth, K. (2017). A Doughnut for the Anthropocene: humanity's compass in the 21st century. *The Lancet Planetary Health*, *1*(2), e48–e49.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., … Foley, J. A. (2009). A safe operating space for humanity. *Nature*, *461*(7263), 472–475. https://doi.org/10.1038/461472a

Sala, S., Amadei, A., Beylot, A., & Ardente, F. (2021). The evolution of life cycle assessment in European policies over three decades. *Int J Life Cycle Assess*. https://doi.org/10.1007/s11367-021-01893-2

Sala, S., Ciuffo, B., & Nijkamp, P. (2015). A systemic framework for sustainability assessment. *Ecological Economics*, *119*, 314–325.

Sala, S., Farioli, F., & Zamagni, A. (2013). Progress in sustainability science: lessons learnt from current methodologies for sustainability assessment: Part 1. *The International Journal of Life Cycle Assessment*, *18*(9), 1653–1672.

Saouter, E., Biganzoli, F., Ceriani, L., Pant, R., Versteeg, D., Crenna, E., & L., Z. (2018). *Using REACH and EFSA database to derive input data for the USEtox model. EUR 29495 EN, Publications Office of the European Union, Luxemburg, 2018, ISBN 978-92-79-98183-8, doi: 10.2760/611799, JRC 114227.*

Seppälä, J., Posch, M., Johansson, M., & Hettelingh, J. P. (2006). Country-dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator. *International Journal of Life Cycle Assessment*, *11*(6), 403–416. https://doi.org/10.1065/lca2005.06.215

Sovacool, B. K. (2012). The political economy of energy poverty: A review of key challenges. *Energy for Sustainable Development*, *16*(3), 272–282. https://doi.org/https://doi.org/10.1016/j.esd.2012.05.006

Sovacool, B. K., Burke, M., Baker, L., Kotikalapudi, C. K., & Wlokas, H. (2017). New frontiers and conceptual frameworks for energy justice. *Energy Policy*, *105*, 677–691. https://doi.org/https://doi.org/10.1016/j.enpol.2017.03.005

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., & De Wit, C. A. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855.

Steinberger, J. K., & Roberts, J. T. (2010). From constraint to sufficiency: The decoupling of energy and carbon from human needs, 1975–2005. *Ecological Economics*, *70*(2), 425–433.

Struijs, J., Beusen, A., Jaarsveld, V. H., & Huijbregts, M. A. J. (2009). Aquatic Eutrophication. Chapter 6 in: Goedkoop, M., Heijungs, R., Huijbregts, M.A.J., De Schryver, A., Struijs, J., Van Zelm, R. (2009). *ReCiPe 2008A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level. Report I: Characterisation Factors, First Edition*.

Tarvydas, D. (2022). *Clean Energy Technology Observatory: Clean Energy Outlooks: Analysis and Critical Review? 2022 Status Report on Technology Development, Trends, Value Chains and Markets* (Issue KJ-NA-31-261-EN-N (online)). Publications Office of the European Union. https://doi.org/10.2760/309952 (online)

UN General Assembly. (2015). Transforming our world: the 2030 Agenda for Sustainable Development. In *New York: United Nations*.

UNECE - United Nations Economic Commission for Europe. (2020). *Pathways to Sustainable Energy. Accelerating Energy Transition in the UNECE Region*. https://unece.org/fileadmin/DAM/energy/se/pdfs/CSE/Publications/Final_Report_PathwaysToSE.pdf

UNEP. (2016). *Global guidance for life cycle impact assessment indicators. Volume 1. ISBN: 978-92-807-3630-*

4.

UNEP. (2020a). *Guidelines for Social Life Cycle Assessment of Products and Organizations* (C. Benoît-Norris, M. Traverso, S. Neugebauer, E. Ekener, T. Schaubroeck, S. Russo Garrido, M. Berger, S. Valdivia, A. Lehmann, M. Finkbeiner, & G. Arcese (eds.)). United Nations Environment Programme (UNEP).

UNEP. (2020b). *Guidelines for Social Life Cycle Assessment of Products and Organizations 2020* (G. (eds.). Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese (ed.)). United Nations Environment Programme (UNEP). https://www.lifecycleinitiative.org/wp-content/uploads/2020/12/Guidelines-for-Social-Life-Cycle-Assessment-of-Products-and-Organizations-2020-sml.pdf

UNEP. (2021). *Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA)* (M. Traverso, S. Valdivia, A. Luthin, L. Roche, G. Arcese, S. Neugebauer, L. Petti, M. D'Eusanio, B. M. Tragnone, R. Mankaa, J. Hanafi, C. Benoit-Norris, & A. Zamagni (eds.)).

Valdivia, S., Backes, J. G., Traverso, M., Sonnemann, G., Cucurachi, S., Guinée, J. B., Schaubroeck, T., Finkbeiner, M., Leroy-Parmentier, N., Ugaya, C., Peña, C., Zamagni, A., Inaba, A., Amaral, M., Berger, M., Dvarioniene, J., Vakhitova, T., Benoit-Norris, C., Prox, M., … Goedkoop, M. (2021). Principles for the application of life cycle sustainability assessment. *International Journal of Life Cycle Assessment*, *26*(9), 1900–1905. https://doi.org/10.1007/s11367-021-01958-2

van der Hulst, M. K., Huijbregts, M. A. J., van Loon, N., Theelen, M., Kootstra, L., Bergesen, J. D., & Hauck, M. (2020). A systematic approach to assess the environmental impact of emerging technologies: A case study for the GHG footprint of CIGS solar photovoltaic laminate. *Journal of Industrial Ecology*, *24*(6), 1234–1249.

Van Oers, L., de Konin, A, Guinee, J., & Huppes, G. (2002). *Abiotic Resource Depletion in LCA. Road and Hydraulic Engineering Institute, Ministry of Transport and Water, Amsterdam.*

Van Zelm, R., Huijbregts, M. A. J., Den Hollander, H. A., Van Jaarsveld, H. A., Sauter, F. J., Struijs, J., Van Wijnen, H. J., & Van de Meent, D. (2008). European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. *Atmospheric Environment*, *42*, 441–453. https://doi.org/10.1016/j.atmosenv.2007.09.072

Verones, F., Hellweg, S., Antón, A., Azevedo, L. B., Chaudhary, A., Cosme, N., Cucurachi, S., de Baan, L., Dong, Y., & Fantke, P. (2020). LC-IMPACT: A regionalized life cycle damage assessment method. *Journal of Industrial Ecology*, *24*(6), 1201–1219.

Vos, R. O. (2007). Defining sustainability: A conceptual orientation. *Journal of Chemical Technology and Biotechnology*, *82*(4), 334–339. https://doi.org/10.1002/jctb.1675

WCED. (1987). *Report of the World Commission on Environment and Development: Our Common Future*. Oxford University Press.

WMO. (2014). *Scientific Assessment of Ozone Depletion: 2014, Global Ozone Research and Monitoring Project Report No. 55, Geneva, Switzerland.*

Yaghmaei, E., & Poel, I. van de. (2021). *Assessment of responsible innovation: Methods and practices*. Taylor & Francis.

List of abbreviations and definitions

CETO Clean Energy Technology Observatory

CFF Circular Footprint Formula

CSRD Corporate Sustainability Reporting Directive

CRM Critical Raw Materials

CTUh Comparative Toxic Unit for humans

DPSIR Driver-Pressure-State-Impact-Response

EPBT Energy Pay Back Time

EROI Energy Return on Energy Invested

ESRS European Sustainability Reporting Standards

LCA Life Cycle Assessment

LCC Life Cycle Costing

LCSA Life Cycle Sustainability Assessment

LCT Life Cycle Thinking

PB Planetary Boundaries

RED Renewable Energy Directive

SAF Sustainability Assessment Framework

SDGs Sustainable Development Goals

SJOS Safe and Just Operating Space

S-LCA Social Life Cycle Assessment

SSbD Safe and Sustainable by Design

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Annexes

Annex 1. Definitions

Term	Definition	References (*if applicable*)
Criteria	An aspect with an assessment method and a minimum threshold or target values (on which a decision may be based)	
Decision Framework	The decision structure made of principles, methods, and indicators to proceed from the relevant information to final outcomes that are necessary to inform future actions. The collected frameworks can be either recommended by experts in guidance documents and articles or implemented in design tools.	
Due diligence	The process through which organizations identify, consider, and address the potential environmental and social impacts related to their activities and the ones of their business relationships, as an integral part of their decision-making and risk management system.	OECD. (2016). Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas. Third Edition.
Endpoint method-model and indicator (LCA)	The category endpoint is an attribute or aspect of the environment, human health, or resources, identifying an environmental issue giving cause for concern. Hence, endpoint method (or damage approach)/model) is a characterisation method/model that provides indicators at the level of Areas of Protection (natural ecosystems, human health, resource availability) or at a level close to the Areas of Protection level.	ISO (2006). ISO 14040:2006 Environmental Management - Life Cycle Assessment - Principles and Framework.
Energy dependency	Energy dependency shows the extent to which a country relies upon imports in order to meet its energy needs. It is calculated using the following formula: net energy imports/ (gross inland energy consumption + international maritime bunkers).	Eurostat (2020) Energy, transport and environment statistics. 2020 edition.
Environmental cause-effect chain	Also known as an environmental mechanism. System of physical, chemical and biological processes for a given impact category, linking the life cycle inventory analysis result to the common unit of the category indicator (ISO 14040) by means of a characterisation model.	ISO (2006). ISO 14040:2006 Environmental Management - Life Cycle Assessment - Principles and Framework.
Environmental pressure	The quantified cause of a change to the environment	
Framework	The rationale and the structure for the identification of sustainability dimensions as well as the way to integrate concepts, parameters, methodologies, methods, models, tools and indicators.	Sala, S., Farioli, F., Zamagni, A. (2013). "Progress in Sustainability Science: Lessons Learnt from Current Methodologies for Sustainability Assessment: Part 1." International Journal of Life Cycle Assessment 18, 9, 1653–72. https://doi.org/:10.1007/s11367-012-0508-6.
Impact	The quantified result of a change to the environment caused by human activity that can be positive or negative	
Impact category	Class representing environmental issue of concern, e.g. climate change, acidification, ecotoxicity etc.	ISO (2006). ISO 14040:2006 Environmental Management - Life Cycle Assessment - Principles and Framework.
(social) Impact subcategory	It is a constituent of an impact category that is assigned to a stakeholder group, for example	UNEP. (2020). Guidelines for Social Life Cycle Assessment of Products and Organizations 2020 (G. (eds.). Benoît Norris, C., Traverso, M., Neugebauer, S.,

	"Health and Safety" for the stakeholder group "Workers". Multiple subcategories, possibly across various stakeholder groups, may be part of an overarching impact category.	Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese (ed.)). United Nations Environment Programme (UNEP).
Indicator	A parameter, or a value derived from parameters, which points to, provides information about, or describes the state of a phenomenon, with a significance extending beyond that directly associated with its value (OECD 2003). The indicator could be quantitative or semi- quantitative or qualitative derived from a model, often trough a tool or direct measurement	Adapted from OECD, OECD. 2021. Glossary of statistical terms. Retrieved November 16, 2021 (https://stats.oecd.org/glossary/detail.asp?ID=830)
Life cycle assessment	Methodology for assessing life cycle impacts standardised by ISO 14040:2006 and ISO 14044:2006	ISO (2006). ISO 14040:2006 Environmental Management - Life Cycle Assessment - Principles and Framework.
Life cycle thinking	Life Cycle Thinking (LCT) is about going beyond the traditional focus on production site and manufacturing processes to include environmental, social and economic impacts of a product over its entire life cycle. The main goals of LCT are to reduce a product's resource use and emissions to the environment as well as improve its socio-economic performance through its life cycle.	https://www.lifecycleinitiative.org/starting-life-cycle-thinking/what-is-life-cycle-thinking/
Materiality assessment	Materiality assessment is a process to select topics that are more important because of their impact on stakeholders and/or on the business. The Global Reporting Initiative consider material issues to be the ones that reflect the organization's significant social impacts; or that substantively influence the assessments and decisions of stakeholders. This is also recommended by ISO 26000.	UNEP. (2020). Guidelines for Social Life Cycle Assessment of Products and Organizations 2020 (G. (eds.). Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese (ed.)). United Nations Environment Programme (UNEP).
Measurement	Direct measurement of a certain aspect following a procedure	
Methodology	A collection of individual methods, which together address the different safety, environmental, economic and social issues and the associated effect/ impact (e.g. risk assessment, LCA, LCC, sLCA....)	
Method	A procedure for measurement or a set of models, tools and indicators that enable the calculation of indicators' values for a certain parameter	
Midpoint method and indicator (LCA)	In LCA, the midpoint method is a characterisation method that provides indicators for comparing environmental interventions at the level of a cause-effect chain between emissions/resource consumption and the endpoint level (where effects and damage are assessed)	
Model	A model supporting the quantitative assessment of safety/environmental/social/economic parameters adopted in order to calculate a particular indicator	
Parameter	Refers to a value, a constant, as a mathematical term. In environmental science and particularly in chemistry and microbiology,	

	a parameter is used to describe a discrete chemical or microbiological entity that can be assigned a value.	
Primary data	Refers to data that has been directly collected by the practitioner, via interview, survey, or participant observation for instance.	UNEP. (2020). Guidelines for Social Life Cycle Assessment of Products and Organizations 2020 (G. (eds.). Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese (ed.)). United Nations Environment Programme (UNEP).
Product	Any goods or services which are supplied for distribution, consumption or use on the Community market whether in return for payment or free of charge	EU (2010). Regulation (EC) No 66/2010 of the European Parliament and of the Council of 25 November 2009 on the EU Ecolabel. OJ L 27, 30.1.2010, p. 1–19
Product design	'Product design' means the set of processes that transform legal, technical, safety, functional, market or other requirements to be met by a product into the technical specification for that product.	EU (2009). Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 Establishing a Framework for the Setting of Ecodesign Requirements for Energy-Related Products.
Reference scale	Reference scales are ordinal scales, typically comprised of 1 to 5 levels, each of which corresponds to a performance reference point (PRP)	UNEP. (2020). Guidelines for Social Life Cycle Assessment of Products and Organizations 2020 (G. (eds.). Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese (ed.)). United Nations Environment Programme (UNEP)
Secondary data	Refers to data that has been initially collected and manipulated by another person/institution than the practitioner or collected for another purpose than the one being currently considered or, often a mix of the two. For example, a publication, third party audit, or a database.	UNEP. (2020). Guidelines for Social Life Cycle Assessment of Products and Organizations 2020 (G. (eds.). Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese (ed.)). United Nations Environment Programme (UNEP)
Social hotspot	A social hotspot is a location and/or activity in the life cycle where a social issue (as impact) and/or social risk is likely to occur. It is usually linked to life cycle stages or processes. It needs to contribute significantly to the impact (overall, by impact category or subcategory). In other words, social hotspots are unit processes located in a region where a problem, a risk, or an opportunity may occur in relation to a social issue that is considered to be threatening social well-being or that may contribute to its further development.	UNEP. (2020). Guidelines for Social Life Cycle Assessment of Products and Organizations 2020 (G. (eds.). Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese (ed.)). United Nations Environment Programme (UNEP).
Social performance	Social performance refers to the principles, practices, and outcomes of businesses' relationships with people, organizations, institutions, communities, and societies in terms of the deliberate actions of businesses toward these stakeholders as well as the unintended externalities of business activity measured against a known standard. Commonly, social performance is measured at the inventory indicator level.	UNEP. (2020). Guidelines for Social Life Cycle Assessment of Products and Organizations 2020 (G. (eds.). Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese (ed.)). United Nations Environment Programme (UNEP).
Stakeholder	Individual or group that has an interest in any activities or decisions of an organization	UNEP. (2020). Guidelines for Social Life Cycle Assessment of Products and Organizations 2020 (G. (eds.). Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese (ed.)). United Nations Environment Programme (UNEP).
Stakeholder category	Cluster of stakeholders that are expected to have similar interests due to their similar relationship to the investigated product system	UNEP. (2020). Guidelines for Social Life Cycle Assessment of Products and Organizations 2020 (G. (eds.). Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese (ed.)). United Nations Environment Programme (UNEP).

Subcategory/impact subcategory	It is a constituent of an impact category that is assigned to a stakeholder group, for example "Health and Safety" for the stakeholder group "Workers". Multiple subcategories, possibly across various stakeholder groups, may be part of an overarching impact category	UNEP. (2020). Guidelines for Social Life Cycle Assessment of Products and Organizations 2020 (G. (eds.). Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese (ed.)). United Nations Environment Programme (UNEP).
Supply chain	A supply chain, or logistics network, is the system of organizations, people, technology, activities, information, and resources involved in moving a product or service from supplier to customer. Supply chain activities transform natural resources, raw materials, and components into a finished product that is delivered to the end customer. In sophisticated supply chain systems used products may re-enter the supply chain at any point where residual value is recyclable. Supply chains link value chains.	UNEP. (2020). Guidelines for Social Life Cycle Assessment of Products and Organizations 2020 (G. (eds.). Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, T., Russo Garrido, S., Berger, M., Valdivia, S., Lehmann, A., Finkbeiner, M., Arcese (ed.)). United Nations Environment Programme (UNEP).
Sustainability dimensions	Refers to the four dimensions of sustainability addressed in this study: safety, environmental, social and economic	
Tool	Software, applications, databases supporting the analysis done by adopting specific methods and the related models (e.g. a software for LCA calculation, or a QSAR tool)	

Annex 2. Description of available methods, indicators, tools and databases for each aspect of the SAF for clean energy technologies

Aspect[1]	Method	Indicator	DPSIR classification of the indicator	Tools/ Databases	Reference scale
Critical Raw Materials (CRMs)	Several methods exist for the identification of CRMs and their consideration in sustainability assessment. The GeoPolRisk is considered one of the best approach (Gemechu et al., 2016) in a recent review (Bianchi et al., 2021).	The method is based on the combination of - Herfindahl-Hirschman Index (HHI) - World Bank's Worldwide Governance Indicators (WGI).	Pressure (resource related)	n.a.	n.a.
Market demand	No specific guidance is available in the context of sustainability assessment. Assessment based on energy statistics and literature review for insights on forecasts.		Driver	n.a.	n.a.
Cost of energy	No specific guidance is available in the context of sustainability assessment. Assessment based on energy statistics and literature review for insights on forecasts.		Driver	n.a.	n.a.
Technology-specific permitting requirements	No specific guidance is available in the context of sustainability assessment.		State	n.a.	n.a.
Energy security	No specific guidance is available in the context of sustainability assessment.		Impact		
Resource efficiency and recycling	LCA		Resource related	n.a.	To be evaluated at the technological level, considering the status of the tecnology and the same scale
Energy balance	LCA	Energy Pay Back Time (EPBT) Energy Return on Energy Invested (EROI)	Resource related	n.a.	To be evaluated at the technological level, considering the status of the tecnology and the same scale
Climate change	LCA / Product Environmental Footprint (PEF)	Global warming potential (GWP100)	Impact	Commercial LCA tools/databases	To be evaluated at the technological level, considering the status of the

Aspect[1]	Method	Indicator	DPSIR classification of the indicator	Tools/ Databases	Reference scale
					tecnology and the same scale
Ozone depletion	LCA / Product Environmental Footprint (PEF)	Ozone Depletion Potential (ODP)	Impact	Commercial LCA tools/databases	To be evaluated at the technological level, considering the status of the tecnology and the same scale
Particulate matter/Respiratory inorganics	LCA / Product Environmental Footprint (PEF)	Human health effects associated with exposure to $PM_{2.5}$	Impact	Commercial LCA tools/databases	To be evaluated at the technological level, considering the status of the tecnology and the same scale
Ionising radiation, human health	LCA / Product Environmental Footprint (PEF)	Human exposure to ^{235}U	Impact	Commercial LCA tools/databases	To be evaluated at the technological level, considering the status of the tecnology and the same scale
Photochemical ozone formation	LCA / Product Environmental Footprint (PEF)	Tropospheric ozone concentration increase	Impact	Commercial LCA tools/databases	To be evaluated at the technological level, considering the status of the tecnology and the same scale
Acidification	LCA / Product Environmental Footprint (PEF)	Accumulated Exceedance (AE)	Impact	Commercial LCA tools/databases	To be evaluated at the technological level, considering the status of the tecnology and the same scale
Eutrophication, terrestrial	LCA / Product Environmental Footprint (PEF)	Accumulated Exceedance (AE)	Impact	Commercial LCA tools/databases	To be evaluated at the technological level, considering the status of the tecnology and the same scale
Eutrophication, aquatic freshwater	LCA / Product Environmental Footprint (PEF)	Fraction of nutrients reaching	Impact	Commercial LCA tools/databases	To be evaluated at the technological level, considering the status of the

Aspect[1]	Method	Indicator	DPSIR classification of the indicator	Tools/ Databases	Reference scale
		freshwater end compartment (P)			tecnology and the same scale
Eutrophication, aquatic marine	LCA / Product Environmental Footprint (PEF)	Fraction of nutrients reaching marine end compartment (N)	Impact	Commercial LCA tools/databases	To be evaluated at the technological level, considering the status of the tecnology and the same scale
Land use	LCA / Product Environmental Footprint (PEF)	Soil quality index[4] aggregating: Biotic production, Erosion resistance, Mechanical filtration and Groundwater replenishment	Impact	Commercial LCA tools/databases	To be evaluated at the technological level, considering the status of the tecnology and the same scale
Water use	LCA / Product Environmental Footprint (PEF)	User deprivation potential (deprivation weighted water consumption)	Impact	Commercial LCA tools/databases	To be evaluated at the technological level, considering the status of the tecnology and the same scale
Resource use, minerals and metals	LCA / Product Environmental Footprint (PEF)	Abiotic resource depletion (ADP ultimate reserves)	Impact	Commercial LCA tools/databases	To be evaluated at the technological level, considering the status of the tecnology and the same scale
Resource use, energy carriers	LCA / Product Environmental Footprint (PEF)	Abiotic resource depletion – fossil fuels (ADP-fossil)[5]	Impact	Commercial LCA tools/databases	To be evaluated at the technological level, considering the status of the tecnology and the same scale
Child labour	Reference scale	Percentage of working children under the legal age or 15 years old (total, male and female) – country level	Pressure	ILOstat PSILCA SHDB	vhr: >10 hr: 5-10 mr: 2.5-5 lr: 1-2.5 vlr: <= 1
Forced labour	Reference scale	Frequency of forced labour (estimated prevalence of	Pressure	Global Slavery Index PSILCA SHDB	vhr: ≥ 1.2; hr: 0.6 -1.2; mr: 0.4 -0.6

Aspect[1]	Method	Indicator	DPSIR classification of the indicator	Tools/ Databases	Reference scale
		population in modern slavery, victims per 1,000 population) - country level			lr: 0.2 -0.4; vlr: < 0.2
Equal opportunities / discrimination	Reference scale	Gender wage gap (%) - country level	Pressure	ILOstat PSILCA SHDB	vhr: >=30% and <=-30 hr: 20% - <30% and -20% - >-30% mr: 10% - <20% and -10% - >-20% lr: 5% - <10% and -5% - >-10% vlr: 0% - <5% and 0% - >-5%
		Women in the labour force (ratio) – country/sector level	Pressure	ILOstat PSILCA SHDB	vhr: <0.2 hr: 0.2-<0.4 mr: 0.4-<0.6 lr: 0.6-<0.8 or >1.5 vlr: 0.8-<1 or >1-1.5
Freedom of association and collective bargaining	Reference scale	Right to strike / Right to association / Right of collective bargaining (point in scale)	Pressure	OECD/AIAS database on Institutional Characteristics of Trade Unions, Wage Setting, State Intervention and Social Pacts (ICTWSS) PSILCA SHDB	vhr: 0 hr: 1 lr: 2 vlr: 3
	Reference scale	Trade union density (%)	Pressure	ILOStat PSILCA SHDB	vhr: 0-20% hr: >20-40% mr: >40-60% lr: >60-80% vlr: >80%
Working hours	Reference scale	Hours of work per employee and week (hours)	Pressure	ILOStat PSILCA SHDB	vhr: <20 and >60 hr: 20 - <30 and 55 - <60 mr: 30 - <40 and 48 - <55 lr: 40 - <48
Fair salary	Reference scale	Sector average wage, per month Living wage, per month	Pressure	ILOStat Wage indicator PSILCA SHDB	Assessment based on combination of the three indicators as in Maister et al. 2020

Aspect[1]	Method	Indicator	DPSIR classification of the indicator	Tools/ Databases	Reference scale
		Minimum wage, per month (Eur/month) country/sector level			
Health and safety	Reference scale	Rate of non-fatal accidents at workplace (# per 100,000 employees) - country/sector level	Pressure	ILOStat PSILCA SHDB	vhr: ≥ 3000 hr:2250 – 3000 mr: 1500 – 2250 lr: 750 – 1500 vlr: 0 – 750
	Reference scale	Rate of non-fatal accidents at workplace (# per 100,000 employees) - country/sector level	Pressure	ILOstat database PSILCA SHDB	vhr: ≥ 40 hr: 25 -40 mr: 15-25 lr: 7.5 -15 vlr: 0 -7.5
	Reference scale	DALYs due to indoor and outdoor air and water pollution (DALYs per 1000 inhabitants) – country level	Pressure	PSILCA SHDB	vhr:>50 hr: 30-<50 mr:15-<30 lr: 5-<15 vlr: >0-<5
	Reference scale	Presence of sufficient safety measures (cases of violation per 100,000 employees) country-sector	Pressure	PSILCA SHDB	vhr:> 0.0565 hr: 0.0215 - < 0.0565 mr: 0.0095- < 0.0215 lr: 0.0025 - < 0.0095 vlr: < 0.0025
	Reference scale	Workers affected by natural disasters (% of population) country level	Pressure	PSILCA SHDB	vhr: >=10 hr: 5-<10 mr: 3-<5 lr: 1-<3 vlr: 0-<1
	Reference scale	Violations of mandatory health and safety standards (number of cases)	Pressure	PSILCA SHDB	vhr: >=5e-6 hr: < 1.5e-6 - <5e-6 mr: < 8e-7 - <1.5e-6 lr: < 2.5e-7 - <8e-7 vlr: < 5.5e-8 - <2.5e-7

Aspect[1]	Method	Indicator	DPSIR classification of the indicator	Tools/ Databases	Reference scale
Responsible materials sourcing	Descriptive, should look at severe risks in technologies value chains and can be based on due diligence guidance for minerals supply chain (OECD, 2016).	The OECD Guidance indicates areas of risks to be taken into account in a due diligence process, through a qualitative assessment.	Pressure	The list of conflict-affected and high-risk areas under Regulation (EU) 2017/821[3] can be used to verify the risk of conflicts in the main supplier countries.	n.a.
Access to material resources (incl. water, land, food)	Descriptive, based on narratives and literature review		Pressure	Can include insights from the Environmental justice Atlas[4]	
Contribution to economic development	Reference scale	% of GDP (positive impact)	Pressure	PSILCA SHDB	no opportunity: 0-<1 low opportunity: 1-10 medium opportunity: >10-25 high opportunity: >25
Affordable energy access	Several indicators/methods exist, but no specific guidance is available in the context of sustainability assessment.		Impact		
Public acceptance	Descriptive, based on narratives and literature review		Response	Can include insights from the Environmental justice Atlas[5]	n.a.
Rural development	While specific guidance in the context of sustainability assessment is not available, relevant indicators can be selected from the FAO Guidelines on defining rural areas and compiling indicators for development policy (FAO 2018)[6], adapting them to capture the impact of energy technologies on	Example of indicators from the FAO report, based on SDGs: -Proportion of population below the international poverty line -Prevalence of moderate or severe food insecurity in the population - Proportion of population with access to electricity - Proportion of population with primary reliance	Impact		n.a.

Aspect[1]	Method	Indicator	DPSIR classification of the indicator	Tools/ Databases	Reference scale
	rural development	on clean fuels and technology			

[1] In this report, we used the word "aspect" to generally indicate the issues/topics to be assessed under each sustainability pillar. This corresponds to the term "impact category" used in LCA and the term "social subcategory" used in Social LCA. In this methodology the term "category" refers to stakeholders (workers, local communities, society, value chain actors, consumers, children).

[3] https://www.cahraslist.net/

[4] https://ejatlas.org/

[5] https://ejatlas.org/

[6] https://www.fao.org/3/ca6392en/ca6392en.pdf

Annex 3 List of frameworks considered for the selection of social aspects and description

Framework name	Description
a) Guidelines for Social Life Cycle Assessment of Products and Organizations	The Guidelines for Social Life Cycle Assessment (S-LCA) of Products and Organisations provide a roadmap and a body of knowledge to help stakeholders in the assessment of social and socio-economic impacts of products' life cycles, their related value chains and organizations. Awareness about value chain social issues such as child labor used for harvesting cotton, unpaid wages of factory workers and safety issues when using a product, raises the question of what the extent of product and organization social impacts are and how they can be improved. To answer this question, the S-LCA Guidelines present a methodology to assess the social impact of products using a life cycle perspective. This methodology builds on the more commonly known Life Cycle Assessment (LCA), which focuses on environmental impacts. The importance of social sustainability in moving towards sustainable development is undeniable. Now, more than ever, social sustainability, social inclusion and leaving no one behind must be critical parts of our thinking and efforts to build back better and greener (UNEP, 2020).
b) Clean Energy Technology Observatory reports	The European Commission has set up the Clean Energy Technology Observatory to help address the complexity and multi-faced character of the transition to a climate-neutral society in Europe. CETO is a joint initiative between the Joint Research Centre (JRC), implementing the Observatory and DGs Research and Innovation (R&I) and Energy (ENER) on the policy side. Starting from 2022, CETO monitors the EU research and innovation activities on the clean energy technologies needed to achieve the European Green Deal's objectives. It builds on the previous work within the Low Carbon Energy Observatory. One of the main purposes of CETO is to provide a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It produces a series of annual reports addressing the following themes: technology maturity status, development and trends (2030 – 2050 and beyond), value chain analysis, global market and EU positioning along with the question of clean technology system integration.
c) Better Regulation	The better regulation guidelines set out the principles that the European Commission follows when preparing new initiatives and proposals and when managing and evaluating existing legislation. The guidelines apply to each phase of the law-making cycle. The following tools have been considered for the analysis: Tool 30: Employment, working conditions, income distribution, social protection and inclusion Tool 32: Health impacts Tool 35: Developing countries
d) OECD Guidelines for Multinational Enterprises on Responsible Business Conduct	The OECD Guidelines for Multinational Enterprises on Responsible Business Conduct are recommendations addressed by governments to multinational enterprises. They aim to encourage positive contributions enterprises can make to economic, environmental and social progress, and to minimise adverse impacts on matters covered by the Guidelines that may be associated with an enterprise's operations, products and services. The Guidelines cover all key areas of business responsibility, including human rights, labour rights, environment, bribery, consumer interests, disclosure, science and technology, competition, and taxation. The 2023 edition of the Guidelines provides updated recommendations for responsible business conduct across key areas, such as climate change, biodiversity, technology, business integrity and supply chain due diligence, as well as updated implementation procedures for the National Contact Points for Responsible Business Conduct. (OECD 2023)

e) Product Social Impact Assessment Handbook - 2020	The Product Social Impact Assessment Handbook is a guidance developed by companies involved in the Roundtable for Product Social Metrics. It provides guidance on the data collection, hotspot identification, circular economy and impact assessment. The Social Topic Report is the companion of the Handbook and provides the definitions of 25 social topics, the reference scales and performance indicators. The social topics are selected based on the understanding of mutual dependency between an organisation, its workers, the local communities, the small-scale entrepreneurs and of course their customers (Goedkoop et al., 2020).
f) Directive (EU) 2022/2464 on Corporate sustainability Reporting	This Directive amends the previous directive governing the reporting of non-financial information in financial disclosures. It extends the scope of reporting obligations to a much wider set of companies headquartered or operating in the European Union. The new obligations will apply from the 2024 financial year. The Directive requires member states to introduce measures to ensure that sustainability disclosures include information on plans and strategies to ensure a corporate entity's business model and strategy are compatible with the transition to a sustainable economy, the global temperate target of 1.5 Degrees, and the goal of achieving climate neutrality by 2050, as well as the exposure of the entity to coal, oil and gas. Businesses are also required to report on social and human rights factors. Reporting standards should be aligned with the work of the Task Force for Climate Related Financial Disclosures.
g) Final Report on Social Taxonomy of the Platform on Sustainable Finance	In 2020 the EC published the Taxonomy Regulation which provides uniform criteria for companies and investors to determine which economic activities can be considered environmentally sustainable. The taxonomy initially only covers environmental activities and objectives and contained only limited reference to social sustainability. For this reason, the EC mandate the Platform on Sustainable Finance to also work on extending the taxonomy to social objectives. In this context, this platform has published a Final Report on Social Taxonomy that summarises the main initial observations and recommendations on this mandated task. The key elements of a social taxonomy in the current EU legislative environment on sustainable finance and sustainable governance include: i) the social objectives and sub-objectives; ii) what types of substantial contribution the activities can make to become socially sustainable; iii) ideas of a structure of Do No Significant Harm; iv) methodology for selecting sectors for these objectives; v) list of desirable characteristics on qualitative and quantitative metrics for Technical Screening Criteria (EU Platform on Sustainable Finance, 2022).
h) Proposal for a Corporate Due Diligence Directive (COM(2022) 71 final)	On 1 June 2023, the European Parliament has agreed on its position on the Directive on corporate sustainability due diligence (the CSDDD). The CSDDD requires in-scope companies to conduct due diligence on, and take responsibility for, human rights abuses and environmental harm throughout their global value chains. The CSDDD aims to foster sustainable and responsible corporate behaviour.

Annex 4 List of social subcategories identified in the frameworks analysis and selected aspects (in bold)

Stakeholders category	Social subcategories	N° of frameworks including the aspect	a)	b)	c)	d)	e)	f)	g)	h)
Workers	**Child labour**	8	x	x	x	x	x	x	x	x
Workers	**Forced labour**	8	x	x	x	x	x	x	x	x
Workers	**Equal opportunities / discrimination**	8	x	x	x	x	x	x	x	x
Workers	**Freedom of association and collective bargaining**	8	x	x	x	x	x	x	x	x
Workers	**Working hours**	8	x	x	x	x	x	x	x	x
Workers	**Fair salary**	7	x	x	x	x	x		x	x
Workers	**Health and Safety**	7	x		x	x	x	x	x	x
Workers	Social benefits / social security	6	x	x	x	x		x	x	
Workers	Smallholders including farmers	4	x		x			x	x	
Workers	Employment relationship	2	x					x		
Workers	Sexual harassment	1	x							
Value chain actors	**Supplier relationships**	7	x	x	x	x	x	x	x	
Value chain actors	Fair competition	3	x		x	x				
Value chain actors	Promoting social responsibility	3	x	x		x				
Value chain actors	Respect of intellectual property rights	3	x		x	x				
Value chain actors	Wealth distribution	2	x		x					
Society	Contribution to economic development	6	x	x	x	x	x		x	
Society	Prevention and mitigation of armed conflicts	3	x			x		x		
Society	Technology development	3	x	x		x				
Society	Corruption	3	x			x		x		
Society	Ethical treatment of animals	3	x		x	x				
Society	Poverty alleviation	2	x		x					
Society	Public commitment to sustainability issues	1	x							
Local community	**Access to material resources**	7	x	x	x	x	x		x	x
Local community	Access to immaterial resources	6	x	x	x	x	x		x	
Local community	Safe and healthy living conditions	6	x		x	x	x		x	x
Local community	Respect of indigenous rights	5	x			x		x	x	x
Local community	Local employment	5	x		x	x		x	x	
Local community	Community engagement	5	x			x	x	x	x	
Local community	Secure living conditions	3	x		x	x				
Local community	Delocalization and migration	2	x		x					
Local community	Cultural heritage	1	x							
Consumers	Health and safety	6	x		x	x	x	x	x	
Consumers	Consumer privacy	3				x	x		x	

Consumers	Transparency	2	x			x				
Consumers	End of life responsibility	2	x						x	
Consumers	Feedback mechanism	2	x			x				
Children	Children concerns regarding marketing practices	6	x			x	x	x	x	x
Children	Education provided in the local community	4	x	x		x	x			
Children	Health issues for children as consumers	4	x		x			x		x

Annex 5 Description of selected social aspects

Social aspect	Child labour
Stakeholder category	Workers
Aim and approach	At corporate level, the assessment aims to verify if the organization might or is employing children (as defined in the ILO conventions). It should be investigated if the conditions are favourable for the occurrence of child labour, and the existence and quality of prevention and mitigating measures taken by the organization. At sector level, it can be investigated if countries involved in the supply chain have high risk child of labour.
Suggested indicators	*Primary data:* Children are not performing work during the night (an example of unauthorized work by the ILO conventions C138 and C182) Records on all workers stating names and ages or dates of birth are kept on file Working children younger than 15 and under the local compulsory age are attending school *Secondary data at country level:* Percentage of working children under the legal age or 15 years old (14 years old for developing economies (%))
Generic data sources (examples)	Childinfo – monitoring the Situation of Children and Women; UNICEF; The International Labour Organisation (ILO), UNICEF and the World Bank initiated the inter-agency research project. Understanding Children's Work (UCW); U.S. Department of Labor; S-LCA databases.
Specific data sources	Interview with directors or human resources officer; interview with workers and trade union representatives; NGO reports; verification of organizations' documents including sustainability reports; interview with local schools and community members.
Social aspect	Fair salary
Stakeholder category	Workers
Aim and approach	This subcategory aims to assess whether practices concerning wages are in compliance with established standards and if the wage provided is meeting legal requirements, whether it is above, meeting, or below industry average and whether it can be considered as a living wage.
Suggested indicators	*Primary data:* Lowest paid worker, compared to the minimum wage and/or living wage Number of employees earning wages below poverty line Presence of suspicious deductions on wages Regular and documented payment of workers (weekly, bi-weekly) *Secondary data at country/sector level:* - Living wage (country level) - Minimum wage (country level) - Sector average wage (country/sector level)
Generic data sources (examples)	ILO Global Wage Report; Minimum Wage Fixing Convention 1970 (No. 131); Wageindicator
Specific data sources	Country minimum wage; Interview with directors or human resources officer; Verification of organization documents: e.g., wage records; Review of organization-specific reports, such as GRI reports or audit; Interviews with workers; Interview with local NGOs; Review of wage records. S-LCA databases.
Social aspect	Forced labour
Stakeholder category	Workers
Aim and approach	At corporate level, the assessment aims to verify that forced or compulsory labour is not used in the organization, and if the conditions are favourable for the occurrence of forced labour. At sector level, it can be investigated the risk of forced labour in countries involved in the supply chain.
Suggested indicators	*Primary data:* Workers voluntarily agree upon employment terms. Employment contracts stipulate wage, working time, holidays, and terms of resignation. Employment contracts are comprehensible to the workers and are kept on file Birth certificate, passport, identity card, work permit, or other original documents belonging to the worker are not retained or kept for safety reasons by the organization neither upon hiring nor during employment Workers are free to terminate their employment within the prevailing limits Workers are not bonded by debts exceeding legal limits to the employer *Secondary data at country level*:

	- Trafficking in persons (tier) based on the tier placements of countries provided by the Office to Monitor and Combat Trafficking in Persons in the "Trafficking in Persons Report 2018" (U.S. Department of State 2018). - Frequency of forced labour (estimated prevalence of population in modern slavery, victims per 1,000 population).
Generic data sources (examples)	ILO reports on the advancement of the conventions 29 and 105; U.S. Department of Labor's list of goods produced by child labor or forced labor. Walk free Foundation. S-LCA databases.
Specific data sources	Interview with directors or human resources officer; verification with workers interviews or audit; NGO reports; verification of organizations' documents.
Social aspect	Health and safety (workers)
Stakeholder category	Workers
Aim and approach	At corporate level, this subcategory aims to assess both the rate of incidents and the status of prevention measures and management practices. An incident is defined as a work-related event in which an injury or ill health (regardless of severity) or fatality occurred or could have occurred. Similarly, the rate of accidents can be assessed at sector level using county-sector specific data from ILO or ESTAT. The assessment can also take into account country-sectors involved in the supply chain.
Suggested indicators	*Primary data:* Number/percentage of injuries or fatal accidents in the organization by job qualification inside the company Hours of injuries per level of employees Presence of a formal policy concerning health and safety Adequate general occupational safety measures Preventive measures and emergency protocols exist regarding accidents and injuries Appropriate protective gear required in all applicable situation Number of (serious/non-serious) Occupational Safety and Health Administration (OSHA) violations reported within the past 3 years and status of violations Education, training, counselling, prevention, and risk control programs in place to assist workforce members, their families, or community members regarding serious diseases *Secondary data at country/sector level:* Rate of non-fatal and fatal accidents at workplace (country-sector level) Presence of sufficient safety measures (cases of violation per 100,000 employees) (country-sector level)
Generic data sources (examples)	European Agency for Safety and Health at Work; ESTAT Health and Safety statistics; United States Department of Labour – Occupational Safety; World Health Organization; World Health Organization, Harvard School of Public Health; World Bank; Global burden of disease; International Labour Organization; S-LCA databases.
Specific data sources	Interviews or questionnaire filled out by management, workers, human resources, governmental agencies, NGOs; Review of enterprise-specific reports; Interviews with workers and union; Review of organization-specific web site and specific reports, e.g. audits; sustainability reporting reports.
Social aspect	Freedom of association and collective bargaining
Stakeholder category	Workers
Aim and approach	At corporate level, the assessment aims to verify the compliance of the organization with freedom of association and collective bargaining standards. In particular 1) whether the workers are free to form and join association(s) of their choosing even when it could damage the economic interest of the organization, 2) whether the workers have the right to organize unions, to engage in collective bargaining, and to strike. At sector level, the assessment can be based on the evaluation of supplier countries for what concerns the right to strike, to association and of collective bargaining as derived from the Database on Institutional Characteristics of Trade Unions, Wage Setting, State Intervention and Social Pacts (at country level), as well as on the trade union density data provided by ILO at country level..
Suggested indicators	*Primary data:* Employment is not conditioned by any restrictions on the right to collective bargaining Presence of unions within the organization is adequately supported (availability of facilities to union, posting of union notices, time to exercise the representation functions on paid work hours) Check the availability of collective bargaining agreement and meeting minutes (e.g. copies of collective bargaining negotiations and agreements are kept on file) Employee/union representatives are invited to contribute to planning of larger changes in the company, which will affect the working conditions Workers have access to a neutral, binding, and independent dispute resolution procedure *Secondary data at country level:*

	Right to strike, to association and of collective bargaining (point in scale) based on Database on Institutional Characteristics of Trade Unions, Wage Setting, State Intervention and Social Pacts (ICTWSS) Trade union density rate
Generic data sources (examples)	International Trade Union Confederation Annual survey report; UN Human Rights index on freedom of association; US Department of States country reports on human rights, including the Freedom of association and Collective bargaining; Database on Institutional Characteristics of Trade Unions, Wage Setting, State Intervention and Social Pacts (ICTWSS); ILOStat; S-LCA databases.
Specific data sources	Interview with directors or human resources officer; interview with workers and trade union representatives; NGO reports Verification of organizations' documents including sustainability reports; interview and/or questionnaire filled out by directors or human resources officer.
Social aspect	Working time
Stakeholder category	Workers
Aim and approach	The assessment aims to verify if the number of hours effectively worked is in accordance with the ILO standards and when overtime occurs, compensation in terms of money or free time is planned and provided to the workers. This can be assessed both at corporate level and also at country-sector level using available statistics.
Suggested indicators	*Primary data:* Number of hours effectively worked by employees (at each level of employment) Number of holidays effectively used by employees (at each level of employment) Respect of contractual agreements concerning overtime The organization provides flexibility *Secondary data at country/sector level:* Daily hours of work per employee Weekly hours of work per employee
Generic data sources (examples)	International Trade Union Confederation, WTO country report • U.S. Department of State Human Rights Country Reports; ILOStat; S-LCA databases.
Specific data sources	Interviews with workers, governmental agencies, management and NGOs; review of audits; review of time records; review of organization-specific reports, such as GRI reports or audits agreement or contracts between organizations and employees.
Social aspect	Equal opportunities / discrimination
Stakeholder category	Workers
Aim and approach	At corporate level, this category can be assessed looking at the presence of formal policies on equal opportunities, at the composition of governance bodies and breakdown of employees per category according to gender, age group, minority, group membership, and other indicators of diversity; assessing the ratio of basic salary of men to women by employee category. At sector level, estimates on, e.g., gender wage gap can be used to assess the risk of discrimination in the sector and in supplier countries.
Suggested indicators	*Primary data:* Presence of formal policies on equal opportunities. Announcements of open positions happen through national/regional newspapers, public job databases on the internet, employment services, or other publicly available media ensuring a broad announcement. Total numbers of incidents of discrimination and actions taken. Composition of governance bodies and breakdown of employees per category according to gender, age group, minority, group membership, and other indicators of diversity. Ratio of basic salary of men to women by employee category. *Secondary data at country/sector level:* Gender wage gap (%) Women in the sectoral labour force
Generic data sources (examples)	Division for the Advancement of Women; Department of Economic and Social affair; World Bank gender equality resources; ILOStat; S-LCA databases.
Specific data sources	GRI Sustainability reports; Review of enterprise-specific reports; Review of violation records (can be national); Interview with NGOs; Interviews with human resources and management; sustainability reports
Social aspect	Responsible materials sourcing
Stakeholder category	Value chain actors
Aim and approach	Procurement practices have strong impacts on the supply chains, driving behaviours. At company level, an organization should consider the potential impacts or unintended consequences of its procurement and purchasing decisions on other organizations, and act with due diligence to avoid or minimize any negative impact. At sector level, this aspects could assessed looking at materials needs

	of specific technologies and checking if relevant suppliers come from Conflict-Affected and High-Risk Areas (CAHRA), following the CAHRA list and definition under the EU Regulation 2017/821.
Suggested indicators	*Secondary data at country/sector level:* Percentage of materials supplied from CAHRA or countries with low governance.
Generic data sources (examples)	https://www.cahraslist.net/ JRC RMIS
Specific data sources	n.a.
Social aspect	Access to material resources and infrastructure
Stakeholder category	Local community
Aim and approach	This subcategory assesses the extent to which organizations respect, work to protect, to provide or to improve community access to local material resources (i.e. water, land, mineral, food, and biological resources) and infrastructure (i.e. roads, sanitation facilities, schools, etc.). The potential impact of a specific technology in terms of resource competition or constrained access to resources can be assessed using a descriptive approach, based on literature review. It can also be assessed if positive impacts are envisaged, in terms of provision of energy infrastructures to a local community.
Suggested indicators	n.a.
Generic data sources (examples)	n.a.
Specific data sources	n.a.
Social aspect	Public acceptance
Stakeholder category	Local community
Aim and approach	The aim is to assess if there might be opposition from local communities towards a certain technology, e.g. based on existing conflicts and protest movements. As it relates to perception, level of information and feelings, it is not necessarily linked to specific impacts but it can give information on the enabling conditions, risk of bottlenecks in the development and permitting phase, and the quality of the decision making process in a certain sector (in terms of inclusiveness, and community involvement). This category is strongly linked with impacts on local communities.
Suggested indicators	Descriptive approach, based on narratives and literature review and analysis
Generic data sources (examples)	Environmental justice Atlas: This database provides an insight into the social acceptance of projects by local communities, and also reports social and environmental impacts of industrial projects. As it is a community-driven tool some biases should be acknowledged. For instance, it requires communities to be informed and literate enough to submit the case. Developing countries with low Human Development Index scores are therefore likely to be under-represented.
Social aspect	Affordable access to energy
Stakeholder category	Consumers
Aim and approach	This aspect aims at considering both the access to energy, (e.g. the percentage of population without access to electricity; duration and frequency of energy shortages or blackouts) and the affordability for households in terms of expenditure for energy compared to the income. For the assessment of specific technologies, it can be assessed in a descriptive way the contribution of a technology in facilitating the access to energy, e.g. in remote location of in terms of lower energy prices.
Suggested indicators	Proportion of population with access to electricity Expenditure for energy compared to the income
Generic data sources (examples)	World Bank; ESTAT; World Health Organization
Specific data sources	n.a.
Social aspect	Contribution to economic development
Aim and approach	This subcategory assesses to what extent the organization/product or service contributes to the economic development of the society. It can be measured at different geographical levels. It is important in the assessment to avoid double counting with the social impacts related to the local community.
Suggested indicators	Share of country GDP (%) Number of jobs created Proportion of informal employment in non-agriculture employment Average hourly earnings of female and male employees, by occupation, age, and persons with disabilities
Generic data sources (examples)	OECD, Economy Watch; World Bank; S-LCA databases

Specific data sources	Interviews with community members, governmental agencies, management, and NGOs; Review of enterprise-specific reports, such as GRI reports or audits
Social aspect	Rural development
Aim and approach	This aspect aims at considering specific impacts on rural areas, determined by the development of an energy project. It can include a variety of aspects, for instance the income and employment in rural areas (e.g. changes in agricultural productivity and yields), education and skills (e.g. vocational training and skill development); entrepreneurship and local economy (e.g. local economy diversification and small business growth and entrepreneurship rates). The assessment should also capture the peculiarities of smallholders including farmers, especially regarding the endowment of factors of production, the role played by the family, the relationships with the market, and the economic size of the smallholders, focusing in particular on aspects related to work. A descriptive approach based on literature review is recommended for this aspect.
Suggested indicators	n.a.
Generic data sources (examples)	The EC common monitoring and evaluation framework (CMEF) establishes a list of indicators to help assessing the performance of the Common Agricultural Policy 2022-27 which include aspects related to rural development.
Specific data sources	n.a.

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