Analysis of the European energy system

under the aspects of flexibility and technological progress

Call: H2020-LCE-21-2015

Grant Agreement Number: 691685

Deliverable

D6.1 Report on LCA-based framework

Deliverable type:	Report
WP number and title:	WP6: Social, Environmental and Economic Impacts
Dissemination level:	Public
Due date:	Month 12 – 30 April 2017
Lead beneficiary:	KTH
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This project REFLEX has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691685.

Document history

Version	Date	Author/Editor	Description
0.1	10.04.2017	Elisabeth Ekener	Initial version, sent to reviewers
1.0	26.04.2017	Nils Brown	Version sent to European Commission with reviewers comments incorporated

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Executive Summary

Realizing the positive vision for climate mitigation requires transformation of global society's supply systems for, and consumption of, energy. Current energy systems also cause significant environmental impacts from other perspectives. At the same time energy systems are important for provision of social welfare and for industrial and agricultural production. It is further known that the energy system that contributes to achieving the positive vision for climate mitigation requires the development of new technologies.

The need for large scale transformation in the energy system and the development of new technologies at the same time implies significant uncertainty. In order to address this uncertainty there is great interest in energy systems modelling (ESMs), tools which for example project techno-economically optimtized future energy systems on a global, national or transnational scale. In general these tools are very proficient for projection of such macroscopic indicators related to the various energy flows in society, for example primary energy demand for different types of energy carrier and final energy demand for different economic sectors. Most of them also aim to account for the emissions of greenhouse gases due to combustion in the systems studied. However, environmental and social assessment is not a main focus in such tools. This is a significant gap and one way to fill it is to use existing tools for social and environmental assessment. In recent years, some works have made attempts to apply social and environmental life cycle assessment (LCA) to fill this gap. These studies provide important results, however to date there are no coordinated attempts to do so coherently on the scale of an entire energy system as considered by ESMs broadly.

The aim of this work is therefore to develop a coherent and transparent methodological framework to guide and codify the application of eLCA and sLCA specifically for assessing future energy systems as projected by ESMs. The first step recounted in this report consists of an extensive literature review. In a second step, a life cycle based methodological framework is developed. This framework is based on the findings of the literature review and other relevant sources.

The literature review showed that studies that use LCA to assess energy systems beyond that of a single technology are still limited in number. These studies do cover global, national and supranational scales. They are focused on electricity generation, some featuring only selected groups of technologies but others covering entire scenarios. The main focus of these studies is on environmental LCA. Some also attempt to cover social impacts, though few from a life cycle perspective.

There are likewise many studies applying life cycle assessment to evaluate impacts from separate energy technologies and their potential future development. These studies cover many different kinds of technologies that may be significant in future energy systems with ambitious sustainability goals, for example solar PV and wind power. Studies do aim to update inventory to account for possible future developments in a number of ways. For example many aim to connect future developments of the separate technologies to wider scenario developments, or the rate of expansion of global capacity of a particular

technology. A few examples aim to explicitly consider technological improvements based on previous trends in efficiency increase (mainly for fossil combustion plant) or technology scale up (for wind turbines).

The REFLEX SELES framework aims to build on the example of the existing literature and also to propose new steps not found in existing literature. It is a natural choice for the framework to start from the structure of ISO 14044. The product system and the system boundary are established in the framework in terms of the elementary flows, energy products, the transformations between them, and the storage and transport processes that are involved in the processes. According to these concepts, the starting point for the energy system is the initial elementary flows from the environment required to deliver the energy services considered in the assessment. The end point for the system is then the final elementary flows of energy back into the environment after the final energy system transformation. An assessment performed according to the REFLEX SELES framework must include discussion of this wide context of the entire energy system, though it is acceptable that not all elements are included in calculation.

It is assumed that life cycle inventory for energy technologies in future scenarios is established by making appropriate and justified changes to life cycle inventory for current versions of the same technology (e.g. LCI for solar PV in 2050 is based on updating LCI for solar PV as currently produced). The first key criterion when doing so according to the framework is to demonstrate that the changes made are *consistent* with the overall scenario within which the assessment is performed. This follows the example of the NEEDS project. When creating inventory in this way it is proposed that the changes made are described clearly in the assessment report. It is also proposed that changes are based on a common classification of different methods of justification – technological potential, policy normative, trend extrapolation, technological explorative and social explorative. Finally it is proposed according to the REFLEX SELES framework that the initial assumptions about technological development are reconsidered in light of knowledge of how the assumptions affect overall impacts according to the assessment. It is thus proposed that the REFLEX framework will increase clarity and transparency in applying LCA to energy systems scenarios.

1. Introduction

It is well-appreciated that to avoid radical and dangerous climate change on a planetary scale, anthropogenic greenhouse gas emissions (GHG) need to be almost eliminated over the next century compared to current levels (Pachauri et al. 2014). As the provision of energy services are one of the most significant contributors to global GHG emissions, this requires significant changes in global society's supply systems for, and consumption of, energy. These systems also cause large environmental impacts not directly related to global warming such as harmful effects on flora, fauna and humans as a result of toxic combustion emissions. The supply and demand of energy services are likewise significant for the provision of social welfare and for industrial and agricultural production. Among the 17 Sustainable Development Goals (SDGs), defined within the UN Agenda 2030, goal no. 7 Affordable and Clean Energy, explicitly addresses the issue of making energy services available to all. Further, several goals, among them no.1 No Poverty, no. 2 Zero Hunger, no. 4 Quality Education and no. 10 Reduced Inequalities, can all be said to have links to general access to energy for all.

Recognizing the scale of the global challenge, the three pillars of European energy policy, security of supply, competitiveness and sustainability (European Commission 2016a) aim to shift towards a secure, affordable and low carbon energy system. The role of technological innovation in meeting this global challenge has also been recognized by EU policy makers and is expressed in the long-term Integrated Strategic Energy Technology (SET) Plan (European Commission 2016c). Innovation is required for example in the areas of renewable energy generation (such as efficiency and power capacities), energy storage (e.g. as thermal energy or as stationary or vehicle batteries), e-mobility and for Information Technology-linked 'smart' solutions exploiting flexibility options (European Commission 2016c). Such systems are clearly very different from the types of technologies that have characterized energy systems in previous decades.

The formulation of sound policy instruments to achieve the transition of the energy system and the desired technological innovation requires an understanding of how the different options available in the future energy system will impact the environment, society and industrial and agricultural production. To do this, the significant uncertainties need to be identified and appropriately addressed. From the innovation perspective, many promising technologies are at an early stage of their development, implying significant uncertainty on their physical performance and their potential effects on society. In turn it is uncertain as to which is the best mix of technologies to contribute to achieving the desired policy objectives. Indeed, certain raw materials (e.g., aluminium, steel, and copper) are needed to develop technologies for the future energy system, but the competitiveness to obtain these resources are progressively increasing in a limited planet. Attention must also be paid in these assessments to environmental impacts besides the CO_2 emissions, as well as the social impacts of these different energy systems. Indeed, in light of the pervasive role of energy systems for all society's stakeholders, the social values of future societies at local and global level are also unknown.

Given these significant uncertainties, there is great interest in exploring potential future energy system on a medium to long term. Projections for indicators such as the share of renewable energy sources or scenarios analysis and impact assessment considering different level of energy efficiency are the target for many research areas. Such exploration provides valuable knowledge for policy makers and private decision makers on for example the development of robust strategies to achieve public policy objectives and private organizations' objectives. One example is the practice of energy systems modelling (ESM) where a wide variety of complex quantitative tools are used to project for instance techno-economically optimized future energy systems on a large scale, e.g. global, transnational or national (E3MLab 2016; Herbst et al. 2012; IEA/OECD 2016; Schade et al. 2010; Fichtner et al.; Fragkos et al. 2017). In general these tools are very proficient for projection of such macroscopic indicators related to the various energy flows in society, for example primary energy demand for different types of energy carrier and final energy demand for different economic sectors. Most of them also aim to account for the emissions of greenhouse gases due to combustion in the systems studied. However, environmental and social assessment is not a main focus in such tools. For instance, Fragkos et al. (2017) quantified the decarbonization targets 2050 of the European energy system through the PRIMES model. The scenarios were modelled according to parameters such as energy efficiency improvements, increasing penetration of renewables, fuel switching towards natural gas, and technical progress in process related to greenhouse gases emissions abatement. Environmental assessment was limited to evaluating greenhouse gas emissions and wider societal impacts were not addressed.

One way of expanding the scope of energy systems models in this direction is to combine them with existing tools and approaches for environmental and social assessment. An example of such an approach is social and environmental life cycle assessment (sLCA and eLCA). On this front there exist to date a number of attempts to apply the eLCA approach to evaluate parts of a future energy system beyond single technologies (e.g. Stamford and Azapagic 2014; Gibon et al. 2015; García-Gusano et al. 2016b). However there are no attempts to do so coherently on the scale of an entire energy system as considered by ESMs broadly.

1.1 Aim and report structure

The aim of this work is therefore to develop a coherent and transparent methodological framework to guide and codify the application of eLCA and sLCA specifically for assessing future energy systems as projected by ESMs. Two research steps are used to achieve this aim. The first step consists of a literature review to inform our work with the state of the art in this area. There are no known recent review studies about the view on, and sustainability of, future energy system. Therefore, it is of interest to review how the future energy system and its environmental and social impacts are being assessed and built up through scenario methodology. Further, to review how tools for assessment of energy system (e.g. ESM, e-LCA and s-LCA) are being adapted to assess social and environmental impacts of future energy systems thus far. The intended outcome of this report, the life cycle based methodological framework, is presented in step two. This framework is build up considering the main findings of the literature review (e.g. important parameters and most researched environmental and social impacts) and the gaps that need further attention in order to give useful insights to assist policy analysis and decision support.

This report is structured as follows: first the overview and characterization of energy system, life cycle approaches and energy systems models are described. Next, the working methodology and research questions are introduced. Findings of the literature review are discussed. Finally, the proposed framework and further work are presented.

2. RELEVANT STATEMENTS FOR DEFINING THE LIFE CYCLE BASED FRAMEWORK FOR ENERGY SYSTEM

2.1 CHARACTERISATION OF ENERGY SYSTEM

When considering energy systems, a clear definition of a ‘system’ is required. The definition by Asbjørnsen avoids ambiguity and matches the purpose of this report: A system is defined as a “structured assemblage of elements and subsystems, which interact through interfaces. The interaction occurs between system elements and between the system and its environment” (Asbjørnsen, 1992). Input, output and transformation are three characteristics of a system. A national electricity grid, a solar-PV system, a coal power plant, etc. can be seen as sub- or energy systems. In each case there are inputs in the form of energy resources (e.g. natural gas, hydro, wind, solar, geothermal heat, etc.). There are outputs, which depend on what we use energy for, i.e. the end-use (e.g. mobility, heating, illumination, etc.). Energy conversion, also refer to energy transformation is in between.

Many researchers have tried to define an energy system from different point of view. Taking a process viewpoint, an energy system consists of “an integrated set of technical and economic activities operating within a complex societal framework" (Hoffman and Wood 1976) The IPCC Fifth Assessment Report also defines an energy system as "all components related to the production, conversion, delivery, and use of energy" from the perspective of structure (Allwood et al. 2014) and it also implies energy production, conversion, delivery, and use of energy together make up the energy system.

Bottom up comprehensive ESMs themselves, such as PRIMES (E3MLab 2016) or IEA WEM (IEA/OECD 2016) do aim to take account of energy systems in a way that relates well to the IPCC definition. As a typical example, WEM considers three main demand sectors (namely buildings, transport and industry), two transformation sectors (electricity and heat on the one hand and oil refining on the other) and three energy supply sectors (bioenergy, fossil oil, fossil coal and fossil gas). In WEM each sector is further subdivided into variously sub-sectors and technology and resource types of which there are over 100 in total (IEA/OECD 2016). The above example also shows that apart from the mentioned three characteristics, energy systems are also characterized by many other factors that make them highly complex, for example size or scale, technology deployed, type of energy transformation, conversion efficiency, performance, etc.

2.2 LIFE CYCLE APPROACHES

The life cycle approach and life cycle assessment first began to be widely applied and developed in the 1990s. Since then many studies have been done, and the development of the approach has been characterized as one of steadily expanding and more specific standards - ISO 14040 (ISO 2006b), ISO 14044 (ISO 2006c), ISO 14025 (ISO 2006a), International Reference Life Cycle Data System (Wolf et al. 2012), Product Environmental

Footprint (Finkbeiner 2014). Also many third-party bodies for awarding environmental product declarations have been established (EPD International AB 2016; ASTM 2016; Institut Bauen und Umwelt e.V. 2016; The Norwegian EPD Foundation 2016).

In recent years, standards and processes have also been developed for social LCA according to UNEP/SETAC in order to cover more sustainability aspects. In 2009, a guidance document on how to conduct a social life cycle assessment (s-LCA) was issued by the UNEP/SETAC Life Cycle Initiative. s-LCA is a methodology that draws on e-LCA, but focusses on social issues - how humans and their societies are impacted - rather than the environment. s-LCA is a relatively new method, and a limited number of case studies has been conducted so far.

For many years it has been established that life cycle methods be used for policy assessment in the EU. However it is clear that this recommendation is still far from having reached any broader acceptance.

3. Work Methodology

A priority for the framework is to develop a transparent method for environmental and social impact assessment using inputs from large energy system models where the changes in energy technologies, supply chains and systems are accounted for. In the main part of the literature review, three analytical perspectives were applied. Firstly, the available studies were analyzed based on their general approach to defining energy systems and energy technologies and coordinating social and environmental approaches. The intention is to understand how energy systems are interpreted and interlinked to the environment and society simultaneously. From the second analytical perspective, available studies were considered regarding how they aimed to account for long term future system changes when assessing the energy system and technologies. The principle is to point out the research efforts concerning the view of the future energy systems and its improvements, such as strategies and elements for future change (e.g. resources availability, policy measures and social acceptability). In the third analytical perspective, studies were investigated in detail considering in detail how future energy systems and their impacts are assessed by applying tools such as environmental life cycle assessment (E-LCA), social life cycle assessment (S-LCA), and Energy Systems Modelling (ESM). On the one hand, E-LCA and S-LCA are the preferable tools to evaluate the environmental and social sustainability of product and services (Ciroth et al. 2011; Rodríguez-Serrano et al. 2017). On the other hand, ESM are the favored tool to project future energy systems provide knowledge for decision support to policy makers (European Commission 2016b). Therefore, the investigation considers studies that applied these tools singly or linked with each other.

The literature search was done using well-known research databases such as Science Direct, Scopus and Google Scholar. Table 1 below shows the search terms that were combined in various ways to achieve this. In addition, because of their high degree of relevance, reports published from the previous EU project New Energy Externalities Development for Sustainability (NEEDS) - were also considered. Publications from 2003 to 2017 are considered.

Table 1: Basic search terms that were combined as part of the literature search

social life cycle assessment
environmental life cycle assessment
life cycle sustainability assessment
integrated life cycle assessment
energy system
energy scenario
energy technology
electricity production
biofuel
vehicle fuel
energy
energy system modelling
energy systems model
emerging technologies
energy supply
energy demand

Having those three purposes in mind, relevant questions are presented according to the working groups that the papers are screened:

1. *Scope:*

    a. *How is the energy system defined? (e.g. Energy supply: electricity, heat / energy demand: which sector (s)?*

    b. *Which are the relevant technologies addressed? Single Technologies?*

2. *Strategic perspective approach:*

    i. *What is the overall view of the future in each assessment - long term unlikely considerations through explorative scenarios or specific possible developments through predictive assumptions?*

    ii. *What specific factors are considered (e.g. market penetration, economies of scale, resource availability, policy measures, social acceptability etc.) when making future changes (positive and negative) to energy technologies, supply chains and systems?*

    iii. *In what dimensions of sustainability are impacts considered (environmental, social, and socioeconomic) and for each dimension what impact categories are considered (e.g. global warming potential, toxicity, human rights, governance, safety, supply security etc.)*

3. *Tools:*

   a. *LCA (S-LCA and E-LCA):*

      i. *What data and information is used for the assessment and what is its representativeness for the systems studied?*

      ii. *How sensitive are assessment results to necessary assumptions about future development of technologies and related impacts on society?*

   b. *ESM + LCA:*

      i. *What are the methods of creating future life-cycle inventory by using ESM and LCA tools?*

      ii. *What are the assumptions, limits and gaps of coupling ESM and LCA?*

During the literature review extra sources were also sought which are often not treated by energy systems models, but extremely relevant for the framework proposed. For example, for a social assessment, a description of the societal context in which the energy system exists is of significant interest.

Finally the REFLEX framework is proposed. It is based on the outcomes of the literature analysis. In places where the current literature does not adequately cover an area that needs to be taken up in the framework, this is highlighted in the framework and other sources are used.

4. IDENTIFYING THE CONSISTENT FEATURES OF THE LITERATURE REVIEW AND ITS GAPS

To address the methodological developments in e-LCA and s-LCA for assessing future energy systems through ESM, fifty scientific papers and reports were reviewed. Figure 1 shows the distribution of the reviewed papers according to the three working groups: scope, strategic perspective approach and tools.

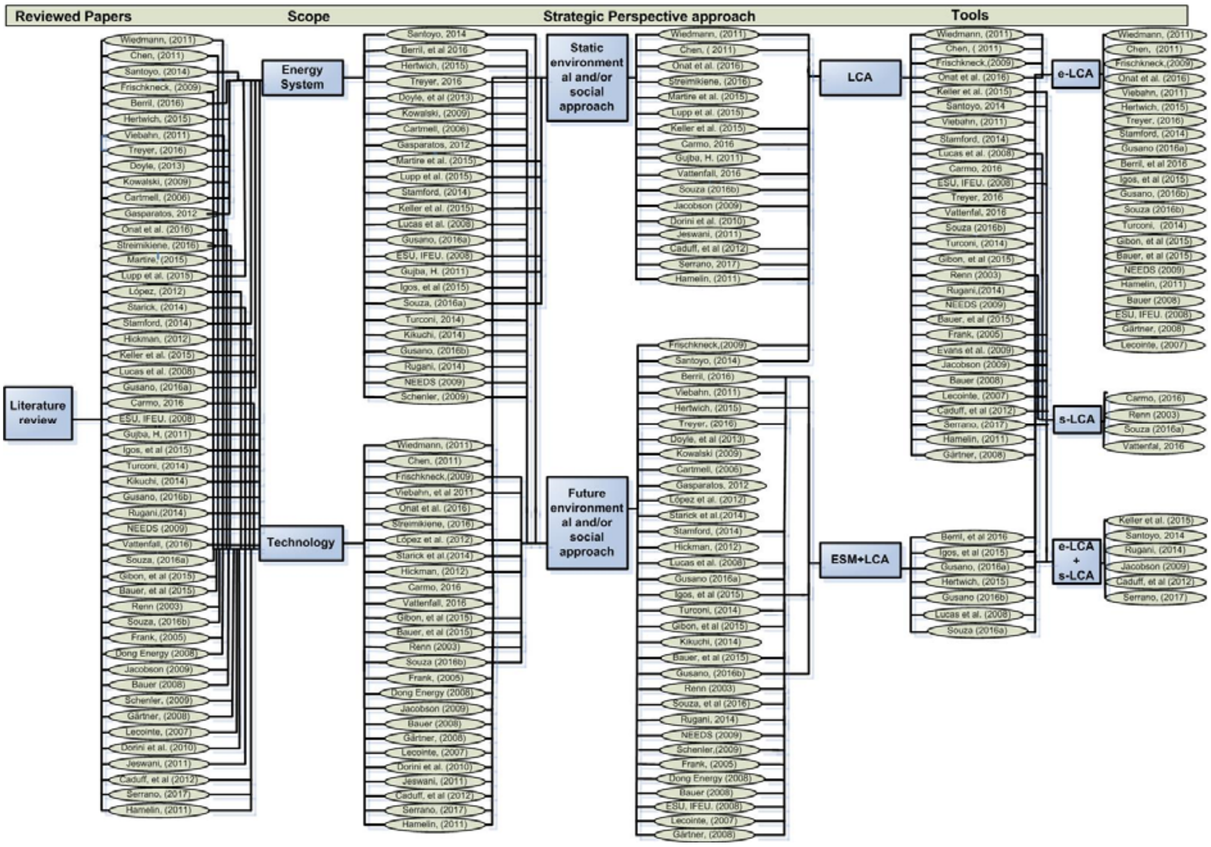


Figure 1 - Clustering of reviewed papers and report used in this paper

After a thorough review of all of these 50 publications, a total of 35 life cycle assessment studies were identified. From the 35 LCA studies, 5 LCA studies assessed the environmental impacts of partial energy system scenarios with inputs from energy systems models (Berrill et al. 2016; Hertwich et al. 2015; Igos et al. 2015; García-Gusano et al. 2016a; García-Gusano et al. 2016b). Lucas et al. (2007) was the single study identified that provided understanding of the social impacts related to strategies for transport system considering inputs from large models. Souza et al. (2016) had the initiative to integrate input-output based model to s-LCA. The social impacts chose were often those closely related to environmental impacts considered in e-LCA (see e.g. Santoyo-Castelazo and Azapagic (2014)) who considered human toxicity as social impact in their electricity system assessment. In other cases the social impacts were limited and related to a specific technology under the sustainability assessment methodology in static perspective approach. Onat et al. (2016) limited the social impacts to considering taxes and injuries in their consideration of electric vehicle technologies. Rodríguez-Serrano et al. (2017) categorized the social impacts of concentrated solar power in labor rights, health and safety, human rights, governance and community infrastructure). Nonetheless, the 50 publications were taken into account for discussion of their distinguishing attribute, parameters and data sources since they provide interesting and useful methodological information for environmental and social impact assessment.

4.1 Scope

An explicit statement of assessment of energy system starts with the scope definition. The reviewed studies differ significantly in their scope. Except for a handful of papers (Kikuchi et al. 2014; Doyle and Davies 2013; López et al. 2012; Hickman et al. 2012; Lupp et al. 2015; Cartmell et al. 2006), most of the reviewed papers with scope in energy system, and particularly those with an explicit focus on life cycle assessment, focus only on electricity supply. Their goals diverge according to methodologies of assessment (e.g. sustainability assessment or environmental footprint), to geographical boundaries (at the global, national or local level), technical boundaries (e.g. power plant technologies assumed or lifecycle phases) or methods for integrating social and environment perspectives through sustainability considerations (participatory approaches, multi-criteria decision analysis or DPSIR) and impacts categories for environmental and social assessment.

Some papers, (i.e. Santoyo-Castelazo and Azapagic 2014; Hertwich et al. 2015; Turconi et al. 2014; Stamford and Azapagic 2014; Treyer and Bauer 2016) mainly looked at different parts of electricity production. Santoyo-Castelazo and Azapagic (2014) conducted a MCDA to assess ten environmental sustainability criteria (global warming (GWP), abiotic depletion, acidification, eutrophication, freshwater toxicity, marine toxicity, human toxicity, ozone depletion, photochemical ozone creation or summer smog, terrestrial toxicity) two economic criteria (capital and annualized costs) and one social criteria (human toxicity) to the case of electricity supply in Mexico. They analyzed 11 different scenarios for 2050 with various technologies mixes. Stamford and Azapagic (2014) focused their sustainability assessment on scenarios for the decarbonization of the electricity mix in the United Kingdom. In total, 36 sustainability indicators were established through a participatory approach for the assessment of different electricity technologies. Some authors (i.e. Hertwich et al. 2015; Turconi et al. 2014; Treyer and Bauer 2016) looked at environmental impact of parts of electricity production in a global and national level for Denmark and the United Arab Emirates. Hertwich et al. (2015) however did not evaluate biomass and nuclear power plants in their life cycle scope.

In Renn (2003) three energy scenarios was developed on a regional level. The scenarios represented different political world-views on future energy supply, with differing choices on technologies as well as the demand side (energy efficiency and conservation). The assessment criteria for the scenarios were identified with the help of an MCDA process using values based on the outcome of stakeholder interviews. The chosen criteria were Economic aspects (6 indicators, including security of supply), Environment and health (5 indicators) Social and political aspects (7 indicators; Dignity and rights, Competence in one's own sphere of life, Political stability and legitimacy, Avoiding vulnerability, Effects on other societal areas, Social justice Fair international distribution of energy). The actual assessment on the selected criteria as then done by expert groups, scoring the on a scale 0-100 (100=optimal system).

Despite the fact that Kikuchi et al. (2014) did not apply a life cycle approach, they brought up a scenario analysis of the future Japanese energy system by accounting for the relationships between available technologies considering both energy supply and demand. In the energy flow model developed, Kikuchi et al. (2014) figured out technological options which their infrastructure or consumables are arguably part of the foreground elements of the future energy system to be addressed in an LCA. They are fuel for transportation, fuel for residential heating, fuel for commercial and industrial heating as well as infrastructures for centralized conversion sectors, the infrastructure of technologies for distributed energy conversion, infrastructure for penetration of new-generation automobile technologies and infrastructure for implementation of storage technologies.

Doyle and Davies (2013) applied a social practice approach to the household heating in Ireland through the development of future scenarios based on a participatory backcasting study. The authors concluded that many studies were often based only on simplistic behavioural assumptions for assessment of household heating consumption which were not sensitive to the radical socio-cultural, technological and organizational innovations in the future.

López et al. (2012) addressed transport issues, where the use of scenarios were developed to understand the impact of transport strategies on energy consumption at a European level. These strategies were of two kinds; technology improvements in vehicle technologies and fuels, and measures to control transport demand. Eight scenarios until 2030 combining different components of the two strategies were defined, and they were assessed using MCDA encompassing carbon dioxide, particulate matter and NOx emissions as well as noise. For the social assessment the issues of transport safety and equity were addressed. Additionally, accessibility and employment were considered, even though they were not explicitly labelled as social criteria by the authors.

In Hickman et al. (2012) transport futures were examined by assessing the sustainability impacts of different transport policy trajectories. Two scenarios with different packages of policy measures on a regional level in the UK were developed in an iterative process. These were developed to be in compliance with national and local policies, being deliverable and feasible and finally being in alignment with previously established sustainability criteria on a local level; vibration and air quality from an environmental perspective, and accessibility, safety and access to jobs from a social perspective. Both resulting scenarios were achieved low carbon dioxide emissions.

In Lupp et al. (2015) an integrated impact assessment was conducted building on the DPSIR (Driving Forces, Pressures, State, Impact, Response) approach. It was complemented by spatial scenarios considering the impacts of increased bioenergy use in a region in Germany. The scenarios were explorative and reached until 2030. The issues assessed were soil erosion, nitrate leakage, groundwater, habitat, aesthetic values and recreational opportunities. Assessment was done qualitatively in a participatory approach involving regional stakeholders in the fields of agricultural production, planning and energy use, and experts.

In Cartmell et al. (2006), scenarios of different approaches for bio solid co-combustion in the UK were developed. Four broad indicators were applied in the assessment – economic performance, social impact, environmental performance and flexibility. Risk was determined by interviews with relevant stakeholders. The relative performance of the options with respect to these indicators was established qualitatively using a simple scoring system and drawing on the previous analyses. The scoring was done on a scale -2 (very negative), through 0 (neutral, or balance of negative and positive), to +2 (very positive). Each score on the scale was defined for the four different indicators by a short descriptive text.

There are a number of articles presenting important features of a sustainability assessment framework (e.g. Gasparatos and Scolobig 2012; Sala et al. 2013; Zijp et al. 2015). Some important features identified in these works were a geographical and temporal scope, the importance of considering both environmental and social aspects, the importance of acknowledging values brought into the assessment, consideration of how the sustainability was viewed, way of handling uncertainty and transparency and importance of participatory approaches. Regarding values, already choosing the type of assessment approach means that the values of the analysts were entering the assessment. Three types of SA approaches were identified by Gasparatos and Scolobig (2012): monetary, biophysical and indicator-based. The authors list five features usually desired in sustainability assessment; integrated or triple-bottom line assessment; predictive or ex-ante assessment; precautionary assessment; participatory assessment and distributional assessment. Of the three approaches, the indicator-based approach seemed to offer the best possibility to address all these. According to their evaluation, the first two can be captured with such a tool, while the last three may be captured, depending on methodological choices Gasparatos and Scolobig (2012). Another issue brought forward by several scholars (e.g. Gasparatos and Scolobig 2012; Sala et al. 2013; Zijp et al. 2015) is how uncertainty and the transparency of the assessment are handled. It is important to transparently describe the processes of assessment while presenting the results, and to discuss the results in the context of uncertainty.

Several studies scoping the future development of emerging and existing technologies were found (Wiedmann et al. 2011; Viebahn et al. 2011; Hamelin et al. 2011; Rodríguez-Serrano et al. 2017) (Frankl et al. 2005) (DONG Energy, 2008) (Gärtner, 2008) (Bauer et al. 2008) (Lecointe et al. 2007)(Caduff, et al. 2012)(Souza et al. 2016). In the same way that the papers considering multiple technologies ('systems') did, the scope of these assessments vary according to system boundaries (geographical and technical), number of environmental and social impacts and methods of integrating environmental and social considerations.

Štreimikienė et al. (2016) used MCDA to assess six different electricity generation technologies in Lithuania (nuclear, natural gas, bio CHP, geothermal, hydro and wind). All technologies were in operation except one that was in a planning phase (nuclear). The list of technologies and their features were defined by experts. Also the assessment was conducted by a group of experts, assessing the different technologies considering aspects such as contribution of renewable energy, climate change and other emissions, waste treatment and natural local conditions, and social welfare (jobs, economic security), education, energy, and culture and public acceptance.

Wiedmann et al. (2011) explored different wind technology-specific processes to assess the economy-wide global greenhouse gases emissions associated with wind electricity generation. The authors based their assumptions on the planned wind parks with a power capacity of about 20 GW in the United Kingdom.

Viebahn et al. (2011) and Rodríguez-Serrano et al. (2017) carried out an environmental and sustainability assessment of concentrated solar tower power (CSP) in Africa, Europe and Mexico respectively. The scope of the work was to analyze the technological development of CSP power plants. Viebahn et al. (2011) considered the effect of varying the following parameters: increase of lifetime, increase of material use due to up-scaling, increase of storage time, higher efficiency, change of material use by learning curves and change of energy mix for producing raw materials.

4.2 Strategic perspective approach

The environmental and social impacts of future energy system including innovative technologies are a methodological challenge. Strategies and perspectives have to explicitly draw up to indicate a tactical and carefully formulated approach. According to Figure 1, 33 papers considered the energy system or energy technologies in light of their potential future development. They often considered different preserving scenarios to express their results according to a certain target to be reached (e.g. Kowalski et al. 2009; Frischknecht et al. 2009; Frankl et al. 2005; DONGEnergy 2008; Bauer et al. 2009; Lecointe et al. 2007; Gärtner 2008). In Kowalski et al. (2009) five scenarios focusing on sustainable energy futures for Austria in 2020 were assessed using a life cycle approach against 17 sustainability criteria. First an assessment of the different scenarios was done using a life-cycle approach. The social and economic aspects were assessed qualitatively ranging from low to high and included the following areas: regional self-determinacy, social cohesion, employment, effect on public spending, import dependency, noise, quality of landscape, social justice, ecological justice, security of supply, costs, constant & variable costs, diversity of technologies, employment, technological advantage. Impacts on climate change, air quality, resource use and water quality were assessed quantitatively based on the Gemis database as well as on expert judgement.

Frischknecht et al. (2009) described the challenges and suggested how to perform environmental assessment of future technologies. The authors assumed that emerging and innovative technologies are assessed based on their current performance which is often measured in lab-scales or small-scale pilot plants. The discussion forum 38 described by the authors showed the results according to different strategic options for the environmental assessment of future technologies. The most favorable strategy was long-term future life cycle inventories (LCI) mainly developed in the NEEDS project. In this context, the authors ensured the reliability and consistency of assessment of future scenarios have to be based on the interdependencies between energy generation, material production and transport and improvement of technologies.

Several studies (Frankl et al. 2005; DONGEnergy 2008; Bauer et al. 2009; Lecointe et al. 2007; Gärtner 2008) analyzed the technological pathways and the role of single power technologies in a future energy system. These final reports which are part of NEEDS project provide technical data, costs and life cycle inventories for photovoltaic solar cells (Frankl et al. 2005), offshore wind turbines (DONGEnergy 2008), advanced fossil power generation (Bauer et al. 2009), nuclear power (Lecointe et al. 2007) and biomass cogeneration power plants (Gärtner 2008). The NEEDS studies also considered the development of processes for road transport, and the production of important materials such as steel and concrete as secondary processes to the central transformation processes for power production (IFEU 2008).

Through the NEEDS project, LCI data for specific technologies was developed covering three time horizons, namely 2010, 2025 and 2050. Furthermore, for each future time and technology, three overarching scenarios are considered – optimistic/realistic, pessimistic and very optimistic. These scenarios differ between socio-economic framing conditions and their impact on market uptake and technical innovations. For electricity generation with solar photovoltaic panels, changes in future processes were posited in a number of areas – module lifetime, module efficiency, material demand for systems and system efficiency and share of installed capacity between different PV technologies. In all these categories, the future updates in technologies are based on estimates in light of the then existing roadmaps and technology assessments. The variations in these parameters for each of the overarching scenarios considered in the NEEDS approach are based on different rates of growth of total installed PV capacity in each overarching scenario. The pessimistic scenario assumes growth according to the then current 'Energy Technology Perspectives' from the International Energy Agency (International Energy Agency 2006) meanwhile the optimistic/realistic and very optimistic scenarios assume growth according to different scenarios in an industry report (EPIA 2006).

The overarching NEEDS scenarios were differentiated for offshore wind also by assuming different trajectories for the growth of installed capacity (in MW) and total production (in GWh) (DONG Energy 2008). The pessimistic scenario is based on the then current World Energy Outlook's projection for 'business as usual' (International Energy Agency 2006). Meanwhile the optimistic realistic scenario is based on the moderate scenario from the same study that includes all implemented and planned policy measures. Finally, data for the very optimistic scenario is based on a future scenario established by a wind power sector organization (European Wind Energy Association 2002).

The development of turbine capacity (in terms of MW electricity production) is calculated based on the size of turbine required to meet the global installed capacities according to the overarching scenarios, and the assumed size of turbine. Hence the more optimistic the scenario, the larger the size of the turbine. This parameter is then key for calculating the weight of key components in future turbines – the nacelle, the rotor, the tower and the foundation. The study then uses expert prediction (from DONG Energy department for Wind Power Technology) to establish the availability of different technical solutions for the system foundation. A particular foundation technology is selected for each turbine for each overarching scenario, e.g. gravitation foundation for 2025 very optimistic and floating foundation for 2050 very optimistic. There is no reasoning presented as to why these selections are made. The study also posits future changes in the material used for the rotor and the tower (but the nacelle is assumed to have an unchanged material composition). For the rotors, the proportion of carbon and natural fibres are expected to grow in the future, at the expense of glass fibre and epoxy that are currently used. This change is based on a general and unreferenced technoeconomic prediction that carbon fibre will become more competitive in the future. It is also posited that concrete will replace steel in towers in the future, though this is not supported by documentation either.

Gärtner (2008) developed different sets of LCI data for biomass CHP which were differentiated according to different assumptions about the total availability of biomass in the EU. The optimistic/realistic scenario and the very optimistic scenario both assumed biomass production according to the maximum available taking into account the need to mitigate non-climate environmental impact associated with biomass (e.g. biodiversity and land use). They do differ however in their assumptions about how much of the total available biomass was made available for biomass CHP and how much was made available for other purposes. This assumption was not clearly justified. The pessimistic scenario however posits a biomass use for CHP based on the assumption that only then existing policies were used to encourage its uptake. Only two factors were adjusted for the CHP conversion plant in all of the cases considered. Firstly, the efficiency of the conversion from biomass to electricity and heat was updated for each set of future inventory. This was justified in the work due to the interest in optimizing the use of the limited quantities of biomass available, though not more than so. It was also assumed that non-GHG air emissions of such things as particles and NOx will reduce through future policy implementation, though it was not referred to how this policy implementation will come about. It was also suggested that better fertilizer application will reduce ammonia emissions from poplar cultivation, though it was not cited how this will happen, or any technical reference given.

Bauer et al. (2009) focused primarily on the net efficiency of electricity production from the combusted fossil material for major fossil types currently used in electricity production such as fossil coal, fossil lignite and fossil gas. The general approach was to review the literature and base assumed changes (increases) on this data. Mostly for fossil-based electricity production, the NEEDS overarching very optimistic scenario was based on the best available figure in the literature or occasionally (in the case of electricity produced from fossil lignite) beyond this. Reasons for going beyond the highest efficiency predictions were not given. For the other overarching scenarios, the assumed increases were lower. In general, all air emissions, GHG and non-GHG were assumed to be linearly proportional to the total quantity of fossil material combusted and no other changes from present values were assumed. There was not assumed to be any change in the material used in the production of the power plants themselves. This was justified on the basis that the impacts arising from the capital for fossil-based electricity production were much lower than the very large impacts caused by the combustion of the fossils themselves. It was further assumed in the study that in the future there was no change in the impacts arising from the supply chains for fossil lignite and fossil coal respectively. For the supply of fossil gas it was assumed that pipeline leakage was reduced, by various amounts, greater for the NEEDS overarching very optimistic scenario, less for the realistic optimistic scenario. For the NEEDS overarching pessimistic scenario no improvement from the present was assumed. In additional, for fossil-based electricity production with carbon capture and storage, key parameters assumed were the decrease in net electricity production due to the technology and the net capture efficiency of carbon dioxide. No specific reference was given for these assumptions.

In Lecointe et al. (2007), the NEEDS overarching scenarios for nuclear technologies were distinguished based on how the total nuclear generation capacity changes – increasing significantly for the very optimistic scenario, less so for the realistic optimistic scenario and no change in the pessimistic scenario. This was then reflected in the type of technology, where in the pessimistic scenario only the European pressurized reactor brought to market by 2050. Meanwhile in both the more optimistic scenarios fast breeder reactors were assumed to have been brought to market. Most of the original data about technology characteristics for each type of plan were not reported in the document rather were based on unpublished industry data and reports.

Though the NEEDS project focused specifically on technologies for electricity production, it also considered the development of background processes involved, for example, road transport, iron and steel production and clinker production.

The ESU & IFEU report (ESU and IFEU 2008) updated only two aspects of life cycle inventory in any of the future inventory scenarios for road transport – fuel demand per vehicle km and air emissions. For the NEEDS overarching realistic optimistic scenario, it was assumed that fuel demand reduced based on the implementation of as good as all the efficiency improvements noted in the in the work in the engine, drivetrain, rolling resistance and air resistance. The pessimistic scenario assumed only improvements implemented as a result of legal requirements. The reduction in fuel demand in the realistic optimistic scenario was calculated as the average of the two. Air emissions of CO_2 and some non-GHG emissions (e.g. heavy metals and CO_2) were proportional to the fuel demand. For others, such as carbon monoxide and particles, changes in emissions were calculated based on information from a previous study based on the German TREMOD model (Knörr et al. 2006).

Likewise, ESU and IFEU (2008) considered clinker production because it was a key component for the production of concrete that is ubiquitously used in society and the energy system. The main change assumed was a reduction in the required thermal energy demand for production. For the NEEDS overarching optimistic realistic scenario, it was assumed that this reduces to the levels of Best Available Technology according to (Integrated Pollution Prevention and Control 2001a) in the future. For the NEEDS overarching very optimistic scenario it was assumed that a new technology is introduced – the fluidized bed and that by 2050 the theoretical thermal energy requirement is achieved. None of the NEEDS scenarios considered that the clinker content of cement and therefore concrete will be reduced in future production. This was in spite of the fact that the report acknowledges that clinker reduction was already being achieved at the time in many parts of Europe. For sinter production and pig iron production (for iron and steel production), energy demand for each process was also based on best practice (Integrated Pollution Prevention and Control 2001b) and the theoretical thermal optimum for the NEEDS overarching realistic optimistic and very optimistic scenarios. Non-GHG air emissions and water emissions from each of the processes were firstly assumed to reduce according to BAT (Integrated Pollution Prevention and Control 2001b) and then reduced according to assumptions for which no reference is given. No alternative technologies for steel production were considered. Processes for the production of aluminium were updated in NEEDS for energy demand for the process as well as material demands. It was assumed for the overarching scenarios realistic optimistic and very optimistic that energy demand in the future will reach values specified as best practice in all these categories though at differing rates. Air emissions for specifically aluminium production were not updated because they were assumed not to be large for the process itself as compared to emissions from electricity required for the process.

Caduff et al. (2012) provides an interesting approach where learning curves were applied to the case of GWP due to wind turbines. Analyzing historical data on turbine size and total installed capacity, and calculating the materials required for each size they showed that a doubling of total capacity in the past has led to a decrease in GWP per unit electricity produced of 14 %. On the other hand, the authors are wary to point out that their method is not suitable for making long term predictions.

The remaining papers that were not driven by long-term considerations with simultaneous processes changes, they were often based on a specific development and the major system remained according to current trends (e.g. Chen et al. 2012; Onat et al. 2016; Hamelin et al. 2011; Martire et al. 2015; Souza et al. 2016).

Souza et al. (2016) performed an assessment of possible future systems for bioethanol production, however they did not change the assessment parameters or methodology to account for differences between the future and the present, rather a present perspective was used throughout.

Chen et al. (2012) developed a graphical representation considering the possibilities of shifting for innovative technologies in the future. The authors took into account assumptions regarding the efficiency improvement, socio-economic conditions to replace old technologies for new ones and the number of technologies needed in the envisioned future. Therefore, the authors identified large uncertainties to predict various socio-economic factors (such as incentives by the government, market penetration and oil prices).

Hamelin et al. (2011) performed an environmental life cycle assessment of different fuels for future biogas power plants showing the importance to assess the availability of fuels for biomass power plants with limited resources in Denmark. The technology for biomass power plants was assumed to remain the same. Only the fuels for biomass were assessed.

In Onat et al. (2016), alternative electric vehicle technologies in a United States context were assessed including all life cycle stages; from manufacturing of vehicles and batteries, through vehicle operation to the end-of-life. The authors adopted two alternatives to draw up their analysis; one with BAU electricity generation taking the current power infrastructure of United States and another alternative assuming only solar charging station for the electric vehicles. The authors conducted a MCDA to address the environmental impacts related to carbon, water, energy, hazardous waste, fishery, grazing, forestry, cropland, carbon dioxide uptake land, while social impacts were limited to taxes and injuries.

Martire et al. (2015) performed a sustainability assessment of the rather short-term targets for the development of local energy supplies in Italy. Under this target condition, the authors analyzed three alternatives individually: the BAU; mechanization focus (harvesting activities are highly mechanized), biomass focus (More biomass mobilized) and technology focus (more efficient combustion activities). The indicators considered in the sustainability assessment were: energy use, GHG, air pollution and employment. Indicators were evaluated quantitatively.

4.3 TOOLS

Extending environmental life cycle assessment or social life cycle assessment using inputs from large energy system and transport models is a work-in-process already under development by some studies ((Hertwich et al. 2015; Berrill et al. 2016; Igos et al. 2015; García-Gusano et al. 2016a; García-Gusano et al. 2016b; Lucas et al. 2008). Therefore, no study was identified that integrated simultaneously social and environmental life cycle assessment using energy system modelling as inputs.

Hertwich et al. (2015) carried out a study which developed an integrated hybrid LCA model to compare environmental impacts in terms of greenhouse gas (GHG) emissions, eutrophication, particulate matter formation, and aquatic ecotoxicity from wind, solar, hydropower, hard coal and gas as deployed in the IEA's BLUE Map scenario (a decarbonization scenario) as well as their baseline scenarios for global electricity systems in 2050 and in the base year 2007. To include the improved production of certain materials such as aluminium, copper, nickel, iron and steel, the NEEDS database is used (see previous sections). Technological improvements with regard to the electricity conversion technologies are reflected in the improved conversion efficiencies, load factors, and next-generation technology adoption.

Berrill et al. (2016) also presented a life cycle assessment of 44 electricity scenarios which considered energy storage and grid extension for Europe in 2050. The scenarios considered include the systems based largely on low-carbon fossil fuel energy alternatives and the systems with high share of variable renewable energy (VRE). The environmental categories including climate change, particulate matter formation, freshwater ecotoxicity, freshwater eutrophication, land occupation and mineral resource depletion are examined in this study. Technology improvements in this paper are achieved using the method developed by Hertwich et al. (2015).

Igos et al. (2015) undertook a combination of energy system models and a hybrid input-output model to predict the life cycle environmental impact of energy policy scenarios for Luxembourg. A set of economic input-output tables are built starting from the existing hybrid model. According to energy systems models, an adaption in terms of the energy-technological data and economic parameters of life cycle inventory is conducted to reflect the future technological improvement and to strengthen the consistency of the overall model.

The above studies are conducted through exogenous combination of energy systems models and life cycle models to assess life cycle environmental impacts of energy scenarios. The strength of exogenous combination mentioned above is the application of dynamic LCA. Nevertheless, some studies (García-Gusano et al. 2016a; García-Gusano et al. 2016b) conducted the integration of two models in an endogenous way to assess the impacts of national electricity systems for Norway and Spain respectively. The strength of this approach is to provide the prospective techno-economic and life-cycle results in one overall model. However, the static LCI data is applied though the technology improvements has been considered in energy system models such as changes of efficiencies, capacity factors, etc.

To date, life cycle assessment tools and energy system modelling was mainly done with focus on environmental issues, although there were identified some initiatives to assess social impacts with inputs from large strategic models, (e.g. Lucas et al. 2008; Souza et al. 2016; Bournaris and Manos 2012; Foolmaun and Ramjeawon 2013; Rugani et al. 2014).

Lucas et al. (2008) had the pioneering approach focused on accessibility of key services and facilities as a primary measure for social performance of a transport system. The study was not performed with a life cycle perspective, though the approach may inform the assessment of the operation of the transport system. They proposed key indicators such as total household expenditure on travel, journey times, safety, quality of life and housing affordability. However it was demonstrated that even with the advanced GIS-based method used it was only possible to evaluate different scenarios for accessibility and safety.

In Souza et al. (2016), the scenarios were built on three different levels of technology; current, fairly outdated; the best available at present and future technologies. The output data from the scenarios were number of jobs, occupational accidents, average wages, wage value profile, woman participation rate and education degree profile, a combination of a process-based LCA approach and an and input-output based model of the sectors is used to assess social impacts on workers. Data is taken from scenarios, and the outcome is calculated based on relation between activity and social effects such as occupational accidents based on official statistics. In the I/O approach, economic activity is translated into socio- economic effects.

Assessing the energy system in Luxemburg in a prospective approach, Rugani et al. (2014), uses data from the Social Hotspot Database to assess the social impacts using S-LCA in a Business as usual (BAU) future scenario, up till 2025 based on projections. They use an I/O approach and the basis of the assessment is the projected energy demand. Also E-LCA is conducted on the scenario in this study.

Combining simultaneously environmental and social assessment with inputs of energy modelling might be challenging. Through the ISO 14040 and 14044, E-LCA is already one of the preferable methodologies to evaluate product and services which includes energy technologies and electricity systems (Rodríguez-Serrano et al. 2017; Hertwich et al. 2015). On the other hand, s-LCA is still unknown for energy systems modellers. S-LCA offers an interesting approach even in cases where the assessed object is not limited to a product but covers, as in our case, a whole technology system. Further, an energy system may consist technological infrastructure, the resources for their construction, and the products or services produced by these technologies, as well as the raw materials and other physical inputs necessary for this production. Also, the separate technologies are mostly tied into a network of other technologies, being a prerequisite for their functioning. Therefore, environmental and social assessments under the scope of sustainability assessments are to a large extent quantitative (such as e.g. LCA) and rely on measured data for their calculations. However, when assessing future scenarios, characterized by large changes and longtime perspective, quantitative data are problematic to provide (Höjer et al. 2008), and a qualitative perspective might need to be added.

do Carmo et al. (2016) applied s-LCA to assess companies engaged in biodiesel production. The companies were rated according to performance (compliance) in four levels. They were then aggregated using an activity factor based on workers employed at each supplier. Issues considered, as well as data when there was no specific company data, were based on the SHDB. The stakeholders considered were workers, local community and society, with seven indicators for workers, and two each for the other two.

Vattenfall (2016) is an example of an sLCA of wind power in a present perspective that complements an EPD based LCA report of environmental impacts for the same functional unit. 15 overall indicators (many of which were further subdivided) were selected for the assessment grouped according to three stakeholder categories - workers, local community and society. The indicators were selected from existing indicator sets - the global reporting initiative (GRI), internal assessments, Roundtable for Product Social Metrics, UNEP/SETAC guidelines. A multi-tiered method was used for data collection, using internal sources for internal processes and questionnaires for direct suppliers. For indirect suppliers, data collection was based on the mass of different components in the wind turbine together with information from direct suppliers about country of origin for each material. Assessment is largely quantitative. Amongst the quantitative indicators are Verisk Maplecroft's risk assessment indicators but also other more specific measures such as hours of training per employee. Care is nonetheless given to extensive qualitative explanation of the index-based indicators used.

Keller et al. (2015) developed a more qualitative approach for Integrated life cycle sustainability assessment (ILCSA) where changes are assessed by the direction of development (+/-) in relation to a references scenario (current state). This concept was already applied in five large European biorefinery projects through stakeholder participation. The assessment of scenarios was identified by the authors as a weakness of this method. The realization of scenarios could cause consequences or contradictions in other sectors outside the original scope of the assessment. This method presented 6 indicators for technology assessment, 13 indicators for environmental assessment, 13 indicators for economic assessment and 5 indicators for social assessment. For s-LCA, production of feedstock, identification of stakeholders, rural development and infrastructure, labour conditions and competition with other sectors were analyzed.

In conclusion, frameworks for assessing a broad range of social impacts of future societies/systems including a life cycle perspective seem to be lacking today. To address this lack, a new framework will need to be designed, even though there are a lot of existing frameworks to build from and to combine different ways in order to get a tool that fulfills the specification.

5. REFLEX SELES FRAMEWORK

Based on the outcomes of the literature review above, the framework for social and environmental life cycle assessment of energy systems scenarios is presented in this section. The framework is called REFLEX Social Environmental Life cycle Energy System (REFLEX SELES). The structure of the REFLEX SELES framework is inspired by the basic standards for life cycle assessment (ISO 14044) and consists of the following steps (Figure 2): scope, inventory assessment, impact assessment and interpretation. Each of the steps of the resulting framework is described in the subsection 5.1. In the subsection 5.2, a detailed definition the product system is presented where it is included the description of unit processes and the energy system (the product system and system boundaries), methods for establishing life cycle inventory for future energy processes and methods for impact assessment and the proposed interpretive steps in the framework. A scope example how REFLEX SELES can be applied is presented in the subsection 5.3.

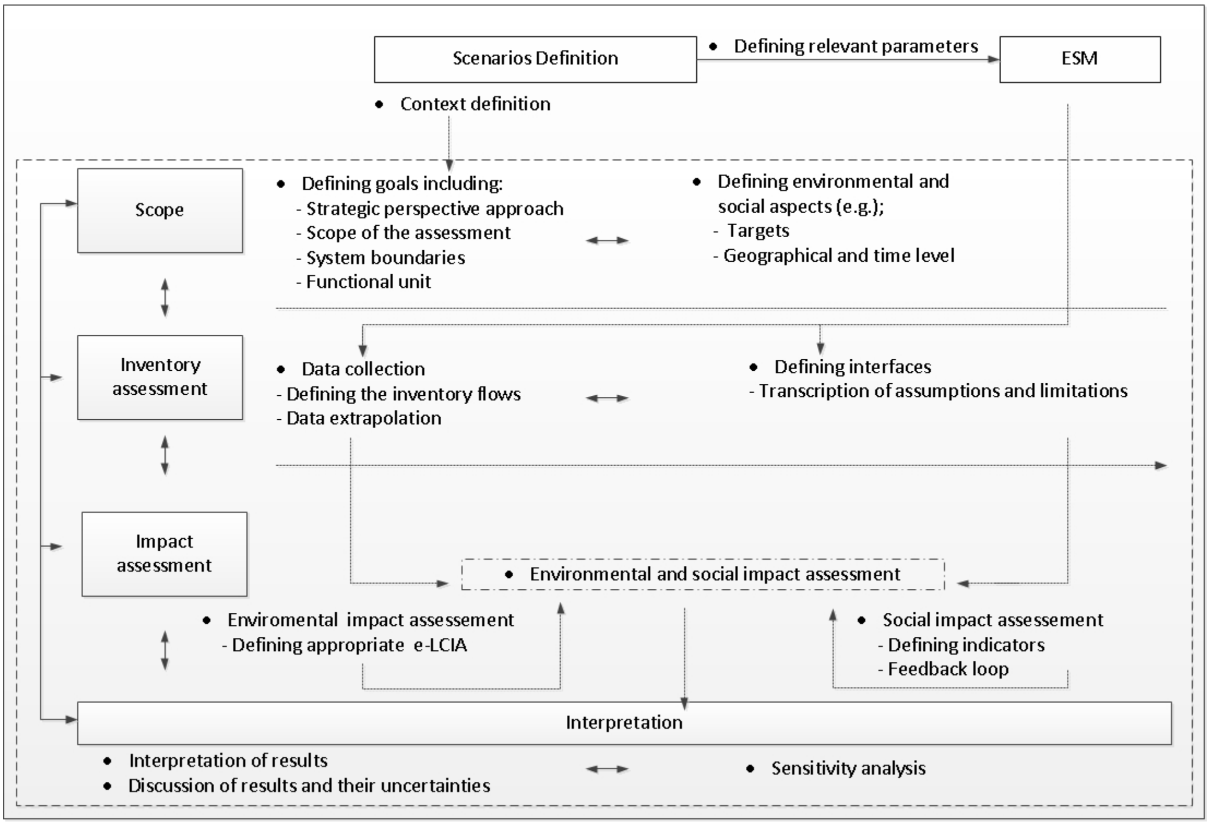


Figure 2 Overview of the environmental and social life cycle assessment framework for energy system scenarios (REFLEX SELES)

5.1 Overall work process of REFLEX SELES framework

Goal and Scope

Following ISO 14044, goal of the REFLEX SELES study should be stated as the first step. The intended application, reasons for carrying out the study, intended audience and whether the results are intended to be used in comparative assertions will vary from case to case. However, overarching for the framework (and therefore for the goal of any given study) is to provide policy makers, energy industry stakeholders and non-governmental organizations and the public at large with knowledge for decision making about future energy systems on a large scale (national or international). The study will fulfill this goal by providing an assessment of the energy system in light of significant societal sustainability objectives from a social, socioeconomic and environmental perspective. This definition is noted in Figure 2 as ‘defining environmental and social aspects’.

Particular details of the scope of the REFLEX SELES framework are as follows:

The **product system** to be studied according to the REFLEX SELES framework is all or a significant part of an energy system, (a system for the provision of energy services). Which parts of the energy system are included in a specific study shall be clearly specified according to the REFLEX SELES framework work process for establishing the system boundary below.

The **functional unit** envisaged in the REFLEX SELES framework is that of the provision of the energy services over a timeslice of a year. On the basis of this functional unit, many different alternative years and alternative process configurations for service supply may be compared in the same assessment. An interesting starting point is to consider the functional unit in base year, and for two alternative configurations of processes in some year in the future (as is common in ESMs):

1. The provision of energy services in 2020
2. The provision of energy services in 2050 (distributed generation scenario)
3. The provision of energy services in 2050 (centralized generation scenario)

Defining the functional unit fulfils the criteria for defining the 'strategic perspective of the assessment' as shown in Figure 2.

Following ISO 14044 the **system boundary** for a specific study carried out according to the REFLEX SELES framework is determined by the specification of the unit processes that shall be included in the study, in light of the goal of the study. The exact level of detail of the description of the unit processes is itself also dependent on the goal of the study. Since the literature review showed that no existing LCA-based study or other work seems to address the description of unit processes to be included in an energy system in a consistent and comprehensive way, a suggestion based on a synthesis of earlier work is made for the REFLEX SELES framework (shown in subsequent sections). The basic categories of unit processes to be described according to this are transformations (between different energy products/elementary flows), storage and transport processes. These and supporting definitions are described more fully in a subsequent section of the report. The subsequent sections also show examples of how these categories of unit processes and categories may be combined to describe the assessment of an energy system. The level of detail to which unit processes are described shall be chosen in light of the overall goal of the study.

For other areas items that shall be considered in the Scope according to the ISO 14044 guidelines for the Scope, no recommendations for the REFLEX SELES framework are established beyond the already existing general guidelines.

INVENTORY

As for any LCA study, inventory data shall be acquired that describe the inputs and outputs for each of the unit processes identified by the product system description and included in the system boundary, for all of the alternatives considered. The most important aspect to bring up in light of the goal of the REFLEX SELES framework is to explain how inventory related to energy infrastructure in the future is produced.

In particular it is envisaged in light of epistemological principles and the methods of previous studies addressing energy scenarios that inventory for future technologies (for transformation, storage or transport) is based on inventory data describing technologies as they exist now with adapted data for parts of the process that will feasibly be different in the future. If such a strategy is used, it should be clearly stated on the level of each unit process the changes that are considered, and the reason for considering the change.

Scenario consistency: The overarching criteria to justify making any change in data for existing technologies for the equivalent technology in the future is that it should be consistent in light of the overarching scenario that is considered. The literature review shows that the NEEDS studies provide a good starting point here, where for example solar PV and wind power unit processes develop differently in the future depending on the rate of expansion of installed capacity for each technology. Scenario consistency is important both for social and environmental inventory.

View of future: The literature review showed that a wide variety of different principles are referred to when establishing data for technologies in the future from data for current technologies. For the purposes of improving transparency and impact, it is recommended in the REFLEX framework that each change also be categorized according to the principle by which it is justified.

- Technological potential: According to this criteria changes are justified based on a review of a wide variety of sources *estimating* potential developments. These potential developments are often not justified in any systematic way, rather they are justified in light of 'expert judgement'. Scenario consistency can be ensured in such a method by choosing more or less optimistic potential developments depending on the overall scenario description.

- Policy normative: According to this principle, data is adapted to ensure compliance with policy that is enacted in a given scenario (either an existing policy or one that is envisaged in a scenario).

- Trend extrapolation: In this method, the development of a particular performance parameter (typically the electric efficiency of thermal power plant) is systematically predicted for the future based on past developments through time of the parameter. Two different methods of trend extrapolation can be distinguished here - endogenous trend extrapolation and exogenous. In exogenous extrapolation, the trend is considered to continue through time in a way that is not explicitly related to e.g. the increase in installed capacity of that technology - for example a constant improvement through time. Meanwhile in endogenous extrapolation, the development of the parameter in question has an implicit dependency on the development of the indicator through time. Endogenous extrapolation is an example of a learning curve approach, applied elsewhere in the REFLEX project.

- Technological explorative: In this method, a change in future data may be made specifically to assess how such a development may affect environmental and social impacts.

- Social explorative: Consideration of societal changes specifically for the opportunity to explore a possible future

In a step that does not seem to be considered to any great extent in the current literature, it is further proposed in the REFLEX framework that the changes made to account for technology development in the future be revised iteratively in light of the impact assessment results from an environmental and social perspective. This is described more fully in the text below.

IMPACT ASSESSMENT

The principle guiding the choice of impact assessment approach is that it should enable assessment of the societal sustainability objectives from a social, socioeconomic and environmental perspective identified in the goal definition. In practice it is envisaged in an application of the assessment that environmental impact assessment is performed using a standard impact assessment method such as ReCiPe or similar. An appendix to the report lists the life cycle environmental impact considered in the papers reviewed and makes a suggestion for those to be included in the REFLEX SELES framework.

For assessing social impacts, the options are much less clear. As social life cycle assessment is not standardized to the same extent as eLCA, there is no general agreement on the approach. In literature, two different approaches have materialized; the Type I impact assessment method using performance reference points, being generally agreed levels or thresholds for social performance. This approach is the most widely used and is also incorporated in the two databases for social data existing in the market; the Social Hotspots Database (SHDB) and PSILCA. However, this approach can be criticized based on the fact that the aim in S-LCA is to assess social impacts, yet the Type I approach only identifies social performances. Also, there might be social issues for which no generally agreed level or threshold is available. More in line with the aim of S-LCA then is the type II impact assessment approach. This is more in line with the kind of impact assessment applied i E-LCA, where environmental performances (e.g. emissions) are linked to environmental impacts (e.g. Global warming potential GWP) using natural science based relationships. Only, linking social performances (e g. child labour) to social impacts (decreased health status) by scientifically-based pathways seems more challenging, as these relationships are not yet scientifically established.

Neither when it comes to the choice of social issues and indicators, are there any generally agreed set selection. In the existing LCA guidelines (from UNEP) there are 31 subcategories proposed, which may be approximated to social performances. Further, there are five impact categories, which may be seen as social impacts on a more overarching level. However, it is not clear how they combine, neither how any of them can be used to assess social impacts on a generic, individual level.

In the light of the adoption of the Sustainable Development Goals, (SDGs) (ref) by the UN general assembly in 2015, the issues identified there as being important for sustainable development might form the basis on which to assess the social impacts from products. At the EU level, there are the EU Social indicators that also might form basis for a social assessment in this context. In any case, there will need to be a more comprehensive approach to social impact assessment than has been show so far in the literature reviewed. The random pick of one or a few social issues, aimed at complementing the environmental assessment into a sustainability assessment, as applied in the reviewed papers is not sufficient. The appendix to this report also shows categories of social impact assessment considered in reviewed papers.

INTERPRETATION

Two distinct roles for interpretation are proposed according to the REFLEX SELES framework. Firstly unit processes making a significant contribution to each social and environmental impact category shall be identified. The outcome of this procedure shall then be used to identify processes that should be prioritized when adjusting inventory data in light of potential future technology development.

It is also intended according to the REFLEX framework the interpretation phase involve the iterative assessment of social impacts based on the outcome of the environmental impact assessment. This could include for example the social perspective of increased frequency of extreme weather events due to increased concentration of greenhouse gases in the atmosphere, or the health effects caused by the emission of toxic substances.

5.2 Defining the product system and system boundaries

As the earlier literature review shows, life cycle based studies that attempt to focus on energy systems beyond a single technology still view an ‘energy system’ very narrowly, compared to the way that it is considered for example by major energy systems modelling exercises (E3MLab, 2016; OECD/IEA, 2016). Therefore it is necessary to look elsewhere to provide an account of the processes that need to be considered when performing an environmental or social assessment of an energy system with a life cycle approach.

Bottom up comprehensive energy systems models themselves, such as PRIMES (E3MLab, 2016) or IEA WEM (OECD/IEA, 2016) do aim to take account of all energy flows in society according to their chose temporal perspective. These and other models use similar (if not entirely identical) hierarchical structures allowing for a highly detailed, co-ordinated depiction of an energy system that is not considered explicitly in the life cycle based studies carried out up to now and considered in the literature review. Tables 2 through 4 together summarize WEM as a typical example of such a model. It assumes three main demand sectors (Table 2), two energy transformation sectors (Table 3) and three energy supply sectors (Table 4). The tables show that each sector is further subdivided into variously subsectors and technology and resource types of which there are over 100 in total (OECD/IEA, 2016).

Table 2: Main demand sectors in WEM (OECD/IEA, 2016)

Demand sector	Number of	Number of
Buildings (residential and services)	6	18
Transport	5	10
Industry	6	50

Table 3: Transformation sectors in WEM (OECD/IEA, 2016)

Transformation sector	Subdivisions
Electricity and heat	22 electricity production technologies, 13 CHP technologies. Transmission and distribution module.
Oil refining	Considers several crude oil products

Table 4: Energy supply sectors in WEM (OECD/IEA, 2016)

Sector	Number of resource types
Bioenergy	4
Fossil oil	5
Fossil gas	3
Fossil coal	3

The gathering and reporting of official statistics on national and supranational level is another area that has seen considerable codification of society's energy flows that can serve as a useful input for establishing a structure for the REFLEX framework. Particularly interesting here is the United Nations' recent International Recommendations for Energy Statistics (United Nations, 2016, IRES). One particular innovation in this recent document is the Standard International Energy Product Classification (SIEC), 'the first standard classification for energy products' (United Nations, 2016, p. iii). The SIEC also explicitly relates to society-wide statistical product classifications, such as the international Central Product Classification and the Harmonized Commodity Description and Coding System (HS) which then in turn refer to the European Combined Nomenclature standard. Of particular interest for the REFLEX Framework is that Environdec, a well-established third-party EPD certification body also uses the CPC to categorize its LCA-certifications. IRES furthermore proposes common concepts and definitions for statistical reporting on energy flows in society which may be very useful when performing a life cycle-based assessments of energy systems.

According to the discussion above, both the hierarchical structure of energy systems models and the codification provided by statistical reporting frameworks contain elements that are highly interesting for establishing a format for describing an energy system when performing a life cycle-based assessment. However, both approaches have limitations from this perspective as well. Therefore the REFLEX framework aims to draw the most relevant and useful aspects of each one when proposing a format for description of the energy systems considered in the assessment.

As shown in Table 5 three overall types of process are considered - transformation, transport and storage. The definition of transformation is largely based on that used in IRES (United Nations, 2016), however extended for the purpose of the REFLEX framework. Based on this definition there are three different kinds of transformation. Firstly transformation from elementary flows to an energy product (for instance electricity production in a wind power plant, cultivation and harvest of biomass, crude oil recovery) which may be called ‘primary transformations’. Secondly, transformation between different energy products (e.g. electricity and heat production in a biomass-powered steam turbine) which may be called intermediate transformations. Finally transformation from energy products into elementary flows (e.g. use of electricity in a lap-top computer, converting into heat and light) that may be called a ‘final transformation’. The final transformation is also a necessary for the provision of energy services (for which a definition is shown in Table 5).

Table 5 also shows other types of process to be considered according to the REFLEX framework - transport and storage. Such processes that can be considered as storage are the storage of electric potential in batteries (an interesting up-and-coming technology) or the storage of hydrogen produced from electrolysis. Transport processes include transport of electricity through transmission and distribution grids, the transport of fuels by rail, road, sea, air and pipeline for example.

An assessment based on the REFLEX framework that accounts for the entire energy system therefore includes all transformations, transport, and storage processes from the input elementary flows of the energy necessary for energy services on the one hand to the outgoing elementary flows of energy on the other. Having said that, it is feasible to consider as a product system only parts of the energy system that does not consider the system all the way through final transformations to elementary flows. This is exactly what Hertwich et al. (2015) and Santoyo-Castelazo and Azapagic (2014) do when they assess multiple electricity production technologies, but not technologies for final transformation. The addition according to the REFLEX framework in this respect is to point out that if doing a partial assessment then the implications of the exclusion of these processes should be explained, as also highlighted by ISO 14044 ISO. (2006).

Table 5: Terminology used in describing an energy system in the REFLEX framework

Terminology used in the REFLEX framework	Reference
Processes	
Transformation	"the process where all or part of the energy content of an energy product/elementary flow entering a process moves from this energy product/elementary flow to one or more different products leaving the process" (the authors' adaptation of United Nations, 2016, p. 72)
Storage	A process explicitly for the storage of an energy product
Transport	Processes for the transport of energy products
Supporting definitions	
Energy products	The Standard International Energy Product Classification, Table 3.1, (United Nations, 2016).
Energy service	The benefit received as a result of energy use (IPCC, 2014)
Elementary flow	"material or energy entering a system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation" (ISO 14044)

Table 5 also shows some supporting definitions that can be used in the REFLEX framework. It is proposed that energy product classifications based on SIEC be used. Table 6 shows the highest level of classification according to SIEC. Referring to SIEC is useful since it is a largely comprehensive description of the different ways in which energy flows through society that is also coordinated with other systems for statistical reporting and even for product classification for LCA-based environmental performance declarations. The level of disaggregation of energy products used in any given assessment should be adapted to the need of the assessment. Since the REFLEX framework also aims to consider future energy systems including future energy technologies, it is possible that energy products may need to be assessed that are not included in SIEC. In this case this should be noted explicitly in the assessment report. A final important definition here is that of 'elementary flows' from ISO 14044. The distinction between elementary flows and energy products is important here because the input of energy in the form of elementary flows from the environment mark one ultimate system boundary for the energy system. Elementary flows *out* of the system mark the other final boundary for the energy system.

Table 5 also identifies the term "energy service", according to its definition by (IPCC, 2014). This term is not considered either in statistical frameworks such as IRES or explicitly in energy systems models. However it is important because the provision of energy services is the ultimate function of the energy system. Examples of energy services can relate to subsectors in for example WEM, shown in Table 7. Using such subsectors in the REFLEX framework is recommended since doing so can be important for providing information to decision makers.

Table 6: SEIC classes for energy products (United Nations, 2016).

SEIC	Class category	Products in class
0	Coal	21
1	Peat and peat products	4
2	Oil shale/oil sands	1
3	Natural gas	1
4	Oil	23
5	Biofuels	15
6	Waste	1
7	Electricity	1
8	Heat	1
9	Nuclear fuels and other fuels	4

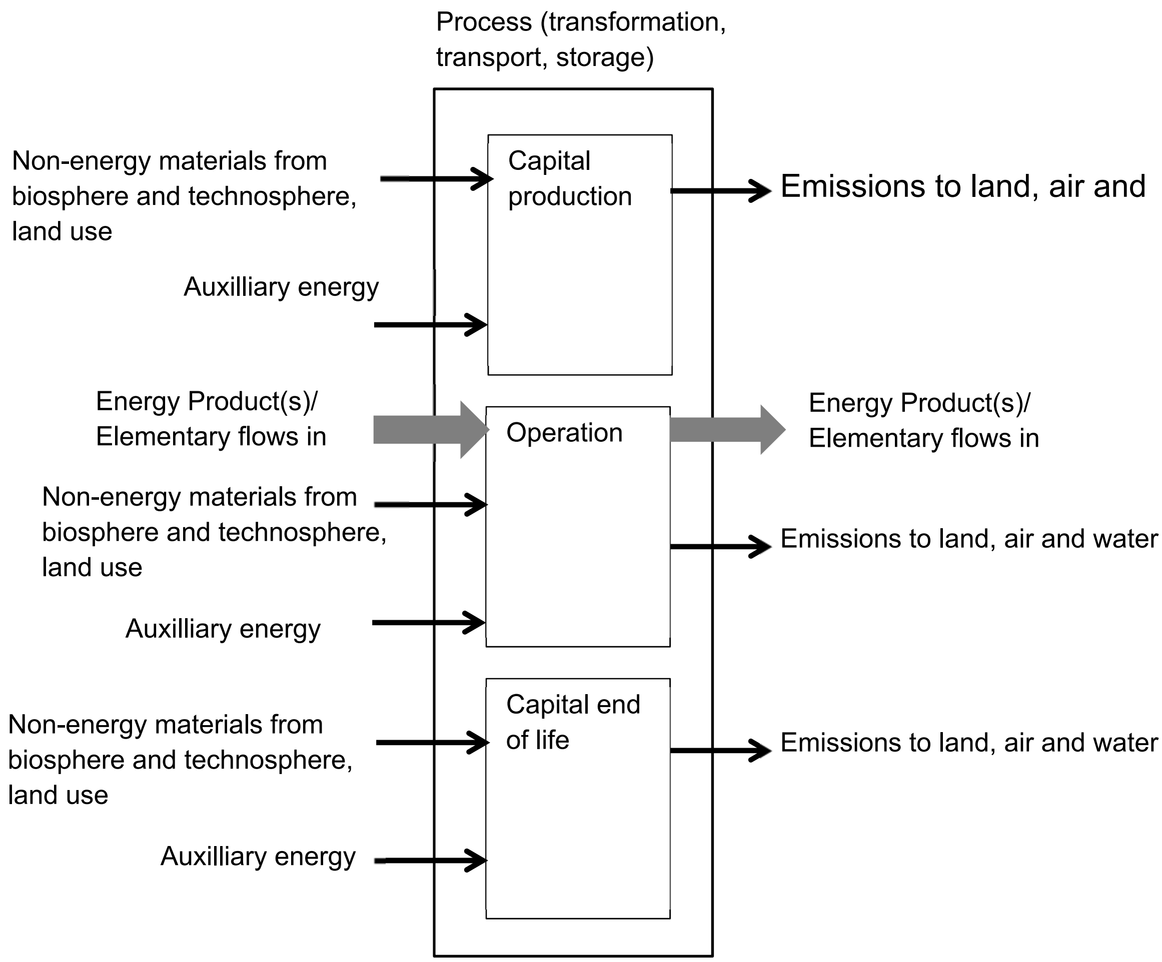
Table 7: Proposed energy service areas based on WEM (OECD/IEA, 2016)

Industry	Transport	Buildings
Aluminium production Iron and steel production Cement production Pulp and paper production Chemical production Other industrial production	Road transport Aviation Rail Navigation Other	Space heating Space cooling Water heating Cooking Lighting Appliances

It is further proposed that each unit process considered according to the system boundary used be described in terms of a number of separate stages, (see figure 3) Since there is currently no standard form for assessing energy systems or processes from a life cycle perspective, the basic stages shown are based a recent European standard for applying a life cycle approach to evaluate the environmental impacts of buildings, SS:EN 15978:2011 (CEN, 2011). By considering the capital production, operation and end of life stages, the inputs and outputs for each process on a cradle to grave basis can be considered. The grey block arrows in (figure 3) represent the main functional flow of energy products/elementary flows into and out of the system required to fulfill energy services. In addition to this, each separate stage is envisaged to require the input of non-energy materials from the biosphere and technosphere and to use land. 'Auxiliary energy' is also shown in the process. This is energy that is required in a particular transformation that is not part of the main flow of energy. In particular this is required in transport processes. For example transporting wood chips by electric trains requires the input of electricity, or process electricity input for producing liquid biofuel from solid.

One important reason for identifying this 'auxiliary energy' input into processes is to be able to identify if and where double counting may occur in the assessment, where some energy is counted once as a functional flow and once again as auxiliary energy. No specific strategy for dealing with double counting is suggested in the REFLEX framework, though its possibility should be recognized and its potential effect evaluated and presented. If it is found to be significant then inventory data should be adjusted in order to address this issue.

Figure 3: Stages included when considering process according to the REFLEX framework.



5.3 EXAMPLE SCOPE ACCORDING TO REFLEX FRAMEWORK

In the following, an example scope for assessing social and environmental impact of energy scenarios in light of REFLEX framework will be discussed. Considering the different influences of decentralized and centralized energy systems on the development of energy storage and transmission technologies as well as the electric vehicles market and mobility structure, apart from power/heating generation technologies, energy storage and transmission, infrastructure for the terminal energy consumption from mobility technologies, i.e. plug in stations (used for E-Mobility) and engines, and primary energy (e.g. diesel) consumption for fuel cell vehicles are discussed and included in the example scope. Overall, the full energy system to be assessed, covering both Heat - and power production and consumption, as well as mobility services,is shown in the upper part of Figure 4.

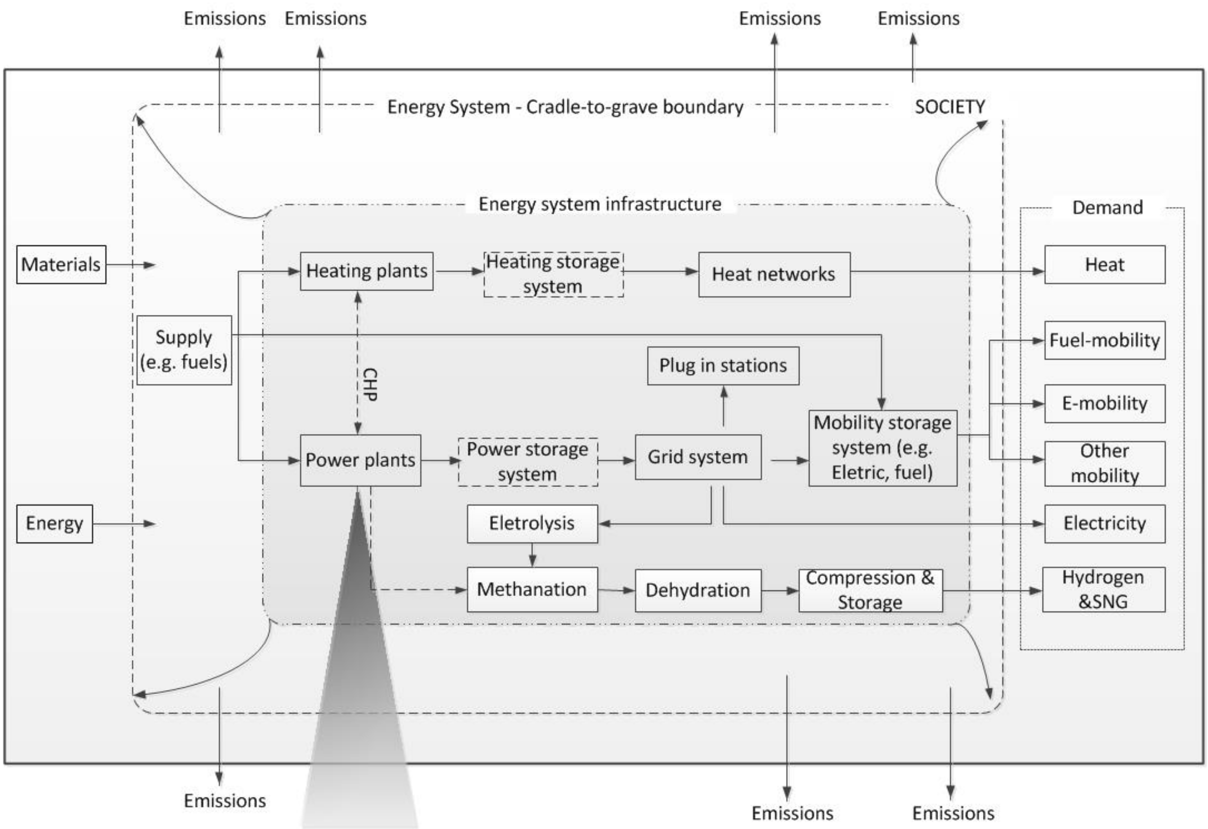


Figure 4: Overall view of the energy system.

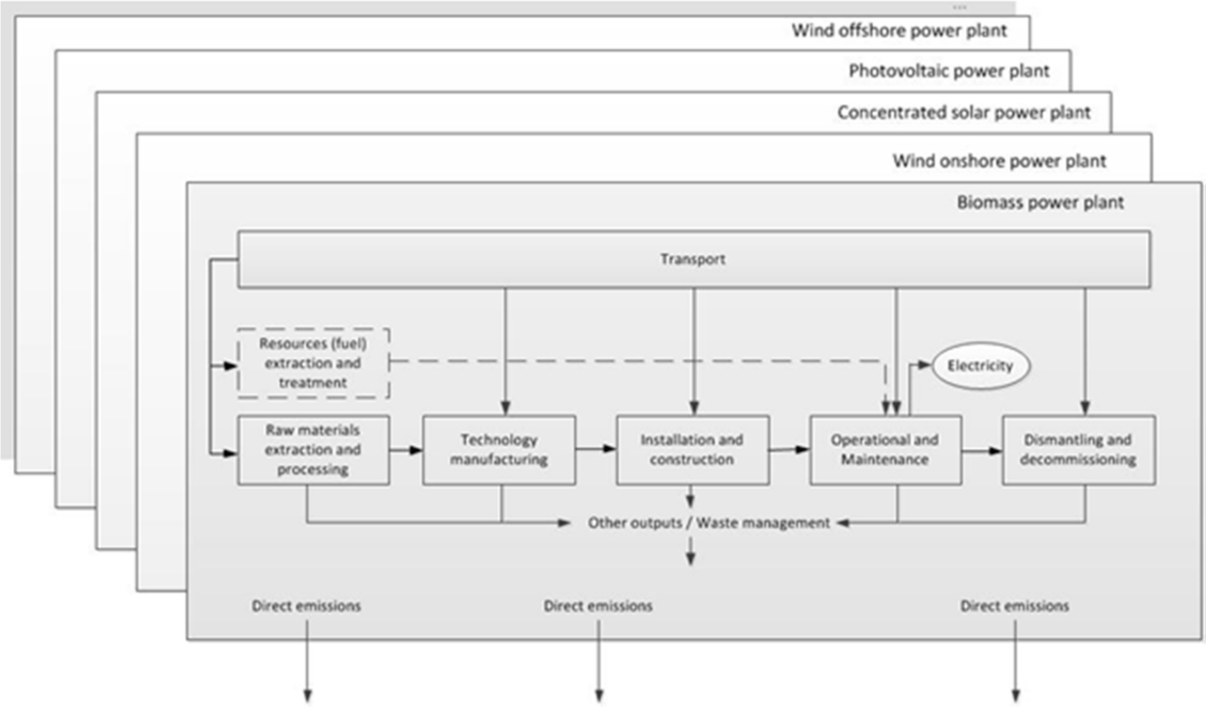


Figure 5: Simplified energy system boundary for environmental life cycle assessment

Departing from this outline of the full energy system to be assessed, we can identify all spots where any social impact might occur. In the left part of the figure, materials and energy are input to the system, in order to produce that capital, i.e. the plants and machinery needed for the energy production, as well as the consumables and fuels needed to run this equipment. For these capitals and consumables, all impacts along the full life cycle need to be considered. In many cases, the life cycle stages for a product stretches way outside the country where it is consumed or used, in this case way outside the EU borders. Here, the application of S-LCA is needed in relation to all capital and all consumables considered. Next, there might arise social impact for the citizens' energy needs supplied in form of heat, power or mobility, linked to how that energy is supplied. Issues to consider are all aspects of accessibility. Primarily physical accessibility, including security of supply, but also accessibility linked to price and the concept of energy poverty. However, the application of E-LCA will not discuss specifically about the geographic uncertainty, though it has potential effects and should be recognized.

Table 8 shows the detailed processes shown in this sketch sorted amongst logistical processes (transport and storage) and transformations processes as detailed elsewhere, according to the main system boundaries shown in the figure – 'energy system – cradle-to-grave boundary' and 'demand'. 'Energy system – cradle-to-grave boundary' which includes all transformations to electricity and heat (including heat pumps, CHP technologies on utility and building scale), is the boundary of environmental life cycle impact assessment. Connected to these transformation processes are further a number of related transformations such as electrolysis, methanation and dehydration. Specific logistical processes are also alluded to in the example shown in Figure 5, such as storage (power storage, heating storage, compression and storage for hydrogen and synthetic natural gas and mobility storage systems). Transport processes explicitly alluded to in the figure include heat networks (for large and small scale transformations) and the electric grid system. Processes for the supply of fuels are also included within the ‘energy system – cradle-to-grave boundary’. Though not explicitly shown, this includes both logistical processes (transport of e.g. wood chips) and transformation processes from elementary flows to energy products (e.g. the cultivation and harvest of biomass), and intermediate transformations between different types of energy product (according to the terminology proposed for the REFLEX framework). On the other hand, the figure also shows that processes occurring in energy demand are not included in the ‘energy system – cradle-to-grave boundary’. Therefore the assessment using Figure 4 as a description does not consider the final conversion of all energy products back elementary flows or the capital that is used to achieve this. Such processes not included are those including electricity consumption for E-mobility and other end-use consumption such as lighting, cooking, road transport, aviation, rail, navigation etc.

Table 8: The processes shown in Figure 4 according to the definitions in the REFLEX framework.

Logistics (storage and transport)	Transformations
Energy system – cradle-to-grave boundary	
- Grid system - Heat networks - Plug-in stations - Mobility storage system (e.g. electric, fuel) - Compression and storage - Power storage system - Heating storage system - Supply (e.g. fuels) – such as transport of harvested short rotation coppice	- Heating plants - Power plants - CHP - Electrolysis - Methanation - Supply (e.g. fuels) – such as cultivation and harvest of short rotation coppice
Demand	
	- Heat - E-mobility - Fuel mobility - Other mobility - Electricity - Hydrogen and SNG

For individual specific technologies or product systems, a cradle-to-grave approach is followed, covering from raw materials extraction to disposal process. Figure 5 meanwhile shows how different processes can be combined when considering e.g. electricity production. ‘Resources (fuel) extraction and treatment’ is an example of a transformation process from an elementary flow into an energy product in the lower part. In this case the energy product in question is biomass (e.g. forestry residues, short rotation coppice or otherwise). Meanwhile the stages ‘raw materials extraction and processing’, ‘technology manufacturing’, ‘installation and construction’ refer to the stage ‘capital production’ as identified elsewhere in the REFLEX framework for transformations (see figure 5). Meanwhile, ‘operation and maintenance’ in the figure refers to the operation stage as shown in figure 3 for a transformation. Finally, ‘dismantling and decommissioning’ refers to what is referred to as ‘capital end of life’ in Figure 3.

CONCLUSION

Studies that use LCA to assess energy systems beyond that of a single technology are still limited in number. These studies do cover global, national and supranational scales. They are focused on electricity generation, some featuring only selected technologies but others covering entire scenarios. The main focus of these studies is on environmental LCA. Some also attempt to cover social impacts, though few from a life cycle perspective.

There are likewise many studies applying life cycle assessment to evaluate impacts from separate energy technologies and their potential future development. These studies cover many different kinds of technologies that may be significant in future energy systems with ambitious sustainability goals, for example solar PV and wind power. Studies do aim to update inventory to account for possible future developments in a number of ways. For example many aim to connect future developments of the separate technologies to wider scenario developments, or the rate of expansion of global capacity. A few examples aim to explicitly consider technological improvements based on previous trends in efficiency increase (mainly for fossil combustion plant) or technology scale up (for wind turbines).

The REFLEX SELES framework aims to build on the example of the existing literature and also to propose new steps not found in existing literature. It is a natural choice for the framework to start from the structure of ISO 14044. The product system and the system boundary are established in the framework in terms of the elementary flows, energy products, the transformations between them, and the storage and transport processes that are involved in the processes. According to these concepts, the starting point for the energy system is the initial elementary flows from the environment required to deliver the energy services considered in the assessment. The end point for the system is then the final elementary flows of energy back into the environment after the final energy system transformation. An assessment performed according to the REFLEX SELES framework must include discussion of this wide context of the entire energy system, though it is acceptable that not all elements are included in calculation.

It is assumed that life cycle inventory for energy technologies in future scenarios is established by making appropriate and justified changes to life cycle inventory for current versions of the same technology (e.g. LCI for solar PV in 2050 is based on updating LCI for solar PV as currently produced). The first key criterion when doing so according to the framework is to demonstrate that the changes made are *consistent* with the overall scenario within which the assessment is performed. This follows the example of the NEEDS project. When creating inventory in this way it is proposed that the changes made are described clearly in the assessment report. It is also proposed that changes are based on a common classification of different methods of justification – technological potential, policy normative, trend extrapolation, technological explorative and social explorative. Finally it is proposed according to the REFLEX SELES framework that the initial assumptions about technological development are reconsidered in light of knowledge of how the assumptions affect overall impacts according to the assessment.

It is thus proposed that the REFLEX framework will increase clarity and transparency in applying LCA to energy systems scenarios.

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APPENDIX: IMPACT CATEGORIES CONSIDERED IN REVIEWED PAPERS AND SUGGESTIONS FOR REFLEX.

Table A1: Environmental impact categories considered in papers, including a suggestion for those to be used in REFLEX - part 1. See part 2 in table A2.

Studies (authors)	Climate change	Metal depletion	Fossil depletion	(Terrestrial) acidification	Freshwater eutrophication	Marine eutrophication	Human toxicity	Freshwater ecotoxicity	Marine ecotoxicity
Wiedmann et al. (2015)	√	√	√						
Santoyo-Castelazo et al. (2014)	√		√	√	√	√	√	√	√
Hamelin et al. (2011)	√			√	√	√			
Berrill et al. (2016)	√	√			√			√	
Hirtwich et al. (2015)	√				√	√		√	
Viebahn et al. (2011)	√								
Fujimoto et al. (2009)	√		√						
Kowalski et al. (2009)	√	√	√		√	√			
chen et al. (2014)	√	√	√	√	√	√	√	√	√
Baard et al. (2011)	√								
Sheate et al. (2008)		√	√						
Martire et al. (2015)	√		√						
Gusano, et al (2016)	√						√		
Bauer, et al (2015)	√			√			√		
Kikuchi, et al (2014)	√	√							
Turconi, et al (2014)	√	√	√	√	√	√	√	√	√
Vázquez, et al (2014)	√	√	√	√	√	√	√	√	√
Viebahn, et al (2007)	√		√	√			√		
Igos, et al (2015)	√	√	√				√		
REFLEX Project	√	√	√		√		√	√	

Table A2: Environmental impact categories considered in papers, including a suggestion for those to be used in REFLEX - part 2.

Studies (authors)	Ozone	Photo-	Terrestrial	Particulate	Agricultural	Urban land	Water	Natural land	Ionising	Bio-
Wiedmann et al. (2015)										
Santoyo-Castelazo et al. (2014)	√	√	√							
Hamelin et al. (2011)		√		√						
Berrill et al. (2016)				√	√	√				
Hirtwich et al. (2015)				√	√	√				
Viebahn et al. (2011)										
Fujimoto et al. (2009)										
Kowalski et al. (2009)				√	√	√				
chen et al. (2014)	√	√	√							
Baard et al. (2011)										
Sheate et al. (2008)										√
Martire et al. (2015)				√						
Gusano, et al (2016)			√							
Bauer, et al (2015)		√		√						
Kikuchi, et al (2014)										
Turconi, et al (2014)	√	√	√	√						
Vázquez, et al (2014)	√	√	√	√	√	√	√	√	√	
Viebahn, et al (2007)		√								
Igos, et al (2015)								√		
REFLEX Project				√	√	√				

Table A3: Social impact categories considered in selected papers from the literature review that may also be used in REFLEX – part 1.

Studies (authors)	Landscape	Ecological	Security	Dignity	Competence	Political	Avoiding	Effects	Social justice,	Fair	Transport
Wiedmann et al. (2015)											
Santoyo-Castelazo et al.											
Hamelin et al. (2011)											
Berrill et al. (2016)											
Hirtwich et al. (2015)											
Viebahn et al. (2011)											
Fujimoto et al. (2009)											
Kowalski et al. (2009)	√	√	√						√		
Chen et al. (2014)											
Baard et al. (2011)											
Sheate et al. (2008)											
Martire et al. (2015)											
Gusano, et al (2016)											
Bauer, et al (2015)											
Kikuchi, et al (2014)											
Turconi, et al (2014)											
Vázquez, et al (2014)											
Viebahn, et al (2007)											
Igos, et al (2015)											
Renn et al. (2003)			√	√	√	√	√	√	√	√	
López et al. (2012)											√
Hickman et al. (2012)											
Lupp et al. (2015)											
Streimikiene et al. (2016)			√								
Onat et al. (2016)											
Lucas et al. (2008)											
Souza et al. (2016)									√		

Table A4: Social impact categories considered in selected papers from the literature review that may also be used in REFLEX – part 2.

Studies (authors)	Equity	Accesibility + deliverable & feasible	Employment	Compliance	In aligment with sustainable development	Aesthetic values	Recreation opportunities	Economic security	Education	Culture	Public acceptance	Regional self-determinacy
Wiedmann et al. (2015)												
Santoyo-Castelazo et al.												
Hamelin et al. (2011)												
Berrill et al. (2016)												
Hirtwich et al. (2015)												
Viebahn et al. (2011)												
Fujimoto et al. (2009)												
Kowalski et al. (2009)	√		√									√
Chen et al. (2014)												
Baard et al. (2011)												
Sheate et al. (2008)												
Martire et al. (2015)			√									
Gusano, et al (2016)												
Bauer, et al (2015)												
Kikuchi, et al (2014)												
Turconi, et al (2014)												
Vázquez, et al (2014)												
Viebahn, et al (2007)												
Igos, et al (2015)												
Renn et al. (2003)												
López et al. (2012)	√	√	√									
Hickman et al. (2012)				√	√							
Lupp et al. (2015)						√	√					
Streimikiene et al. (2016)			√					√	√	√	√	
Onat et al. (2016)												
Lucas et al. (2008)		√										
Souza et al. (2016)			√						√			

Table A5: Social impact categories considered in selected papers from the literature review that may also be used in REFLEX – part 3.

Studies (authors)	Import dependencies	Effect on public spending	Social cohesion	Quality of landscape	Taxes	Injuries	Wages
Wiedmann et al. (2015)							
Santoyo-Castelazo et al.							
Hamelin et al. (2011)							
Berrill et al. (2016)							
Hirtwich et al. (2015)							
Viebahn et al. (2011)							
Fujimoto et al. (2009)							
Kowalski et al. (2009)	√	√	√	√			
Chen et al. (2014)							
Baard et al. (2011)							
Sheate et al. (2008)							
Martire et al. (2015)							
Gusano, et al (2016)							
Bauer, et al (2015)							
Kikuchi, et al (2014)							
Turconi, et al (2014)							
Vázquez, et al (2014)							
Viebahn, et al (2007)							
Igos, et al (2015)							
Renn et al. (2003)							
López et al. (2012)							
Hickman et al. (2012)							
Lupp et al. (2015)							
Streimikiene et al. (2016)							
Onat et al. (2016)					√	√	
Lucas et al. (2008)							
Souza et al. (2016)						√	√