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STORE&GO

Innovative large-scale energy storage technologies and power-to-gas concepts after optimization

D7.1

Report on full CBA based on the relevant environmental impact data

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Content

Executive Summary

To complement the techno-economic evaluation of the Power-to-gas (PtG) technology (private perspective) a broader assessment looking at all the possible impacts on society is also required (social perspective). The assessment of these external effects could lead to a net positive benefit for society that would justify further public funding and support of the technology. For this task, the Social Cost-Benefit Analysis (SCBA) has been chosen given that it takes all possible changes in society welfare into account (main objective of Task 7.1). This Deliverable focuses on the environmental component of SCBA and constitutes the link between environmental impact (Task 5.4) and the monetary valuation needed to weight with other variables in the SCBA.

Results from Task 5.4 are not yet available. Therefore, this Deliverable dwells into the different methodologies for making such conversion. To first have an overview and understanding of the methods to then make a choice on way forward. Results from previous studies have already been collected in Deliverable 5.1 (D5.1) and a summary is presented in this Deliverable to ensure clarity and a smooth transition between tasks. Actual values from STORE&GO will be used as part of D5.6 and D5.8.

Structure for the report is to start with the different methods available to assess the environmental impact and their relation with SCBA (chapter 2) to then list the methods to convert such impact into monetary terms (chapter 3). chapter 4 shows a summary of the Life Cycle Assessment (LCA) for PtG pathways, while chapter 5 summarizes the practical application of this review for the project.

The main output of the Deliverable is twofold. First, the understanding of the methods available that support the decision and second, the values that can be used to convert physical impacts from the LCA in Task 5.4 to monetary input for Task 7.1, which have been captured as Appendix.

1 Introduction

PtG arises as a potential technology that can significantly contribute to decarbonize the energy system. It can use power surplus from variable renewable energy (VRE) that would otherwise be curtailed, it can use CO_2 from biogenic sources to reduce the life cycle footprint of the gas burned and provides an option to connect a potential low electricity production to other sectors. The technology is in its early stages and still has to demonstrate its operational and economic performance at large scale. Because of this, evaluations focus on economic [1–5] and operational [6–8] performance and the possible role of the technology in the energy system [9–11]. Equally important is to look at the broader impact the introduction of the technology can have in the welfare of society, including not only direct impact, but also possible secondary effects that are not part of a conventional investment evaluation.

As part of the STORE&GO proposal the decision has already been made to use cost-benefit analysis (CBA) as methodology to assess the technology impact from an environmental, social and economic perspective. Based on this, the objective of this Deliverable is twofold. First, show the range of environmental impact assessment methods available and how these relate to and can be used in combination with CBA. Second, environmental impact has to be translated into units that are useful for the CBA (i.e. monetization). Therefore, this Deliverable also reviews the methodologies to provide the bridge between both and makes a final suggestion for this process.

Task 7.1 is seen as one of the integrating activities that assesses the impact and potential for PtG. It integrates the environmental component (Task 5.4), with security of supply, competition with other flexibility options in the power system (e.g. storage, network), societal costs and economic performance for the different pathways and business scenarios. D7.1 was originally intended to reflect the full CBA for the environmental impact component using as input the results from Task 5.4. However, the timeline for the results from Task 5.4 was not considered, since final results will only be available for month 36, while some preliminary results will be captured in D5.4 due in month 24. With the present Deliverable having a due date of month 20 it is not possible to assess the full environmental impact and prepare it for the CBA. Based on this, it was decided among the partners to focus D7.1 on a methodological review and leave the CBA implementation to D7.4 and D7.6 (related to Task 7.1), which have timelines more suitable (month 30 and 32 respectively) for the results from Task 5.4 to be available.

Therefore, the focus of this Deliverable is on methodological review (first step) rather than final results. Methods to assess the environmental impact will be reviewed (chapter 2), along with methods to convert this impact to monetary terms that can be used for trade-offs in the CBA (chapter 3). The Deliverable closes with chapter 4 which gives insights in recent scientific work on LCA of Power-to-gas pathways.

2 Methodologies to assess environmental impact

This section discusses two main approaches to assess the environmental impact. Environmental Impact Assessment (EIA) is rooted in government requirements assessing the full consequences of activities to make sure all the effects to society are considered and mitigated. Life Cycle Assessment (LCA) arose with focus on products and processes (small scale) with the added scope of considering all the life stages of the product to later on expand its boundaries and include the consequences over the rest of the system. Environmental impact is also a fundamental component of studies covering the broader effects on economic, social, political dimensions. Methodologies like Multi-Criteria Decision Analysis (MCDA) and CBA fall in this category as both are all encompassing methods. MCDA is meant as a tool to organize all the information, aid the decision process and cover as many aspects as possible to make the decision based on complete and robust information. In turn, each of these main branches has methodologies of their own that are applicable under different circumstances. Given that this Deliverable is focused only on the environmental component, these two techniques are only briefly discussed with a more complete elaboration in D7.6 (which covers the three aspects).

Regardless of the choice for assessing the environmental impact, this will be fed to a CBA. CBA uses monetary terms as common unit. Therefore, any output from the environmental assessment has to be translated to money. For this task, economic valuation (EV) plays a key role as intermediate step and it is mentioned in combination with the other three methods, but only discussed in more detail in the chapter 3. EV is usually part of CBA, rather than a pre-processing step, but when referring to environmental impact, there are already established methods that will facilitate this task.

An overview of the relevant methods for environmental impact is shown in Table 2-1.

Table 2-1: Methodologies related to environmental impact assessment

Methodology	Scope	Strength	Weakness
Environmental Impact Assessment (EIA)	Focuses on consequences of proposed project, mitigation of possible effects and evaluation of alternatives	Full assessment on all aspects (ecological, economic, and social)	It can fall short of monetizing these consequences or combining them into a single indicator
Life Cycle Impact Assessment (LCA)	Assess environmental impact for each of the stages of the life of the product	Covers the entire value chain from resources to use and disposal	Effects on multiple agents and environments can be difficult to compare and monetize
Multi-Criteria Decision Analysis (MCDA)	Provide a framework to evaluate trade-offs between criteria of different nature and aid decision-making	Use input from indicators of different nature (e.g. social, technical, economic)	Can be subjective, dependent on group performing analysis and possible double-counting of effects
Economic Valuation (EV)	Can aid EIA to translate impact to monetary terms	Different types of values can be assessed and multiple methods available	Possible bias and uncertainty depending on method
Cost-Benefit Analysis (CBA)	Monetize all possible effects of a decision and ensure a positive change in social welfare	Wide range of effects considered with a single indicator (money)	Can be time, location and group dependent leading to different results

The methodologies can be split in procedural and analytical ways. Procedural ways focus on steps to follow to guide the assessment, reach and implement the decisions, while analytical ways provide the technical information as input to the decision-making process (this can be both qualitative and quantitative) [12]. See Figure 2-1 below for a broader range of methods to assess the environmental impact.

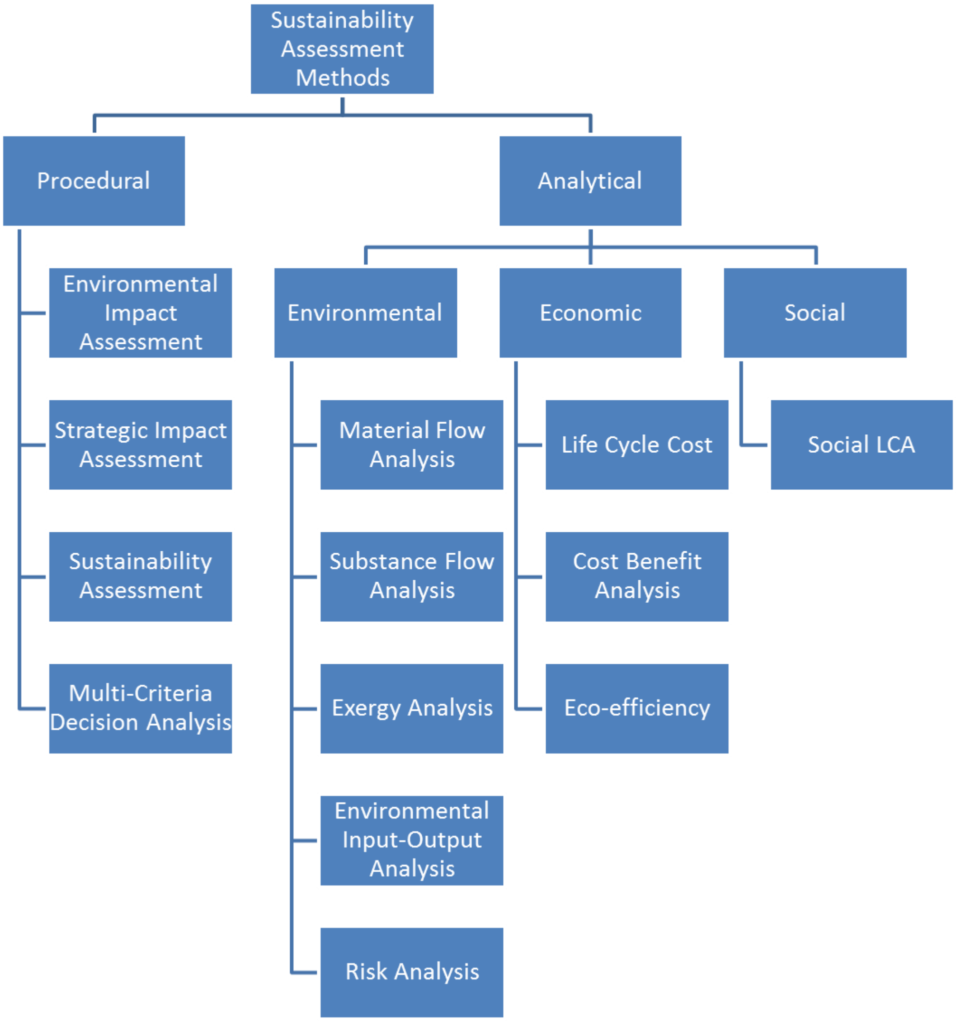

Figure 2-1: Classification of methodologies for sustainability assessment (based on [12])

The intention below is to go through each of these methods explaining the basics for it, but more importantly their relevance to assessing the environmental impact (focus of this Deliverable) and how these are useful for the CBA. After highlighting the basics, strengths and limitations of each one, the link is made between the different methodologies to understand their interaction and its usefulness as input to CBA.

2.1 Environmental Impact Assessment (EIA)

EIA assesses proposed actions (from plan to policies and projects) based on consequences on the environment before the decisions are made to commit to those actions [13]. These effects include social and physical processes (e.g. effects on air quality, land, production change) and different aspects should be analyzed including PPP (People, Planet, Profit) or TBL (Triple Bottom Line representing Social, Economic and Environmental consequences). The target of the assessment is to allow the decision maker to judge information quickly and make the trade-offs between different categories.

EIA emerged in the US in the 1970s as product of the "National Environmental Policy Act". The objective was to make sure federal agencies, whose decisions had an impact on the population, were able to demonstrate that the consequences of those choices had been assessed and explain to the community they were affecting how these had been mitigated. This origin explains the EIA focus on consequences, mitigation and on explaining the way forward on simple terms (to disclose to the public). At the same time, EIA was meant to have a broad application to any proposal that could have an environmental impact rather than address a specific category (e.g. air quality, waste, water).

The adoption of this concept in the EU started at a similar time (1972) with the Paris Summit meeting of heads of state and government of the European Economic Community (EEC). The EIA directive (85/337/EEC) was in force since 1985 and has been amended five times (1997, 2003, 2009, 2011 [14] and 2014 [15]). The directive covers 4 main components: projects that shall have an EIA carried out, projects where the EIA execution is left to the discretion of the Member States, criteria for evaluation and EIA content. In combination these define the process, stakeholders, requirements and steps for the EIA. All relevant industries are covered, including: energy, mining, agriculture, metals and minerals, chemicals, infrastructure and food.

To apply EIA to trans-border issues between Member States, the combination with the Regulation on guidelines for trans-European energy infrastructure is useful (EC/347/2013 [16]), which establishes sustainability as a criterion to define the projects of common interest and where PtG and biogas are explicitly mentioned (Annex IV, 3d) considering their potential contribution to reducing emissions. An even broader scope is given by EC/42/2001 [17], which does not refer to specific projects or policies, but extends it to plans and programs that set the framework for future development. Some differences with the EIA directive are mandatory involvement of competent environmental authorities in the scoping process, monitoring of the effects of the programs and ensuring a minimum quality for the environmental reports.

EIA is also widely applied in the private sector, with around 80 institutions (covering over 70% of the project finance debt in emerging markets) have signed up for obligations on procedures for IA.

Good practices for EIA include following a pre-defined procedure, guaranteeing public participation (to ensure understanding of the consequences and mitigation measures), presenting information in a transparent and objective manner and providing information to facilitate decision-making.

The general steps that EIA follows are:

1. Screening. To establish if the proposed action poses significant risks and impacts.
2. Description of the project. This should cover the different phases of the project (i.e. construction, operations, decommissioning), listing the sources of environmental disturbance and description of the process including the nature and quantity of the materials used.
3. Alternatives that have been considered including the baseline scenario, whereby the baseline scenario is the basis for comparison.
4. Description of the environment. List of all aspects of the environment that may be affected by the development (e.g. population, fauna, flora, air, soil, water, landscape and cultural heritage).
5. Description of the significant effects on the environment. Describe the mechanisms through which significant effects to the environment are incurred. For this, significant effects must be defined, for which the most frequent method used is the Leopold matrix[1].
6. Mitigation. Measures envisaged to prevent, reduce and, where possible, offset any significant adverse effects.
7. Non-technical summary. Make information available to the public in a simple manner.
8. Lack of know-how/technical difficulties (optional). Define focus areas of future research.

Some variations of EIA have emerged in order to pay more attention into a specific area that was considered underrepresented. Some of these variations are SIA (Social) because it was considered

[1] Leopold matrix is a qualitative tool to identify the potential impact of a project on the environment. It has the activity breakdown and their relative magnitude (scale of the impact) and importance (significance of the impact, which is based on judgment).

that EIA focused too much on physical processes rather than social consequences, HIA (Health) lobbied by health professionals and SEA (Strategic) in an attempt to adapt it for high level decision making and the coverage of plans and programs rather than specific projects. Another difference is found in the scope, where EIA is used for private or company use, while SEA refers to the state.

EIA is only a tool to organize the environmental effects and inform decision makers. It happens that projects with a net negative effect are still carried out due to other effects left out of the analysis. This is different from CBA where the focus is on social welfare (broad scope) and decisions with a negative benefit to cost ratio do not bring a benefit to society.

Some of the above concepts can be illustrated with an example of a power plant. Effects on land cover the area used for the facility. From the substances emitted, the most important impact is the emissions upon combustion, which end up in the air, these can be determined in mass (e.g. kg) per unit of input (or output) and the uncertainty associated is low. Next, the closest population center combined with the local weather conditions will determine dispersion and concentration to which the people and nearby environment are exposed (low uncertainty). With a dose-response curve for the local species, the effect of these concentrations can be determined (a variance introduced by heterogeneity of the population). This (effect) is usually enough for the EIA. Further steps involve the valuation of these effects, which involves breaking down the effect EV (following section). Figure 2-2 shows the general sequence of steps with the white boxes corresponding to EIA and the gray ones representing the EV step.

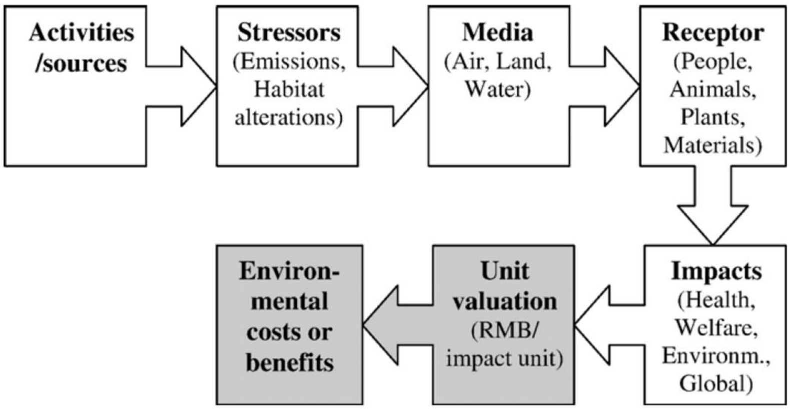

Figure 2-2: Steps in identifying environmental impacts and valuation (taken from [18])

2.2 Life Cycle Assessment (LCA)

LCA is a standardized methodology (ISO 14040/14044 [19,20]) that covers all the stages of a process from raw materials needed and their extraction to manufacturing, transport, production and end life disposal. LCA identifies all the energy and material flows to and from and process and consequences in the environment (human, ecosystem, resources).

According to these standards, the four phases of LCA are:

- Goal and scope definition, including system boundaries, intended application and level of detail.
- Inventory analysis, which covers the collection of input/output data for the system chosen.
- Impact assessment to provide additional information to understand the significance of results.
- Interpretation, which includes the decision making process.

An advantage of LCA is that it extends the environmental impact from direct consequences of the activity to all the life stages of the product. A key disadvantage is that impact is quantified in different units depending on the category, resulting more difficult to establish trade-offs and evaluate alternatives. Therefore, it needs an additional step to monetize impact (similar to EIA) and analyze in combination with other indicators. At the same time, it leaves out social, technical and other aspects that could be covered with a broader methodology. A distinctive feature of LCA is that the environmental impact is expressed on specific terms based on a reference unit (called functional unit and used to normalize the elementary flows).

From the steps aforementioned, the impact (3rd step) can be quantified from consequences directly upon emission (called midpoint indicators because they do not reflect the final damage but instead intermediate variables like acidification or toxicity) or grouped according to the final agent affected (final damage on human health, ecosystems or resources, so called endpoints). The translation to midpoint is based on highly accepted and certain methods (e.g. radiative forcing for global warming), whereas the translation to endpoint (i.e. damage function) is more dependent on method used and assumptions.

The process to determine this impact is similar to the one followed by EIA, starting from emissions, media, concentration, exposure analysis and response by the receptors. There are local conditions (weather, population density, water supply) that will affect both the substance dispersion and reach to the final agent and that will have an impact on how the substances are aggregated in the indicator. Endpoints will be dependent on the concentration and dose-response function of the final agents. Taking climate change to illustrate these concepts, the primary impact (midpoint) is the increased absorption by molecules of the atmosphere within the infrared (IR) window, a secondary impact is the increase in the average temperature of the troposphere, while the final impact (melting of glaciers and antarctic ice, climate instabilities, shift of climate zones, rise of the sea level, spreading of diseases, changes in ecosystems) is harder to allocate to this category only since it depends on the interaction with the rest of the system. The calculation of endpoint highly depends on the reference for normalization (reference substance) and weighting method, where it has been seen [21–24] that results vary widely depending on the methodology used and conversion factors.

The plethora of methodologies to determine these impacts arise from the way the substances emitted are aggregated in the impact category (through characterization factors that represent the conversion of the pollutant to a reference substance), the substance used as reference, local fate and responses, normalization and weighting methods. Some of the most used are mentioned below with tables showing the scope of each methodology in Appendix 1. A split was made in the methodologies, the ones addressing different characterization methods and focusing on mid/endpoint are discussed below, while there is another class that includes the normalization and weighting (not mandatory in ISO 14040). Weighting is done in monetary terms. Given that this is an alternative to monetize the environmental impact, these are discussed in chapter 3 which focuses on monetization methods.

- CML [25]. Relates the possible emission of around 2000 substances and aggregates them into almost 100 impact categories by using characterization factors to group substances with similar nature and impact[2]. These impact categories are mid-points (e.g. abiotic depletion, global warming potential, ozone depletion).
- Ecoindicator 99 [26]. Focuses on interpretation of results and use of endpoints. It has the advantage of combining the impact in a single score. Two steps are required to have a single score, normalization (which involves using a common reference to have the endpoint in a dimensionless unit) and weighting (which depends on the range and view of stakeholders).
- LIME (Life-cycle Impact Assessment Method). Covers the potential damage on socioeconomic impact caused by the use of abiotic resources. Damage categories include loss of primary production, extinction risk and resource depletion.
- ReCiPe [27]. Combines a framework where both midpoint and endpoint indicators can be used. It was the result of combining the strengths of the previous approaches and the harmonization of modeling principles and choices. It uses 18 midpoint indicators which are grouped into the impact to 3 endpoint indicators (human health, ecosystem and resources). This methodology has been developed using European models and has limited validity for not well developed temperate regions.
- IMPACT 2002+ [28]. Another methodology that has both mid and endpoint indicators (14 and 4 respectively), using characterization factors for almost 1500 LCI results. Its strength lies in

[2] https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors

the comparative assessment of human toxicity and ecotoxicity, where the rest of the categories were adopted from previous methodologies. Normalization to a reference substance and weighting is also done. An update of this methodology is IMPACT World+, which goes further in spatial differentiation and uncertainty analysis.

- EDIP 2003 [29]. Focuses on midpoint, includes exposure assessment based on regional information (Europe divided in 44 countries) for non-global categories and covers global as well. It includes normalization, but not weighting.
- LUCAS [30]. Based on EDIP2003, TRACI and IMPACT 2002+ and adapted to Canadian context. It covers around 800 substances with 2000 toxic emissions and uses 10 midpoint categories with no endpoint. It normalizes the impact per category per person and does not use weighting.
- Ecological scarcity method (Ecopoints) [31]. The main differentiator is the use of factors to add the environmental across categories impacting human health and ecosystems. It uses a top-down approach where the factors are defined based on the government (environmental) goals and policies. It focuses on midpoint, but endpoint indicators are indirect results. It was developed for the Swiss context.

There are other methods that either focus on a specific area (e.g. CED, cumulative energy demand for energy consumption, ecological scarcity method for resources or USEtox for toxicity) or aim to reproduce the effort of the above methodologies in reviewing mid and endpoints (e.g. ILCD, International Reference Life Cycle Data developed by Joint Research Center of the European Commission [32] or TRACI, Tool for the Reduction and Assessment of Chemical and other environmental Impacts developed by the Environmental Protection Agency in US [33]). For an overview of the impact categories included in each of these methodologies refer to Appendix 1 and for some of the less known methodologies refer to [34].

The most recent exercise of reviewing and harmonizing these previous methodologies was done by JRC (Joint Research Center from the European Commission), which resulted in the ILCD handbook [32]. As part of this exercise, 156 models were identified which used 11 underlying methodologies, 91 models were analyzed in more detail resulting in the selection of 15 impact categories.

Some of the methodologies are not fundamentally different, but the variation arises due to the application to a local environment (e.g. LUCAS for Canada, TRACI for US, LIME for Japan). The two components that can change in a location are fate (where the substance ends up) and effect on the receptor [30].

An approach to extend LCA beyond the environmental impact is to combine it with LCC (Life Cycle Cost, which would provide the economic component) and SLCA (Social LCA, tackling the social impact of the activity). This combination has the strength of all the life stages of the product or process, while also covering the economic and societal aspect [35]. Note that SLCA has the same end user (e.g. society) that CBA has. However, CBA aims to quantify all the impacts in monetary terms, while SLCA (which is still in its early development stage) can be measured in: quality adjusted life years, wage hours and even factors like child labor through the life stage of a product. A challenge for conducting a SLCA is the lack of a standardized method due to their relative immaturity. For more on the integration of these, including status and weighting refer to [36,37].

LCA can also complement EIA to aid the comparison among alternatives, measure the impact of activities and effectiveness of mitigation actions. This represents an alternative to EV. Global impacts like climate change or resource depletion are usually not included in EIA, which is focused on a local level. On the other hand, EIA address the risk and potential impact on a community, which can complement the lack of spatial definition of LCA [38].

2.3 Multi-Criteria Decision Analysis (MCDA)

CBA aims to cover a wide range of issues affecting society (economic, social and environment aspects) and its monetization. However, in some cases (when environmental or social issues are hard to quantify or the uncertainty is so high that renders the output without significance) impacts cannot be assigned a monetary value. Expansion to MCDA concepts that still cover a wide range of issues, while being able to facilitate their consideration and trade-offs for the decision-making process, is an option. This broader framework is attractive for environmental decisions since it is able to handle conflicting decisions. MCDA also deals with uncertainty and aims to prove assumptions by ensuring a participatory approach with multiple stakeholders. Some reasons to use MCDA rather than CBA are when the CBA identifies important elements that are difficult to monetize and will have a large influence on the decision, when uncertainty associated to the monetization is too high and when the cost-benefit ratio is close to 1, making the introduction of additional elements for the decision, more relevant.

The major steps for a MCDA are:

1. Definition of (multiple) objectives to achieve
2. Identify the alternatives that fulfill the objectives
3. Criteria for evaluation (and weights by policy maker) as well as grouping
4. Impact analysis (describe the consequences of the change in each of the criteria)
5. Forecast of the effect of intervention on the selected criteria
6. Stakeholders and assignment of weight to the criteria according to their importance
7. Scoring of alternatives including normalization and consistency check
8. Examination of results, interpretation and agreement on the way forward
9. Sensitivity analysis

For each of the core steps (criteria synthesis, criteria evaluation, weighting, normalizing) there are several techniques that give rise to a continuously expanding set of methodologies. For an overview of these refer to Appendix 2 or [39,40].

MCDA can be classified in 3 broad categories:

- Value measurement models. Attribute a numerical score (or value) to each alternative.
- Goal, aspiration and reference level models (distance to target). Choosing alternatives that are closest to achieving a goal (used to filter alternatives out).
- Outranking models (the French school). Pairwise comparison of alternatives according to different criteria and elimination of the alternatives that are dominated (i.e. perform worse than other options) in certain criteria. Electree and Promethee are two models in this area.

Some other classifications [41,42] use Analytical Hierarchy Process (AHP, which uses pairwise comparison to assign weights to the criteria and can use incomplete or inconsistent input) as category (instead of the 2nd category above), but given the multitude of techniques, there is also a wide range of classifications.

Since the evaluation will directly depend on the criteria used, their selection is also highly relevant. These should be chosen for each particular project based on its objectives, needs and constraints. Some of the methods for criteria selection are: Delphi method, least mean square, minimax deviation and correlation coefficient [39], where Appendix 2 shows a classification of the methods based on [40].

2.4 Cost-Benefit Analysis (CBA)

CBA emerged in the 1930s to balance the costs and benefits of water-related investments in US. Subsequent applications included the search of a high efficiency in the use of public funds. This resulted in the beginnings of the fusion of the new welfare economics, which was essentially cost-benefit analysis, and practical decision-making. Since the 1960s CBA has enjoyed fluctuating fortunes, but is now recognized as the major appraisal technique for public investments and public policy. CBA enables the comparison between environmental protection and social and economic development to achieve more efficient use of scarce resources.

Broadly, CBA has two main purposes:

- To determine if an investment/decision is sound (justification/feasibility) – verifying whether its benefits outweigh the costs, and by how much;

- To provide a basis for comparing projects – which involves comparing the total expected cost of each option against its total expected benefits.

The second application falls more in the space of CEA (Cost Effectiveness Analysis), where similar options are compared to choose the more effective. Similarities with CBA are the use of monetary terms and the consideration of broad set of costs with the disadvantage of addressing only the costs rather than the benefit-cost trade-offs. It also carries the problem of defining the objective for which solutions will be searched and how broad this problem is (the set of solutions that it can cover).

The following is a list of steps that comprise a generic cost–benefit analysis.

- Problem analysis including definition of objectives
- List alternative projects/policies compared to baseline situation
- List stakeholders
- Select measurement(s) and measure all cost/benefit elements (modeling)
- Predict outcome of cost and benefits over relevant time period
- Convert all costs and benefits into a common currency
- Apply discount rate to calculate net present value of project/policy options and compare
- Perform sensitivity analysis
- Present results in a clear and concise way, including non-quantified items

Instead of just comparing the benefits to the costs, an incremental approach could also be followed where an alternative with the project is compared to a baseline alternative where the project is not carried out.

The range of benefits and costs to include in each project will be different depending on its nature, location, scale and community, among others. The definition of this list is usually based on experts input, who have a better knowledge of the possible consequences of the introduction of new technologies.

It is not only a matter of defining the categories to be used as benefits and costs, but also criteria to quantify and monetize them. For a consistent approach, often either national or EU guidelines have to be followed for carrying out a CBA. For the specific case of the environmental component, this is the core of sections 3.2 and 3.3.

Some other elements to define for each study besides the benefits and costs are:

- Time horizon. Variables like commodity prices, technology performance and system configuration will be different in 2050 than now.
- Discount rate. This will affect the impact of future benefits and costs compared to short term effects. This rate is usually different than the used for economic evaluation since it constitutes the social discount rate.
- Compensation criterion. Different social welfare weights depending on population segregation (larger impact to the poor due to their lower income).

The link of CBA and the environmental component is that the latter is an implicit part of the former (see Figure 2-3 later in this chapter) since CBA covers consequences across the three dimensions (people, planet and profit). On a more specific context for EU policy, environmental impact is one of the key goals (security of supply, affordability/competitiveness of technologies and sustainability) that the CBA should target.

2.5 Other methodologies

This section mentions some of the other methodologies that are used for sustainability assessment, but that were considered as either more limited or specific to be included along with the one selected.

<u>Risk Assessment (RA)</u>

RA deals with consequences and magnitude of events (e.g. equipment malfunction resulting in chemical substances release affecting environment or resulting in human casualties) and their probability of occurrence. It focuses on the sequence of events that can lead to an accident, evaluating the elements that can malfunction. Techniques used are Event Tree Analysis (logical evaluative process) and Fault Tree Analysis (deductive investigatory process). RA also includes dispersion studies to assess the concentrations and exposure levels (exposure assessment) and effect on local environment (through dose-response and hazard assessment).

Material Flow Analysis (MFA)
It focuses on the environmental dimension of sustainability. It constitutes the systematic accounting of the material flows and stocks of a specific material within an economy. It is related to LCA since it provides the balance of materials used and traces back all the processes involved in their production. A difference lies that MFA usually focuses on a specific material, while LCA aims to be as complete as possible in terms of substances tracked. Furthermore, MFA quantifies the resource productivity of an entire economy and it is not suitable to analyze specific processes.

Substance Flow Analysis (SFA)
It is similar to MFA with the difference lying in the application to specific chemical substances that might be of interest for a specific region and input to policy to control its use in an economy. It can be integrated with LCA to be able to track the substances along its life cycle and be able to determine the most effective measures to control its flows.

Exergy Analysis (EA)
Exergy is a measure of the quality of energy and can be used to identify inefficiencies in a process. The concept is scalable and can be broaden to a system or supply chain. Therefore, it can be used to reduce the energy consumption (and more efficient use of resources) for the production of a good or service looking at its life cycle. A limitation lies in the application to non-energy systems.

Environmental Extended Input-Output Analysis (EEIOA)
It uses as basis the input-output concept of macroeconomic models, where all the economic flows are tracked through the different sectors. It can either associate factors to relate emissions, energy, materials, land, among others to the economic flows or alternatively, have parallel matrixes with such flows to be able to track them through the economic activities. It has the advantage of tracking a product through its entire life cycle since it includes the entire economy and the disadvantage of only including the economic flows that are traded in markets and therefore excluding externalities.

Eco-efficiency analysis (EE)
It is an upcoming methodology still in its early stages that uses the ratio between an environmental impact and a financial variable. It can be used for monitoring and benchmarking. It does not have clear guidelines and standards yet and there is a variety of methods for including impacts and weighting among them.

Full cost environmental accounting (FCEA)
It traces direct costs and allocates indirect costs of the possible social, economic and environmental consequences for a proposal. FCEA includes all the costs throughout the product life cycle including: investment, operation, subsidies, externalities, indirect, overhead and past investments in development.

SROI (Social Return on Investment)
It is a similar technique that aims to extend the economic evaluation to the environmental and social aspect relative to the resources invested. Not all the aspects have to be monetized and the numerator includes: monetized, quantified but not monetized, qualitative, and narrative types of information about value.

A difference between SROI and SCBA is that SROI is meant for companies, enterprises and private investors while considering environmental and social aspects, while CBA is originated from social sciences and meant to evaluate social welfare change.

2.6 Link between methodologies

EIA can serve to identify all the possible impacts that a project, proposal or new technology can have. These are useful for CBA since the latter also involves listing all the possible effects the same project should have. CBA in turn can be used for EIA as a tool to provide a ranking for the options and impact. A difference is that EIA will focus on the effects (in order to mitigate them) and alternatives, while CBA focuses on quantifying the change in the welfare of society with the execution of the project. LCA has the advantage of considering the full cycle and all possible consequences of the process activity. However, it is more difficult to take its output, which is already in pre-defined impact categories and single out the individual effects it can have as input to the CBA. LCA and EIA are not necessarily mutually exclusive and its combination has proven useful [38]. CBA can be a tool to expand the LCA beyond the environmental component and include the economic and social aspects by using monetary terms as the common parameter to evaluate trade-offs. MCDA is a broader concept particularly useful when there are factors that are hard to monetize, uncertain, unclear or when multiple policy objectives are being pursued. The relation between the different methodologies is conceptually shown in Figure 2-3.

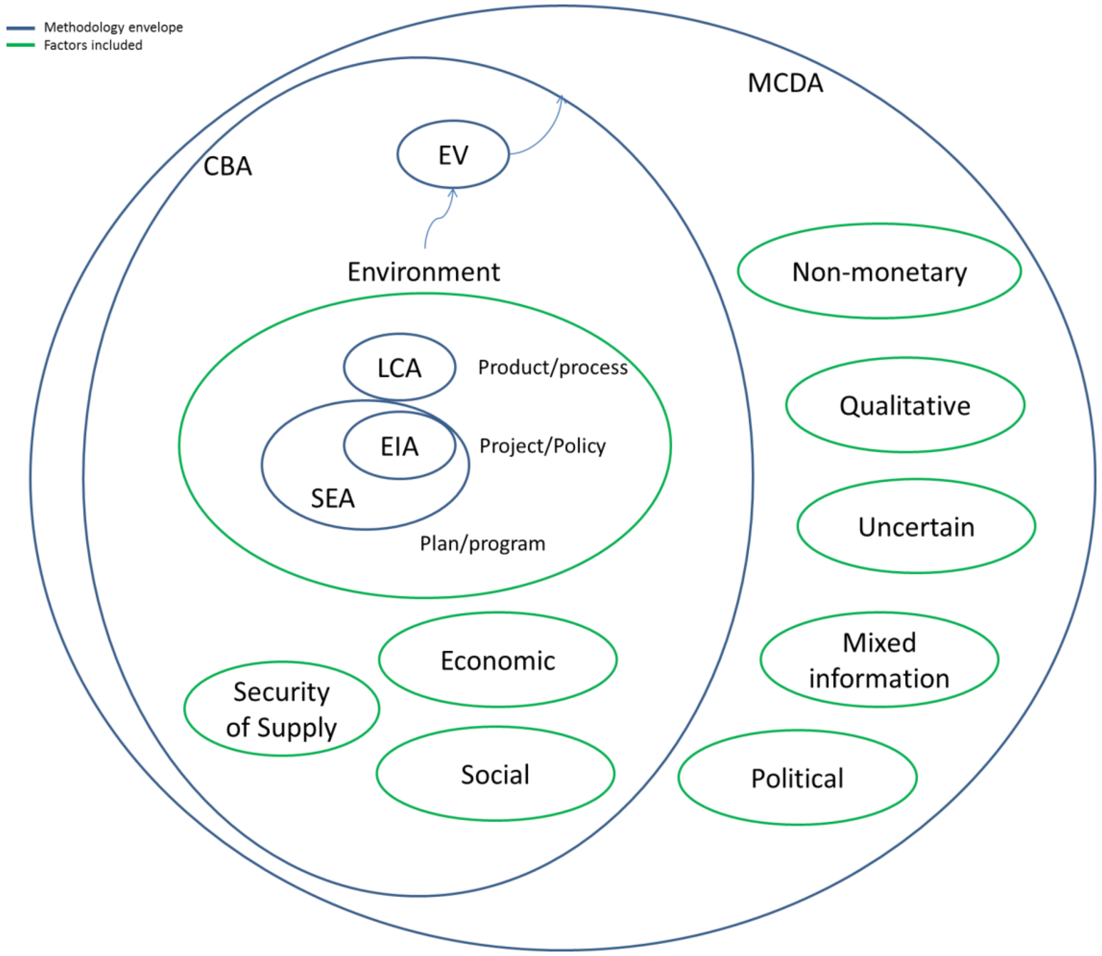

Figure 2-3: Scope and relation between methodologies related to environmental impact assessment

LCA represents a suitable methodology to perform the environmental assessment. It is a robust and proven methodology that has been used in the past to provide the environmental dimension in exercises using MCDA and covering all the aspects of sustainability assessment for energy systems [43], industrial systems [40] and technologies [44]. It is more complete that for example MFA, SFA or exergy analysis, by looking at the entire life cycle of the process, while still focusing on the environmental aspect and leaving the sustainability dimension to another method.

Some problems of using LCA as input to CBA are: the benefits and costs quantified by CBA will be dependent on the specific location, while LCA can be location-independent; LCA usually does not cover process and technology changes in time that could change material and energy flows, while

CBA uses discounting to consider the variation in time. An alternative to overcome these limitations is to use LCC, which can be done in parallel to LCA (same scope, boundaries, definition of functional unit) and ensure consistency. However, LCC only addresses the cost component without quantifying the benefit and lacks a standardized methodology.

To tackle some of the LCA limitations, a sensitivity analysis can be done. Global sensitivity analysis (GSA) has been used in the past to establish the ranking of input parameters having an impact on the LCA results and where recent developments have been achieved [45].

3 Monetization of environmental impact

The conversion of the environmental impact to monetary terms allows the weighting with the benefits or costs from the activity, the inclusion in the project evaluation and comparison with its profitability. Furthermore, it uses a relatable unit to express a harder to grasp impact (i.e. it is easier to relate to "the activity incurs a cost of 100 k€ due to health damages on local population" than to "the activity affects the health of local population"). It also allows extending the envelope of analysis from the process to the entire environment to account for the change in society welfare and to be able to make the trade-offs between the overall benefits and costs for the society. Finally, it allows comparing alternative technologies that satisfy the same need. On the contrary, it carries the disadvantages of a possible high uncertainty of the numbers and the need to quantify the impacts for every specific set of local conditions (e.g. distance to population, population vulnerability).

The remaining of this section is organized in three parts. The first one gives a general introduction to methodologies to assess the monetary valuation. The second one applies these techniques to the environmental aspect. The last one goes through the range of methods to monetize the output of LCA along with some of the values used for this, which are captured in Appendix 4 and Appendix 5.

3.1 Economic Valuation

This is used in combination to the environmental impact (either EIA or LCA) to quantify the full impact of a decision and be able to make trade-offs with the other aspects of sustainability. Value is a measure of the benefits derived from natural resources. This value can be split in (see Figure 3-1):

1. Use value. This can be direct use (utility for consuming a good), indirect (benefits from a secondary activity or externalities) and option (value people give to having the option of using something in the future, even though that might never happen).
2. Non-use value. These are also referred as passive use values and are not directly related to the use of the resource or service, but derived from the knowledge that a resource is preserved. This can be existence (value for knowing something exists, even though it will never be seen or used), altruistic (based on the benefit it might provide to other people and not necessarily the individual) and bequest (value placed on preserving a resource for future generations).

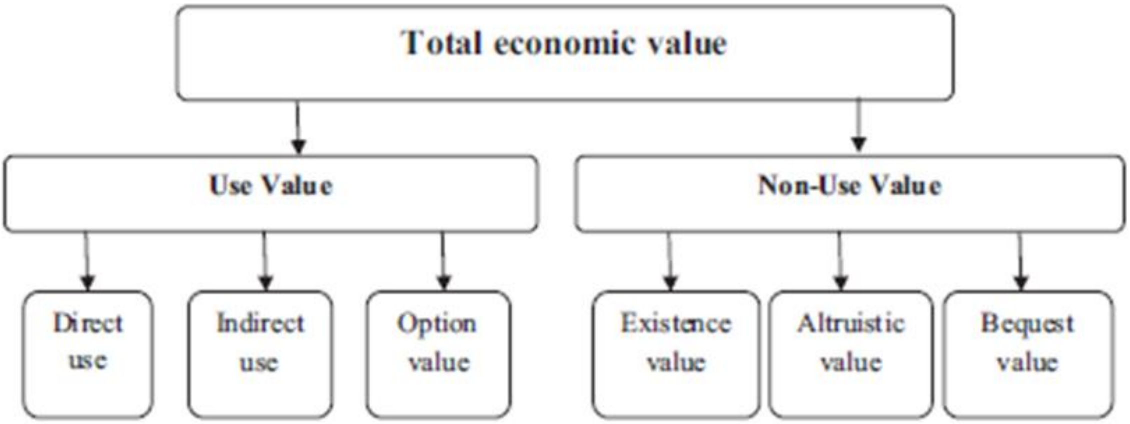

Figure 3-1: Methods to assess the economic value of goods and services (taken from [46])

Some of these categories are not tradable in a market and cannot be directly related to the price of a good or commodity. Even for the ones that have a market price, it might not represent the value as this price is only the maximum amount the people are willing to pay.

The value of a good or service can be translated to the willingness of a consumer to pay (WTP) for it (when the consumer receives a benefit and is willing to give up money in exchange for such benefit) or alternatively the willingness to accept (WTA) a loss or a consequence of the activity (when it has a negative impact).

It has to be noted that the WTP does not constitute the value of the entire good or service, but instead it quantifies the value in marginal changes of the good or service. Therefore, a WTP related to human health quantified in Quality Adjusted Life Years (QALY) does not represent the value of a human life, but instead the value assigned to marginal changes in the years of life [47].

Methods to determine these values can be in turn divided in:

1. Revealed preference. It uses market data on tradable goods and services to approximate the value of non-market goods. It is called revealed because choices made by consumers in real markets give information about their preferences. It is sub-divided in:
   - Market price. For services and goods that are traded in a market and assuming proper functioning where prices reflect consumer preferences and production costs. A limitation is when there are market failures (tax, subsidy, imperfect) and the prices do not reflect the real value.
   - Cost-based. Uses the production cost (i.e. land rent, wages, capital and interest paid) as approximation of the value of the good. It can also refer to avoided cost (costs incurred in the absence of the ecosystem), replacement cost (for replacing ecosystem with artificial technologies) or mitigation cost (for losing the benefits and services of the ecosystem).
   - Hedonic pricing. Value change as an unintended consequence of a change in the environment (e.g. value of houses in an area where a power plant was constructed).
   - Travel cost. Used for ecosystems that provide recreational services, distance labor has to travel to their work or value for infrastructure (e.g. roads). These have in common that value is approximated by the money a consumer will spend to travel to the location.
   - Averting behavior. Value of a non-market good is approximated by the expenses incurred for market goods that are needed to prevent or offset the change in availability of the non-market good of interest.
2. Stated preference. Consumers give explicit information about their preferences through surveys or hypothetical situations. It is preferred when there is no market data directly available or inferred. It is the only way to estimate non-use values. It is sub-divided in:
   - Contingent valuation. Questionnaires to ask people the WTP to increase or enhance the provision of a good or services.
   - Choice modeling. Presents a set of choices with different attributes and prices in order to evaluate trade-offs among the attributes.

An alternative to the above is benefit transfer, which is not a valuation method itself since it uses the value determined in another study and corrects it for location. It is usually used for non-market goods.

3.2 EV applied to environmental assessment

A common application is to use economic valuation to incorporate externalities for the environmental impact in the market price. Externalities can be associated to air pollutants, greenhouses gases (climate change), water use and quality and land use values, among others. An early review by EIA (Energy Information Administration, US) [48], specifically for power generation, identified that there was not a consistent classification and proposed one of their own covering:

- Qualitative treatment. Description of impact during decision-making process
- Weighting and ranking. Scores based on importance within a category
- Cost of control. Abatement cost, current and foreseen for future regulations
- Damage function. WTP of individual to avoid damage
- Percentage adders. A multiplier added to the avoided cost
- Monetization by emission. Use of a € per unit of emission usually imposed by a regulatory body

- Multi-attribute trade-off analysis. Defines a set of attributes to measure key issues and evaluate across a set of competing strategies

The broadest exercise of quantifying externalities across EU is the ExternE project. This is the main international reference for monetary valuations of environmental burdens related to the energy sector [49]. Its objective was to quantify the externalities. External costs (negative externalities) arise when the consequences of an activity impact another group and these are not (fully) accounted for or compensated in the evaluation of the original activity. The monetization of the external effects occurring as environmental impacts leads to the internalization. Therefore, they constitute the costs associated to environmental damages that are not reflected in the market prices of commodities and services [50]. This methodology was developed more than 10 years ago (2005), includes health impact (which has the largest contribution), agriculture (crops), ozone formation, ecosystems, accidents (public risk) global warming, energy security. The approach followed was the impact pathway, which includes quantifying the emissions, analyzing the dispersion in the environment, concentrations that reach the agents, use of the dose-response relation to estimate the consequences and convert those responses to monetary values based on the preferences of the individuals affected. In some cases, either the assessment of all the physical pathways would be too cumbersome (e.g. global warming) or the valuation step cannot be made based on the agents affected (e.g. acidification, eutrophication). Hence, shadow prices have been used to account for the impact on these categories (rather than the impact pathway approach). Impacts like employment and depletion of non-renewable resources are not included since they are considered internal costs rather than external.

The external costs especially if they should be evaluated site specific are not well-studied. These can be calculated by first establishing the link between activity-emissions, emissions-impact and impact-monetary consequences (compensation, mitigation, damage, remediation or abatement). The comparison between an affected (polluted) and non-affected area can be done.

The ExternE methodology follows similar steps of the methodologies explored in the previous section:

- Definition of the activity and scenarios
- Specify the impact categories and externalities
- Estimation of the effects of the activity (in physical units)
- Monetization of those effects
- Assess uncertainties
- Analyze results and draw conclusions

An output of the project was an online tool (EcoSense[3]), which allows assessing the dispersion and exposure processes for single point sources. It differentiates the impact on a local (50 km around the emission source), regional (Europe) and northern hemispheric scales.

EV is particularly useful to quantify the non-market services of an ecosystem. For non-use values (see Figure 3-1), the stated preference is the only set of methods that can be used. Similarly, they have the advantage of having a higher level of abstraction and being applied to non-specific contexts, as opposed to revealed preferences which are usually case, space and time specific [47]. A further category used for environmental impact analysis is budget constraint [51], which determines the WTP of a marginal value of QALY based on the potential economic output per capita per year.

EV can be linked in different ways to the output of the environmental assessment. When EIA is used, the impact over the environment (step 4 in EIA) can be valued through revealed and stated preference methods. Alternatively, the services and benefits provided by the system being evaluated can be listed to value them. Another approach is to quantify the impact of the process through the use of indicators addressing the three dimensions of sustainability (environmental, economic, social) and then these can be translated to value using externalities (chain of consequences and impact for engaging in activity). Considering the environmental cost along with the economic and social cost,

[3] http://ecoweb.ier.uni-stuttgart.de/EcoSenseLE

ensures that the opportunity costs for the production activities are also included, leading to a resource allocation with all the aspects and ensuring the change over the natural capital is also captured.

The estimation of externalities involves the process of assessing the consequences of an activity for a specific location. Similar to EIA, where emission concentration, dispersion, media, receptors and dose-response behavior will affect the environmental impact, the economic valuation will depend on each of these factors as well. Therefore, EV usually has to be conducted in parallel to the EIA to ensure consistency.

EV can be used to quantify the consequences of the activity on human health. VOLY (Value of Life Years Lost) which represents the number of life years lost due to premature deaths is used for the mortality component, while COI (Cost of Illness), which covers all the direct and indirect costs associated to diagnosis and cure (or death) due to a specific illness, is used for the morbidity. Similarly, EV can be used on the resources side to quantify for example what is the value associated to a cubic meter of water a process uses or land that is now used for biomass production instead of farming. The use of EV to extend LCA to LCC usually includes the latter, but not necessarily the impact over the different agents.

For EV, there should be a distinction between function of the system, services provided and possible benefits obtained. First, the biophysical impacts should be calculated to then establish the benefits and proceed to value them.

3.3 Methods to monetize LCA impact

The efforts of the ExternE project were continued in the NEEDS project[4], which ultimate objective was to evaluate the full (direct and external) costs and benefits of future energy systems for individual countries and for the EU as a whole. For this, the integration between LCA and monetary valuation was done as input to policy formulation and scenario building. Further differentiation was done by the CASES project[5], which differentiated the economic impact of metals depending on the medium of dispersion (air, water, and soil) and included the environmental impact evolution in time until 2030. Therefore, the combination of these tackled two key limitations, which are spatial (including the impact per country in EU) and temporal (by including the improvement in technology performance in time) segregation.

There is a mismatch between LCA and ExternE/NEEDS in the number of pollutants that are considered and the number of impact categories. As an example, CML methodology (see section 2.2 for explanation) has around 2000 substances grouped into around 100 impact categories. On the other hand, ExternE methodology only considered 12 pollutants (mostly based on particulate matter, SO_2, NO_x and VOC) focused on 4 categories (human health, biodiversity, agricultural crops and global warming), which was extended to 32 and 4 respectively for NEEDS. This is caused by the large amount of work involved in quantifying the emissions, impact and response of emissions, which will be greatly increased by expanding the database. As an example, to cover the external costs for mostly power generation technologies, NEEDS used the equivalent of 1075 man months from 80 different institutions, with a cost of over 11.3 million€ and executed over 4 years. Therefore, in spite of still being limited in its scope compared to the richness of LCA, it still constitutes one of the most widespread sources for monetization of environmental impact. The cost for pollutants and different impact categories is shown in Appendix 4.

This methodology has already been used to incorporate the LCA component in power cost optimization models on a national [52–54], European [55] and global level [56]. Noting that using damage cost functions is only one of the ways of incorporating the environmental impact into this type of models (the other ones being additional constraints and multi-objective optimization, see section 2 for further details).

[4] New Energy Externalities Developments for Sustainability, http://www.needs-project.org/
[5] Cost Assessment for Sustainable Energy Systems, http://www.feem-project.net/cases/

The above projects are focused on health impact and air pollutants. This is a restriction in scope, but can also constitute an advantage. These numbers can be used to translate pollutants emissions to monetary impact regardless of the source or technology producing them. Therefore, the numbers have been mostly applied to the energy transition in the power sector, but can be also used to technologies in transport or industry. For the case of heating, it is partially covered in CASES, where CHP were included as part of the scope. Unfortunately, district heating constitutes less than 10% of the total heating demand in the EU [57]. Therefore, externalities associated to resource extraction and production of resources used for heating (e.g. NG production) would not be included if such numbers are used. Similarly, externalities for the end use of the commodities and for the energy transformation to satisfy needs (e.g. heat pumps, boilers or industry that do not produce these pollutants but affect the environment through other mechanisms) would not be captured.

An alternative approach to assigning the externality to a specific pollutant is to assign the externality to an impact category. This is the approach for LCA methods that used weighting for the trade-offs among categories and constitute the source for the methods highlighted below (except for ISO). These constitute alternatives to ExternE.

1. International Standard Organization (ISO)

ISO 14008 (Monetary valuation of environmental impacts and related environmental aspects), will be published in late 2018. However, it is not intended to provide a step-by-step guidance on how to carry out the monetary valuation, but instead to provide the framework and common terms in the field to build such guides in the future and provide more transparency and clarity into the items to be covered. A related standard is ISO 14007 (Environmental management: Determining environmental costs and benefits – Guidance), which provides guidance to organizations on determining and communicating the environmental costs and benefits or their activities. The standard cannot be used for conformity assessment. The first working draft was available in June 2017 and the standard is expected to be published in 2019.

2. Environmental Priorities Strategies in product design (EPS)

It was one of the first monetization methods developed in the 1990s and with the latest development published in 2000 (EPS2000). It uses 15 impact categories grouped into 4 damage categories (human health, ecosystem production capacity, abiotic stock resources and biodiversity) using monetary units as weighting variable. It derives value from the WTP to avoid changes in present state of the environment and has the damage cost per unit of impact. A later update was released in 2015 with two versions (excluding and including climate impacts for secondary particles). The reason for the split in these two versions was the uncertain but important valuations of near-term climate forcers (NTCF) such as Nitrogen oxides (NO_X) and Sulphur dioxide (SO_2) emissions. The values for monetization are shown in Appendix 5, while a more detailed breakdown by indicator is available from the EPS website (downloadable files) [6]. Some examples of its application are the assessment of resource depletion for electric vehicles in EU, comparing it to other 7 methods [58], dairy production in Ireland [59] and materials use for low energy buildings in Italy [60], but in general the methodology has a global applicability [47].

3. Ecotax

It is based on environmental taxes for the impact categories in the CML methodology. The use of a tax assumes that, if optimally set, a tax should reflect the social value per unit of environmental intervention. It uses a range of values corresponding to the span of taxes and fees in Sweden (where it was developed). Values for the different categories are reflected in Appendix 5.

4. Stepwise2006

It combines the characterization step from two methodologies (IMPACT 2002+ and EDIP 2003). It aims to reduce the uncertainty and incompleteness of previous methodologies to increase its applicability to CBA. It has 15 midpoint categories grouped in 3 damage categories (human health scored in QALY or Quality Adjusted Life Yea, biodiversity scored in BAHY or Biodiversity Adjusted

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[6] http://www.ivl.se/english/startpage/pages/focus-areas/environmental-engineering-and-sustainable-production/lca/eps.html

Hectare Year and resource productivity directly in $€_{2003}$). A QALY is valued as 74000 € (assuming a person cannot spend more than the average income for a year) and a BAHY is valued at 1400 € (based on the fraction of the wellbeing people are willing to sacrifice to preserve the environment). Values for all the midpoint categories can be found in Appendix 5. The Stepwise2006 application provides values that are valid globally [47].

5. Life-cycle Impact Assessment Method based on Endpoint Modelling (LIME)

It was developed as part of a national Japanese project. It covers 11 midpoint and 4 damage categories (human health, social assets, biodiversity and primary production). The weighting factors were derived from a survey to 400 respondents on their WTP to avoid a unit of quantity of damage.

A review of the above methods specifically to LCA has been done before [47], where the most important elements are mentioned below:

- Most of the methods have been used to quantify negative (costs) externalities, disregarding positive effects.
- Market prices have limited use for LCA given that it is difficult to link the specific price of a good to the environmental impact. The most common application is for resource depletion, which can be subsequently extrapolated to midpoint.
- No applications of hedonic pricing and travel cost to LCA were found.
- Choice experiment allows making trade-offs between impacts rather than focusing on a single one. This replicates better the weighting exercise and it seems more suitable for LCA. It also allows decomposing an endpoint in multiple attributes and establishing the contribution of each one. This is particularly useful for complex endpoints.
- Value for the end point categories is determined through stated preferences in all methods, except for Stepwise2006 which uses revealed preferences.
- With respect to end points, LIME was developed for Japan, ExternE for Europe and Stepwise2006 is valid on global basis, leading to potential differences in the monetary valuation.
- Choice of the reference substance for a category can lead to differences in its monetary valuation due to difference between conversion factors and the monetary valuation.
- In terms of uncertainty, there is a range of 62000 - 84000 €/QALY and 25000 – 100000 €/VOLY (Value of Life Years Lost). In midpoints, the largest differences are a factor 4 for global warming and 2 orders of magnitude for human toxicity.
- Even with the same methodology, location and team, values can be different depending on the experiment setup. For LIME, the second version led to consistently higher values than the ones obtained in the first version.

Regardless of the method applied, it has been observed in previous exercises [50] that the uncertainty associated to the results is high (it can be up to 2 orders of magnitude difference) and there can a low correlation between methodologies [61], leading to different conclusions in the assessment, where in some cases, externalities can constitute more than 90% of the social cost of a service [50] discouraging its use, while in others [48] the introduction of externalities has limited effect on the technology choice. This can be on top of the uncertainty introduced by the characterization (fate and effect) and normalization steps of the LCA.

4 Review of existing literature on LCA of Power-to-gas

The objective of this section is to summarize insights from recent literature on PtG, understand the effect of assumptions on results and the comparison with both fossil references and among renewable options (e.g. hydrogen, methane and liquid fuels). This is covered by Task 5.4 of this project and this section provides an overview to ensure a smooth transition of the data for the SCBA analysis.

The number of studies dealing with LCA of PtG energy systems has been increasing in the last years. A major challenge is comparing results across studies. Due to methodological choices affecting LCA results, the comparability of results is sometimes hampered. Especially the choice of system boundaries, functional units, multi-functionality approach and assumptions concerning PtG performance (e.g. conversion efficiencies) are the major causes for differing results within existing scientific studies. Harmonization of Global Warming Potential for renewable hydrogen across 71 studies has already been done [62] and shows it is a possible solution to that challenge. Figure 4-1 provides the main output, where it is shown the wide range of results for GWP and high dependence on assumptions.

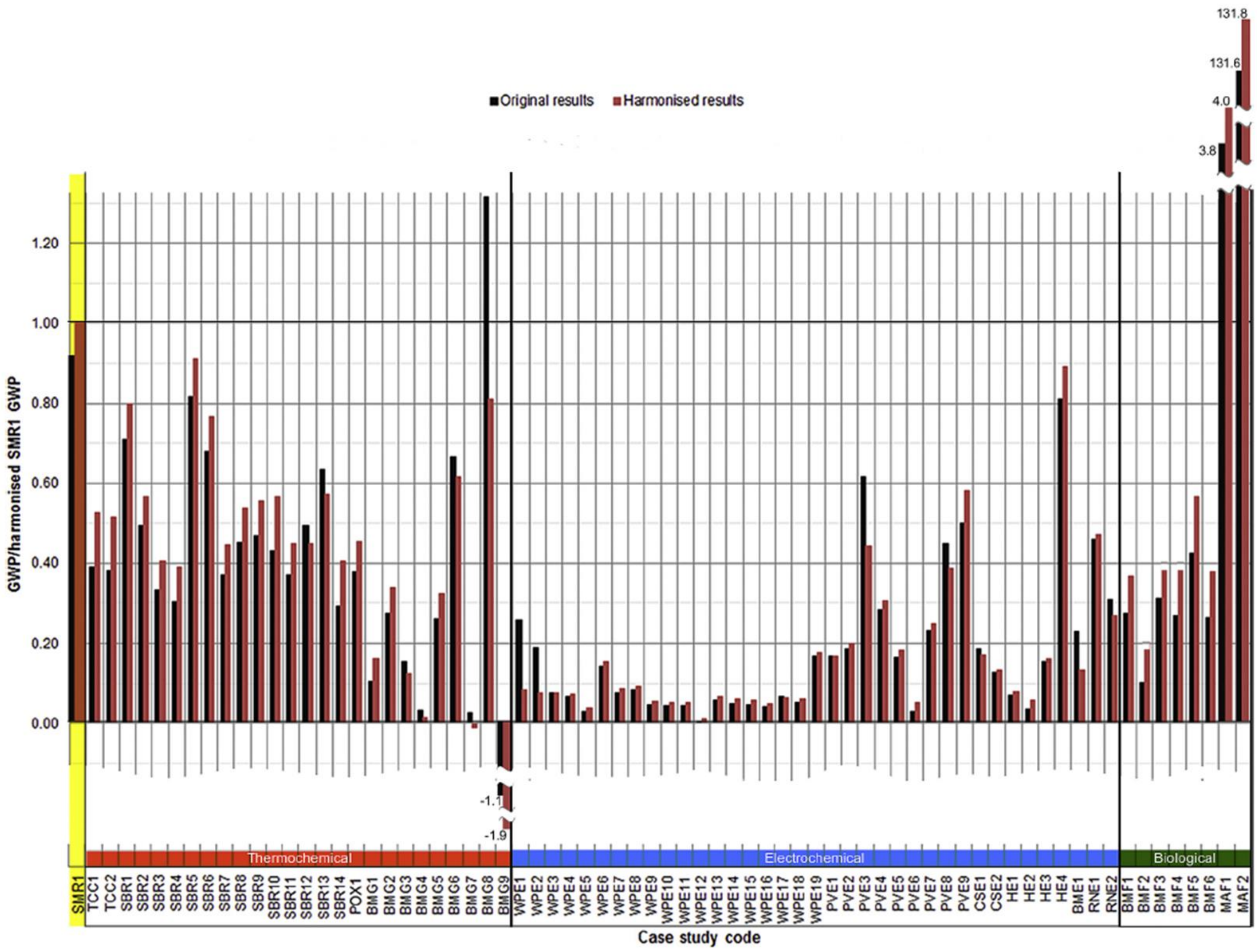

Figure 4-1: Original and harmonized GWP results of renewable hydrogen relative to the harmonized GWP of SMR hydrogen (produced by [62])

As Figure 4-1 shows, the lowest GWP among the PtG conversion technologies is found for the electrochemical process route operating with renewable electricity.

Before stepping into detailed LCA results of PtG systems some aspects of the system boundaries of PtG LCA have to be clarified. This is important as system boundaries are an important aspect in understanding and interpreting LCA results. Figure 4-2 shows the PtG system with its application pathways. Scientific literature on PtG LCA mostly focusses on H_2 and/or CH_4 production ending with the intermediate as energy carrier ("cradle-to-gate" LCA). Additionally there are some recent studies on the application of H_2 and/or CH_4 as a transport fuel ("cradle-to-use" LCA). There is a lack of detailed LCA studies focusing on using PtG derived H_2 for industrial applications and PtG derived CH_4 for heat or electricity generation.

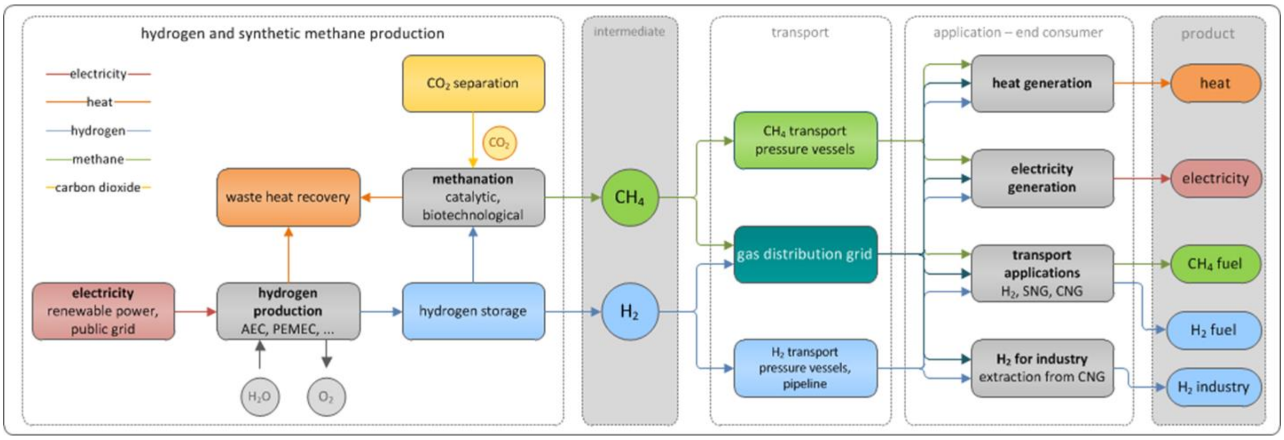

Figure 4-2: PtG system and system boundaries[7]

Boundaries should be as broad as possible to cover the consequences along the entire pathway and they also should be clearly defined since the results are dependent on these.

4.1 Recent LCA of power-to-methane

If H_2 from a PtG process cannot be used directly as an energy carrier – for example due to feed-in restriction in the natural gas grid – it may be used for synthesizing methane under the use of carbon dioxide. Synthetic methane has the advantage that it can be fed into the existing gas grid without any restrictions concerning volumetric shares as is the case for H_2. Depending on the specific case, synthetizing CH_4 may provide advantages for a regional or local energy system. From an LCA perspective the process system and accordingly the system boundaries have to be expanded; electrolysis is followed by CH_4 synthesis. For CH_4 synthesis CO_2 has to be separated – this process step has to be included in power-to-methane LCA too. The following results show that the CO_2 source is crucial to achieve an environmental benefit of synthetic methane compared to natural gas.

Previous work [63] compares alternative routes for syngas and methane production (reverse water gas shift, dry reforming and methanation). Results show that PtG is the option requiring the lowest electricity footprint to be more attractive than the fossil reference (natural gas production). Global warming threshold is 82 gCO_2/kWh. If partial operation is considered (larger contribution of equipment and construction phase), the allowance decreases to 48 gCO_2/kWh. If it is above these values, PtG will result in a net increase of global warming impact. To put this number in perspective, average grid footprint for EU has decreased from around 440 gCO_2/kWh in 2006 to 350 gCO_2/kWh in 2015[8], while renewable options can be 40, 130, 190 gCO_2/kWh for wind, solar and biomass respectively [64]. This translates into either low number of operating hours (to operate purely with wind and solar and having preference for the former) or an increase of GHG emissions, which goes against the purpose of the technology.

Various sensitivities were done with process efficiency, penalty for CO_2 capture and credit for by-products. When the reference case is that CO_2 (from a coal plant) is stored underground, but instead is used as feed for PtG, the electricity threshold is negative (meaning there is no case, not even with

[7] This figure was produced for the "wind2hydrogen" project, which is currently finished at the Energy Institute at the Johannes Kepler University Linz. "Wind2hydrogen" is a research project funded by the Austrian Klima- und Energiefond (KLIEN), project number: 843920. The project results are not publicly available.

[8] Data for CO_2 from Eurostat [env_air_gge], Category: "Fuel combustion in public electricity and heat production" and data for electricity production from "Supply, transformation and consumption of electricity - annual data" [nrg_105a], Indicator: Total net production

100% wind feed to electrolysis, when PtG leads to GHG reduction). 14 impact categories were analyzed as part of the study, showing that PtG can provide a benefit for global warming potential and fossil depletion (with the thresholds of 82 and 40 gCO_2/kWh), for the rest of categories, PtG impact is similar to natural gas and much higher for ozone depletion, freshwater eutrophication and freshwater ecotoxicity (10000, 100 and 100 times higher respectively).

Carbon dioxide (CO_2) is an important input for the production of synthetic CH_4 via the PtG process route. CO_2 is produced in many combustion and production processes, can be separated from flue-gases, and used for CH_4 synthesis. In an LCA context especially the energy demand for CO_2 separation has to be considered as it causes additional greenhouse gas emissions. Figure 4-3 shows that the greenhouse gas emissions of synthetic CH_4 are strongly dependent on the CO_2 source. Nevertheless synthetic CH_4 shows a lower GWP compared to natural gas regardless of the CO_2 source. The only precondition is to use renewable electricity in the PtG process. Nevertheless using biogenic CO_2 source has to be recommended from a climate impact perspective [65].

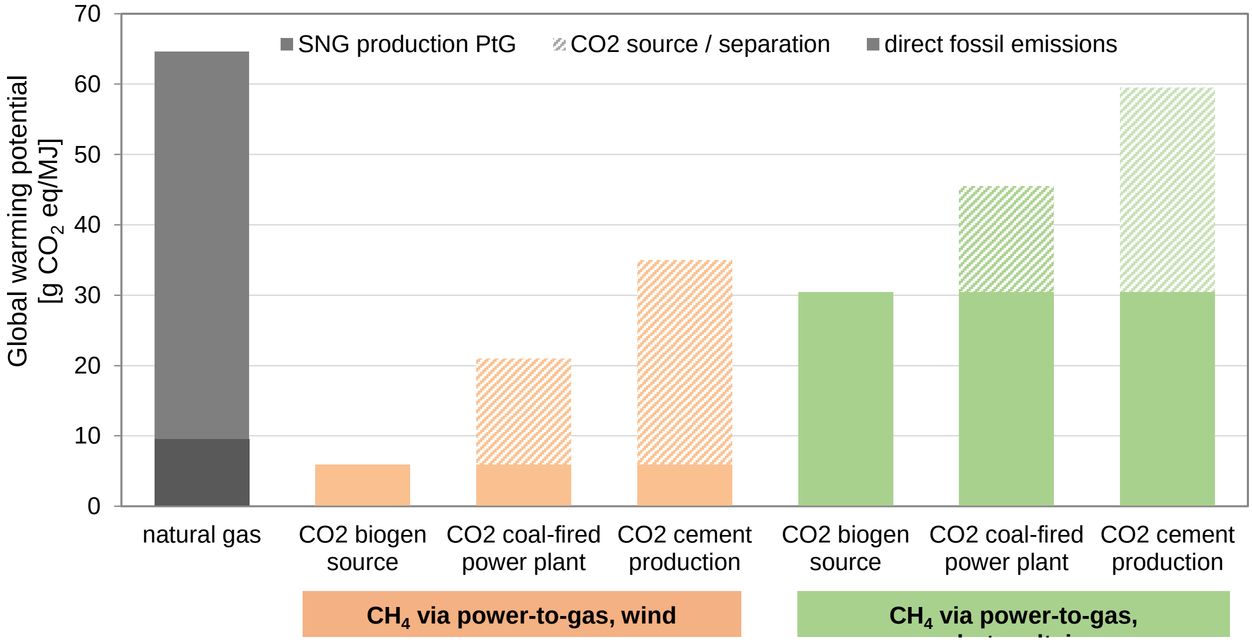

Figure 4-3: Global warming potential of CH_4 produced via power-to-gas with different electricity inputs compared to the benchmark technology steam reforming.

A different approach for accounting the impacts of utilizing different CO_2 sources for methanation is to use system expansion – "avoided burden approach" – which has already been used for LCA of synthetic methane [65]. This approach also accounts for the CO_2 mitigation achieved by CO_2 capture. As a result, for example, the cement production stage has to be included in the LCA approach for the power-to-methane system. The functional unit is 1 kWh electricity fed into electrolysis (wind or photovoltaics). The amount of CO_2 needed to synthesize CH_4 from the amount of H_2 corresponding to feeding in 1 kWh electricity to electrolysis is calculated to finally account for the corresponding amount of co-products originating from the CO_2 source (e.g. cement in the case of cement production as CO_2 source). Also the multi-functionality aspect is considered by applying system expansion, where it is recognized that electricity (or cement) are also products of the larger system. Results of this investigation are shown in Figure 4-4. It is shown that using the avoided burden approach for power-to-methane LCA leads to emission reduction in the majority of scenarios, except the scenario using PV in combination with CO_2 from a cement plant using electricity from hard coal. However, due to the large uncertainty in emissions associated to PV electricity, the net impact for the methane produced can be higher than the fossil reference, even when CO_2 from the atmosphere is used (see Figure 4-4). The scenarios applying wind power for electrolysis lead to the highest greenhouse gas savings compared to using natural gas in mobility applications [65].

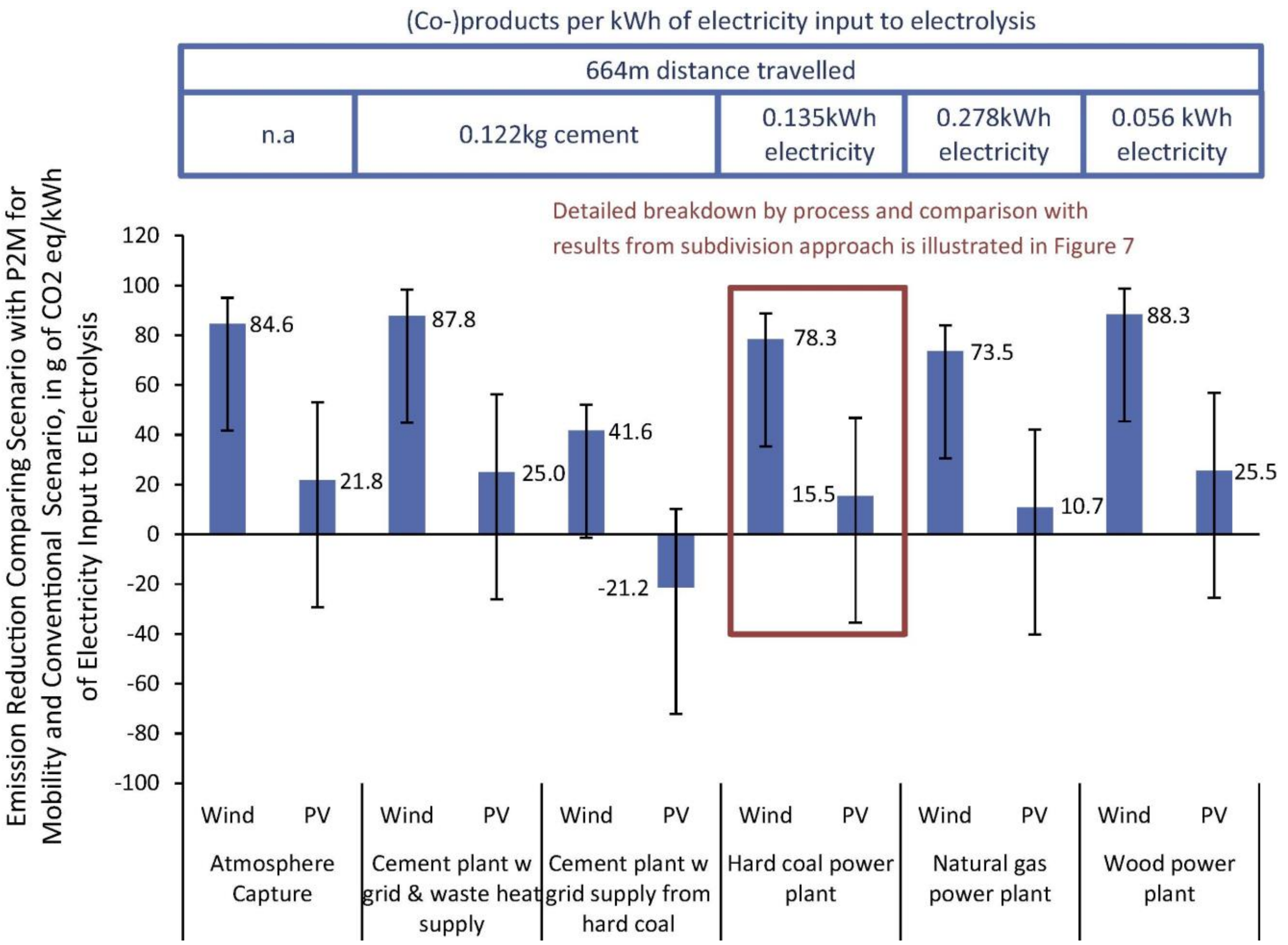

Figure 4-4: Power-to-methane for mobility application: Greenhouse gas reduction compared to natural gas and electricity/cement production without carbon capture (produced by [65])

An advantage of applying the avoided burden approach is to have a very systematic view on the potential environmental impacts of a power-to-methane system also beyond the energy system. A disadvantage is of course that interpreting the LCA results gets more complex and the results lack of comparability with other studies. Additionally, the system expansion approach is somewhat hard to understand for non-LCA experts.

Examining the climate impact of synthetic methane for mobility applications needs expanding system boundaries of LCA from “cradle-to-gate” to “cradle-to-use”. As a result vehicle and road construction are also included in the system boundary [65]. Results are shown in Figure 4-5. Although photovoltaic power is used for electrolysis in all displayed scenarios synthetic methane as fuel only shows greenhouse gas savings compared to natural gas as a fuel if biogenic CO_2 is used for methane synthesis [65]. Using renewable electricity and biogenic CO_2 are a precondition for achieving greenhouse gas savings of synthetic methane in the mobility sector compared to fossil reference. In this case, if CO_2 is from air or biomass, waste heat is used and hydrogen is produced with solar photovoltaics, the footprint for the methane produced and used in transport can be around 10% lower than the conventional gas supply (with an uncertainty of ~ –30 to +17%, see Figure 4-5).

Some limitations of the above study [65] are that the comparison was not done across carriers (e.g. comparing hydrogen and methane as competing alternatives for transport), no other potential technologies were used for hydrogen production (only methane reforming and electrolysis, but no reforming with carbon capture and storage that might be a potential low carbon option for the future) and that the alternative scenario where CO_2 is stored underground (instead of being released by e.g. a power plant) was evaluated.

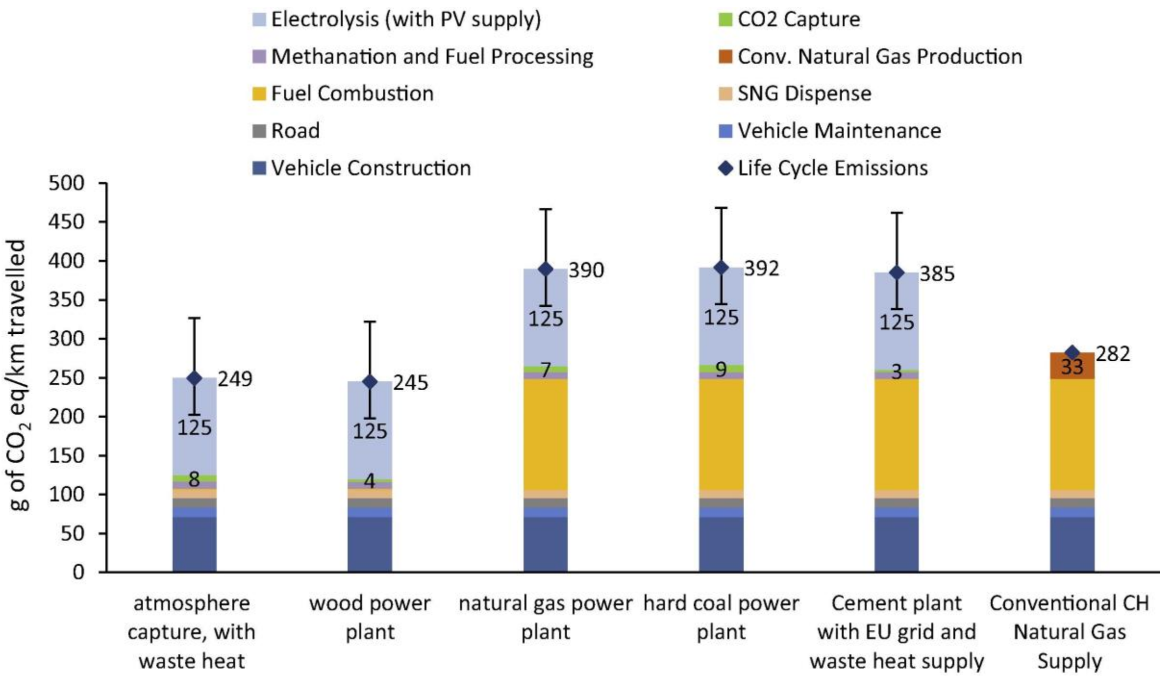

Figure 4-5: Greenhouse gas emissions of power-to-methane for mobility applications (produced by [65])

Another reference process to compare the environmental impacts of power-to-methane pathways is biogas upgrading pathways. A systemic approach is to connect PtG facilities with biogas plants in order to realize synergies – e.g. using electricity from biogas plant for electrolysis and/or using CO_2 from biogas purification for methanation. This evaluation has already been done [66]. Results show that upgrading biogas with PtG has lower GHG emissions (close to 50%) than the natural gas route. However, it was also shown that PtG has higher emissions than standard upgrading (with amines or membrane). This conclusion also applies when the electricity for hydrogen has a lower footprint (France used as reference). When evaluating end point impacts (human health, ecosystem, resources), results are even more pronounced in favor of standard upgrading (amine and membranes) that consistently performs better than PtG. A potential case where PtG can perform better than upgrading with amines is when amines are used and the captured CO_2 is processed with intermittent supply of electricity (composed by 80% renewable and 20% nuclear by 2050 in France).

Another reference study is [67]. Global warming potential of synthetic natural gas (SNG) is compared to fossil natural gas used in transport or chemical production. The research question to be answered is: is it better to use SNG for transport or chemical industry applications from a climate impact point of view? The authors conclude that SNG produced with wind power leads to greenhouse gas savings for both uses – either in the transport or chemical sector. This is based on the assumption of a credit for CO_2 use of -2.68 kgCO_2 per kg of SNG, which is almost equivalent to the stoichiometric use of CO_2 and equivalent of taking the net benefit of CO_2 which is in disagreement with suggestions from [68] that highlights this as one of the common pitfalls of CO_2 use. This highlights again the importance of system boundaries, where taking a limited control volume (such as in [67]) can lead to misleading conclusions.

4.2 Recent LCA of power-to-hydrogen

Although the STORE&GO project finally aims at investigating and demonstrating power-to-methane technology as future component of Europe´s sustainable energy system, environmental impacts of power-to-hydrogen have to be discussed here too as hydrogen is the intermediate for methanation. Important techno-economic aspects concerning electrolyzer technology can be found in e.g. [3]. A comprehensive work on the GWP of PtG systems was done by [69], where both power-to-hydrogen and power-to-methane routes are compared with their fossil reference systems. Different electricity sources were calculated to estimate the GWP of hydrogen. Figure 4-6 shows that H_2 from PtG systems is only favorable compared to the fossil reference processes if electricity from renewable sources are used. The use of the EU-27 electricity mix for H_2 production leads to higher greenhouse gas emissions than the fossil benchmarks of steam reforming natural gas or heavy oil. For H_2 production, an environmental break-even is estimated. This is the maximum specific GWP that the utilized electricity may have so that the H_2 produced shows still a lower GWP than the fossil reference system. The environmental break-even point has been calculated is 190 g CO_2 per kWh for H_2 production from power-to-gas [69]. The same study arrives to the conclusion that methane is only attractive (lower GWP than the fossil reference) if wind electricity is used for electrolysis and if CO_2 is obtained as waste product (no penalty for CO_2 separation). If any of these two assumptions is dropped, GWP for PtG is at least 3 times higher than the fossil reference (up to 5 times if PV is used and penalty for CO_2 capture is included).

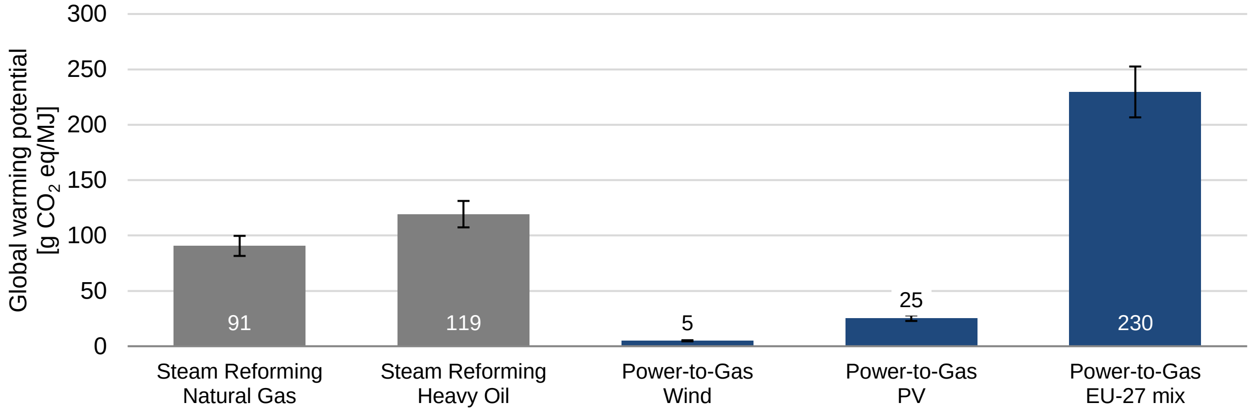

Figure 4-6: Global warming potential of H_2 produced via power-to-gas with different electricity inputs compared to the benchmark technology steam reforming (data from [69]).

The results presented in [69] are in line with findings in literature [70,71], where H_2 production using electricity from renewable resources leads to the highest greenhouse gas savings compared to steam reforming of fossil sources. Few studies consider the potential future option of steam reforming with carbon capture and storage.

One application of hydrogen is as fuel for transport. For an LCA examination the system boundaries have to be extended to support a “well-to-wheel” analysis. This means the entire production chain from the extraction of the raw materials via the processing and transport as well as the operation of the car (see Figure 4-7). For mobility uses, further reference technologies are relevant for the ecological assessment, including fossil fuels references. Additionally the material and energy demand for the production of the vehicle is taken into account.

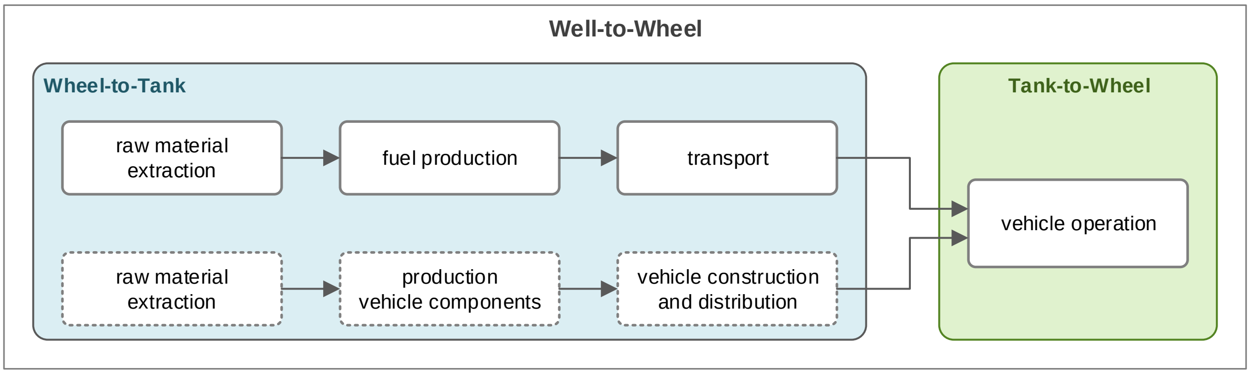

Figure 4-7: System boundary of a Well-to-Wheel analysis[9]

[9] This figure was produced for the “wind2hydrogen” project, which is currently finished at the Energy Institute at the Johannes Kepler University Linz. “Wind2hydrogen” is a research project funded by the Austrian Klima- und Energiefond (KLIEN), project number: 843920. The project results are not publicly available.

Figure 4-8[10] shows that the use of H_2 derived from a PtG plant in mobility applications leads to greenhouse gas savings compared to the fossil reference systems. Again, the most important precondition to achieve these savings is to use renewable electricity in the PtG plant.

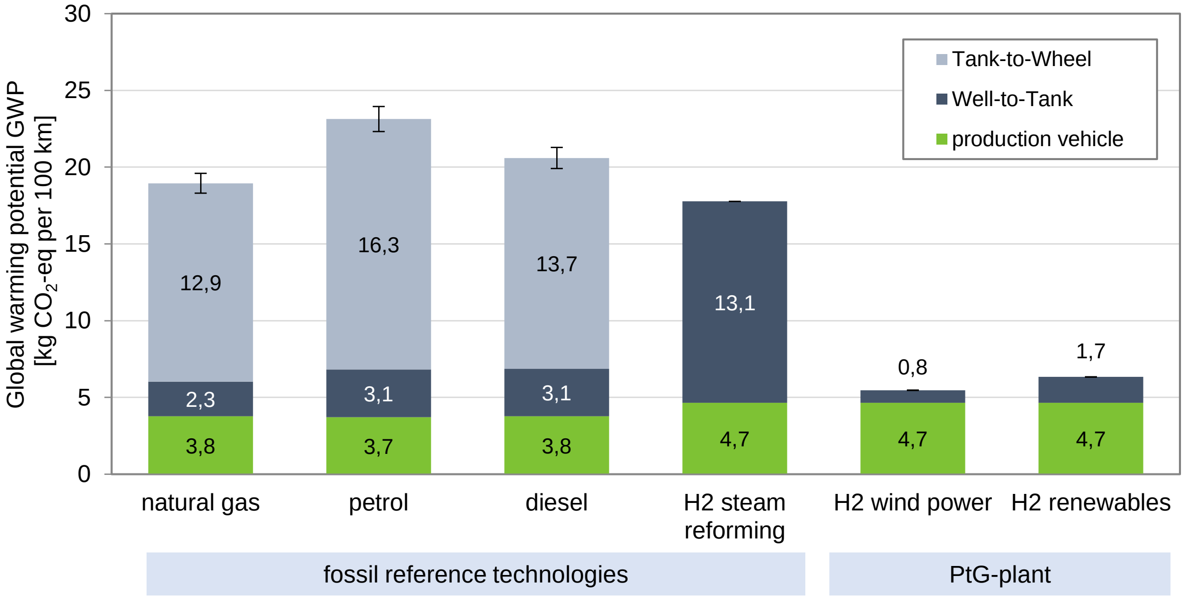

Figure 4-8: Results of the "well-to-wheel" analysis for hydrogen derived from PtG systems

H_2 from PtG plants used as fuel leads to greenhouse gas savings compared to diesel and gasoline [72]. An important aspect to maximize greenhouse gas savings is the load factor of the electrolyzer. It is necessary to ensure a sufficiently high load factor to maximize greenhouse gas savings compared to fossil fuels. However, high load factor can translate into a smaller installed capacity compared to variable generation capacity and the electrolyzer will not be able to absorb large amounts of energy in case it is used for grid stabilizing purposes. It is also recommended not to use excessive supplies and to operate the refueling station with renewable electricity to a large extent [61]. It was also shown that the cumulative energy demand for producing the hydrogen is higher than the energy available in the hydrogen produced (hydrogen contains 82% of the energy invested), whereas conventional oil has a ratio of 20 (20 times more energy in the fuel than the energy used for its production) [72].

Besides the scientific works investigating power-to-hydrogen and power-to-methane systems there are also investigations dealing with LCA of Power-to-X systems [73]. All of the Power-to-X options can lead to a greenhouse gas reduction compared to the fossil references [73]. In detail Power-to-X derived methanol shows a lower climate impact than its fossil reference product derived via natural gas synthesis (see also Figure 4-9). High greenhouse gas emission savings with Power-to-X routes can be achieved if the products are used in transport applications to replace fossil fuels. Another recommendable application from an LCA perspective is to use methane in gas engines for electricity production during peak consumption hours. Previous studies [74] have shown that looking at Power-to-X options, the best use (from an LCA perspective) is to satisfy heating demand (power to heat through heat pumps). This is followed by transport (electric cars), direct electricity storage (PHS, CAES, batteries) and the last alternative is the conversion to another energy carrier. Among chemical compounds, the largest benefit is through the conversion to hydrogen, followed by methane, methanol and syngas.

[10] Work by EIL as part of "wind2hydrogen" project funded by the Austrian Klima- und Energiefonds (KLIEN, project number: 843920). Project results are not publicly available

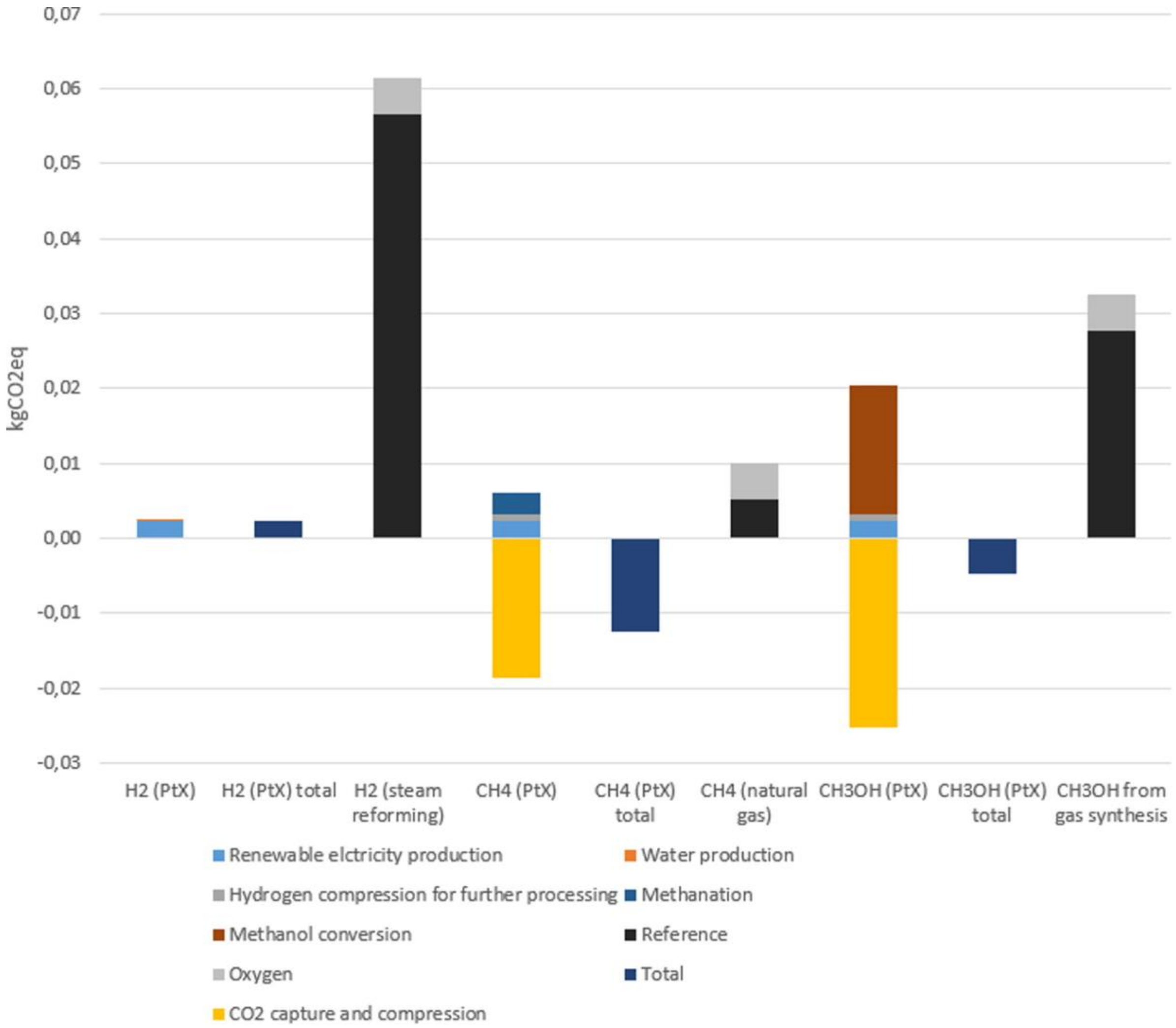

Figure 4-9: GHG emissions from H_2, CH_4 and CH_3OH production via Power-to-X process compared to fossil reference products (taken from [73])

In conclusion, PtG is examined from a life cycle perspective in various scientific studies. Although they differ according to system boundaries, process specific assumptions (e.g.: load hours, conversion efficiencies), functional unit, etc., the main conclusions from the LCA of PtG systems can be summarized as follows:

- The overall environmental impacts above all GWP of PtG applications is also strongly dependent on systemic aspects. It could make sense to use fossil CO_2 - e.g. from coal power plants - for methanation in a transition period despite the resulting questionable climate mitigation effect of synthetic methane [75]. It also has to be considered that CO_2 from cement industry or other industry sectors used for PtG applications has the potential to mitigate GWP in these sectors [75].
- In addition the state-of-the-art relatively low yields of methanation open up the systemic question of preferring surplus electricity from renewable capacities instead of constructing new renewable power plants especially for supplying PtG facilities [75].

The literature overview is just a brief glimpse of scientific discussion on the environmental impacts of PtG pathways. There has been focus on GWP, with only few studies [63,66,74] including other environmental impact categories, where other options seem to be more attractive than PtG. Further research on the other impact categories, across different pathways in a consistent way is needed to make a final statement on the sustainability aspect of the technology.

5 Conclusions

Some key conclusions that can be drawn from the information reflected in this report are:

- Decision making should be based on the three dimensions of sustainability. Therefore it is necessary to apply more than one method in order to account for the environmental, economic and social impacts an emerging technology has compared to the state-of-the-art technology.
- Especially for an emerging technology, it is crucial to have a look at the broader impact. Even if the technology does not prove to be economically viable today, it could be of societal interest to foster its implementation (e.g. due to lower environmental impacts).
- To facilitate comparison of trade-offs among dimensions, monetary terms can be used as common measure as part of a Social Cost Benefit Analysis (SCBA). For this, a stepwise approach is needed. First, the environmental impact is calculated and then it is monetized (through economic valuation).
- Several methods for environmental impact were assessed as part of this Deliverable and the suggested methodology for environmental assessment is Life Cycle Assessment (LCA). The step of Life Cycle Impact Assessment (LCIA) will provide the overall environmental impacts of the investigated power-to-gas pathways. This choice has been made given its standardized approach, wide coverage of activities and impact categories and availability of valuation figures. This is also in agreement with the output to be generated by Task 5.4 within STORE&GO.
- STORE&GO aims at depicting both: the impacts of the power-to-gas (PtG) technology itself and the integration of the technology in the existing or transforming (European) energy system.
- A review of LCA literature on PtG leads to the following conclusions (see Deliverable 5.1 for more detail):
  - Synthetic CH_4 from a power-to-gas system shows the highest greenhouse gas savings if biogenic CO_2 sources are used for methanation and if H_2 is produced via renewable electricity driven electrolysis.
  - Higher load hours for power-to-gas will lead to larger greenhouse gas savings.
  - Transport distance of the produced gas has a direct effect on the environmental impact. Longer transport distances require more energy for compression and subsequently higher greenhouse gas emissions.
  - If the CO_2 used for PtG was supposed to be stored underground, there is no electricity footprint that can make the option more attractive than the fossil option (a negative value would be required to make this route preferred).
  - If there is power surplus, the best use from an environmental perspective is to satisfy heating demand (power to heat through heat pumps). This is followed by transport (electric cars), direct electricity storage (PHS, CAES, batteries) and the last alternative is the conversion to another energy carrier.
  - Benefit for new technologies will highly depend on the reference processes and assumptions used.
  - A more thorough assessment of PtG impact in categories other than global warming is needed.

For STORE&GO, based on the assessment presented before, the suggested approach is:

- Task 5.4 assesses the environmental impact through the use of LCA. The impact will be available both for the technology with different configurations (from the demo sites) and including the broader consequences in the rest of the energy system (with TIMES). All the possible substances emitted will be reduced to 15 impact categories and further to only 3 end-point indicators (human health, ecosystems and resources) and a range of values based on the approaches can be provided as input to the SCBA to be evaluated as sensitivities.
- The impacts can be monetized using Stepwise2006 methodology. It is selected for being one of the most complete methodologies in terms of impact categories, geographical scope, data availability and applicability. Values have been captured in Appendix 5. Values should be taken with caution and sensitivities be developed around it, since there is high uncertainty associated to the numbers. Values are for midpoint categories (not endpoint).

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Appendix 1. Information included in different LCIA methods

METHODS	Acidification	Climate change	Resource depletion	Ecotoxicity	Energy Use	Eutrophication	Human toxicity	Ionising Radiation	Land use	Odour	Ozone layer depletion	Particulate matter/ Respiratory inorganics	Photochemical oxidation
CML (baseline)	✓	✓	✓	✓	-	✓	✓	-	-	-	✓	-	✓
CML (non baseline)	✓	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	-	✓
Cumulative Energy Demand	-	-	-	-	✓	-	-	-	-	-	-	-	-
eco-indicator 99 (E)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	-
eco-indicator 99 (H)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	-
eco-indicator 99 (I)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	-
Eco-Scarcity 2006	-	-	✓	-	-	-	-	-	-	-	-	-	-
ILCD 2011, endpoint	✓	✓	-	-	-	✓	✓	✓	✓	-	✓	✓	✓
ILCD 2011, midpoint	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (E)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (H)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Endpoint (I)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (E)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (H)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
ReCiPe Midpoint (I)	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓
TRACI 2.1	✓	✓	✓	✓	-	✓	✓	-	-	-	✓	✓	✓
USEtox	-	-	-	✓	-	-	✓	-	-	-	-	-	-

Table 1: Availability of impact categories per method. ✓ represents that the impact category is contained in the correspondent method and - that not.

Taken from [76]

Table 1 Pre-selection of characterisation models for further analysis [3]

	Climate change	Ozone depletion	Respiratory inorganics	Human toxicity4	Ionising radiation	Ecotoxicity	Ozone formation	Acidification	Terrest. Eutrophication	Aquatic Eutrophication.	Land use	Resource Consumption	Others
CML2002	O	o		M	o5	o	M	M	M	M	o	M	
Eco-indicator 99	E	E	E	o	o		E	E	E		E	E	
EDIP 2003/EDIP97[6]	O	M	o	M	o	M	M	M	M	M		M	Work environ-ment Road noise
EPS 2000	E	E	E	E	o	E	E	o	o	o	E	E	
Impact 2002+	O	o	E	M E	o	M E	E	M E		M E	o	E	
LIME	E	E	M	E		o	M E	M E	o	E	E	E	Indoor air
LUCAS	O	o		o		o	o	o	o	o	o	o	
MEEuP	O	o	M	M		M	M	M	M	M		water	
ReCiPe	M E	E	M E	M E	o	M E	M E	M E	o	M E	M E	E	
Swiss Ecoscarcity 07	O	o	o	o	M E	M	o	o	o	o	M E	water	Endo-crine disrupt-tors
TRACI	O	o	M	M		M	M	M	o	M		o	
Specific methods to be evaluated	Ecological footprint		7	USETox		USETox		Seppälä		Payet	Ecological footprint	deWulf et al.	Noise Müller Wenk
Specific methods of potential interest (not to be evaluated)				Watson (Bachmann)	Ecotoxicity of radiation (Laplace et al.)		EcoSense (Krewitt et al.)	EcoSense (Krewitt et al.)		Kärrman & Jönsson	8		Meijer indoor air UNEP Indoor air (Bruzzi et al., 2007)

o: Available in the methodology, but not further investigated
M: Midpoint model available and further analysed;
E: Endpoint model available and further analysed

[3] It has to be noted, that not all existing methods used in LCIA could be covered in the analysis but the focus has been on the ones which were identified as most relevant for current best practise in LCA.
[4] Cancer and non cancer effects sometimes taken separately
[5] Optional study specific impact category
[6] EDIP97 for resources, EDIP2003 for the other impact categories
[7] EcoSense, Greco et al., UNEP (Potting et al.)
[8] Bos & Wittstock, 2007, Ertzinger, Milà i Canals, Stan Rhodes

Taken from [34]

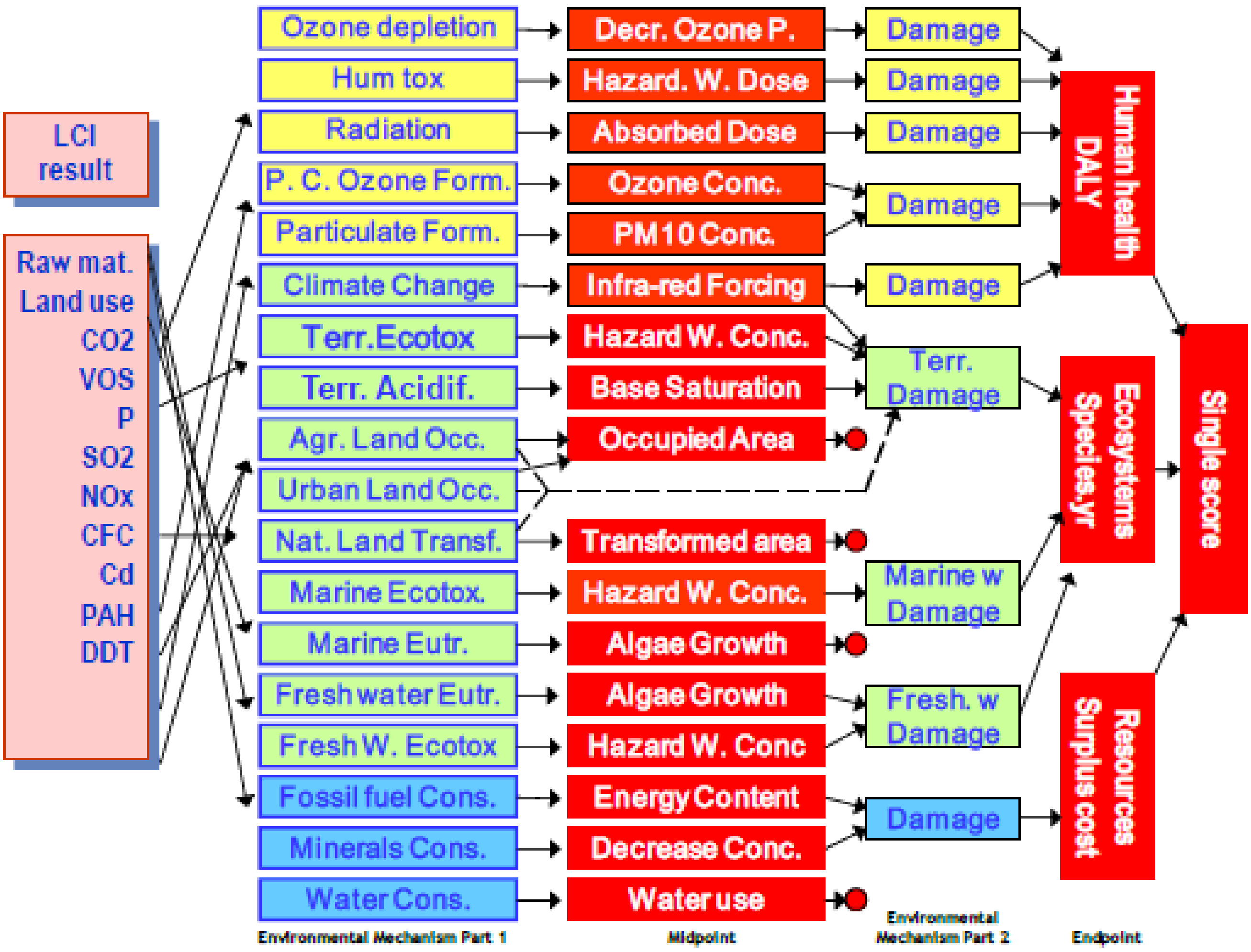


Figure 1.2: Relationship between LCI parameters (left), midpoint indicator (middle) and endpoint indicator (right) in ReCiPe 2008.

Relation between LCI parameters, midpoint and endpoint indicators covered in ReCiPe methodology [27].

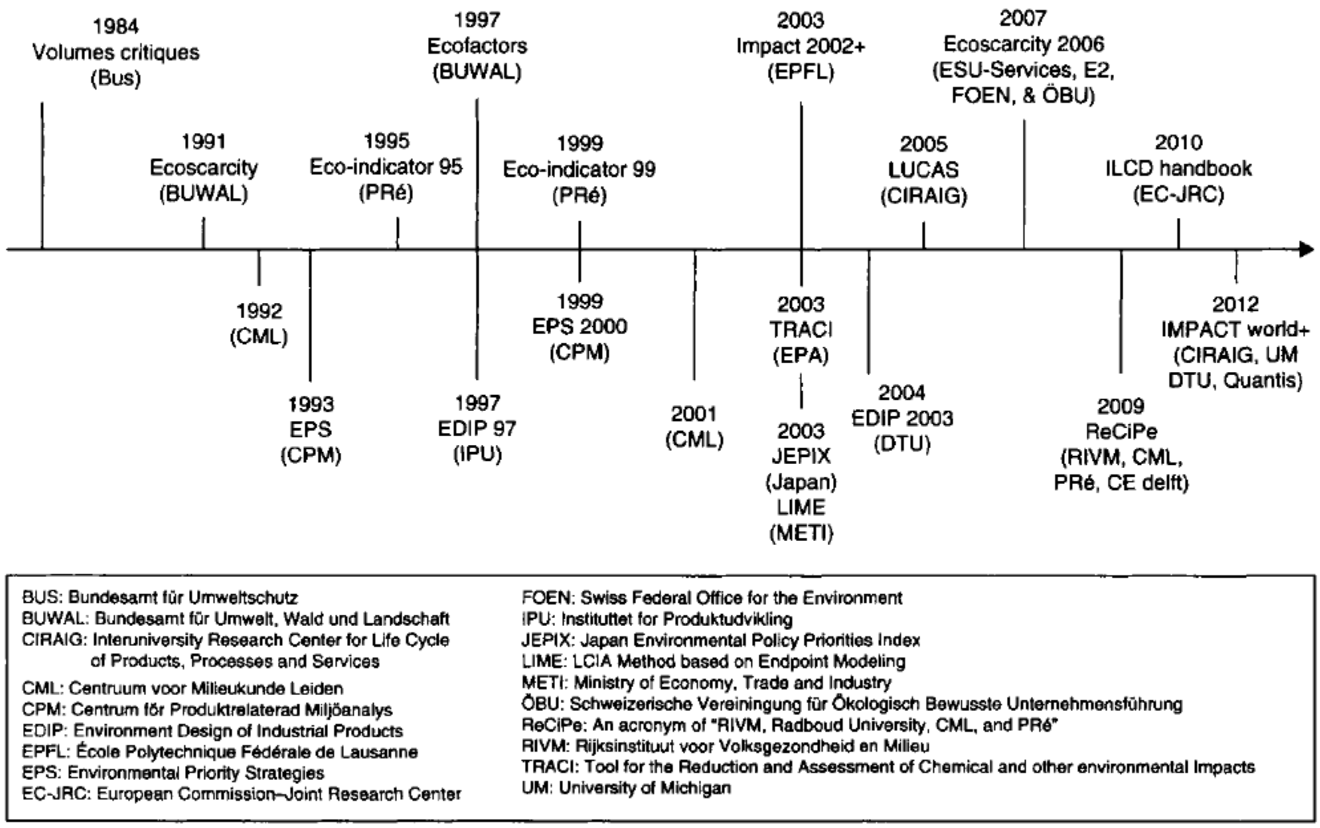


Figure 4.6 Timeline of the introduction of the most common life cycle impact assessment (LCIA) methodologies.

Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products, edited by Mary Ann Curran, Wiley, 2012. ProQuest Ebook

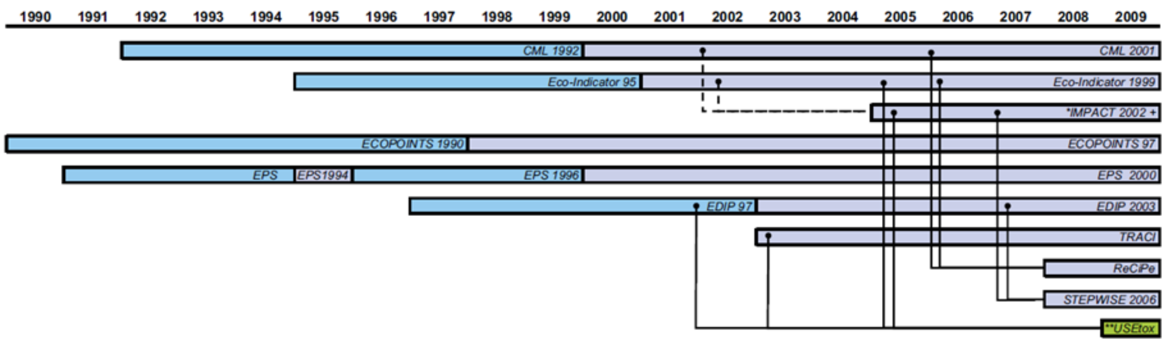
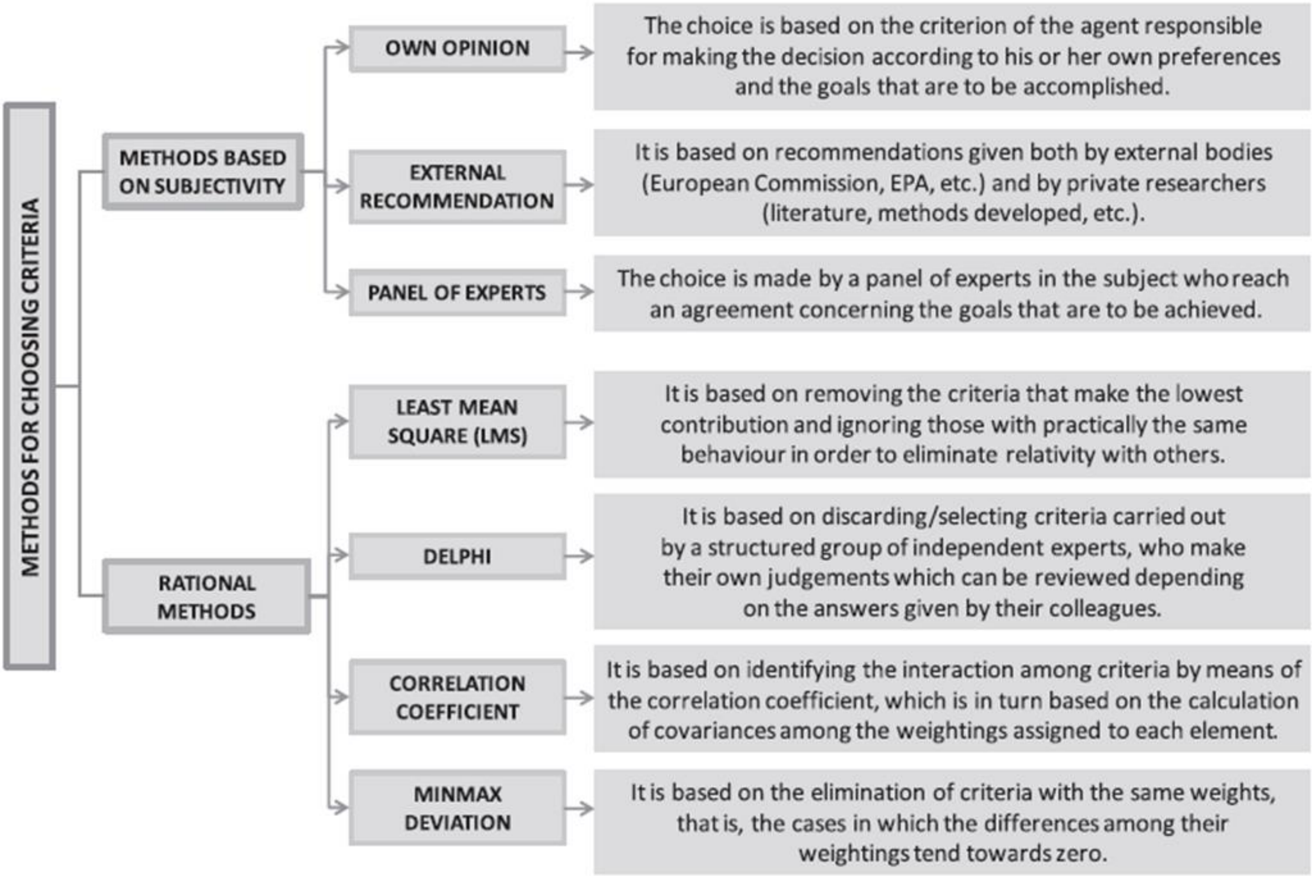


Fig. 1. Development over time for some of the different existing LCIA methodologies. The black connectors show the genealogy of the methodologies (e.g. ReCiPe originated from the previous CML 2001 and Eco-indicator 99). *In IMPACT 2002+ Human- and Eco-tox. impact categories were developed ex-novo, all the other transferred or adapted from CML 2001 and Eco-indicator 99. **USEtox includes only the Human- and Eco-tox. impact categories.

Taken from [21]

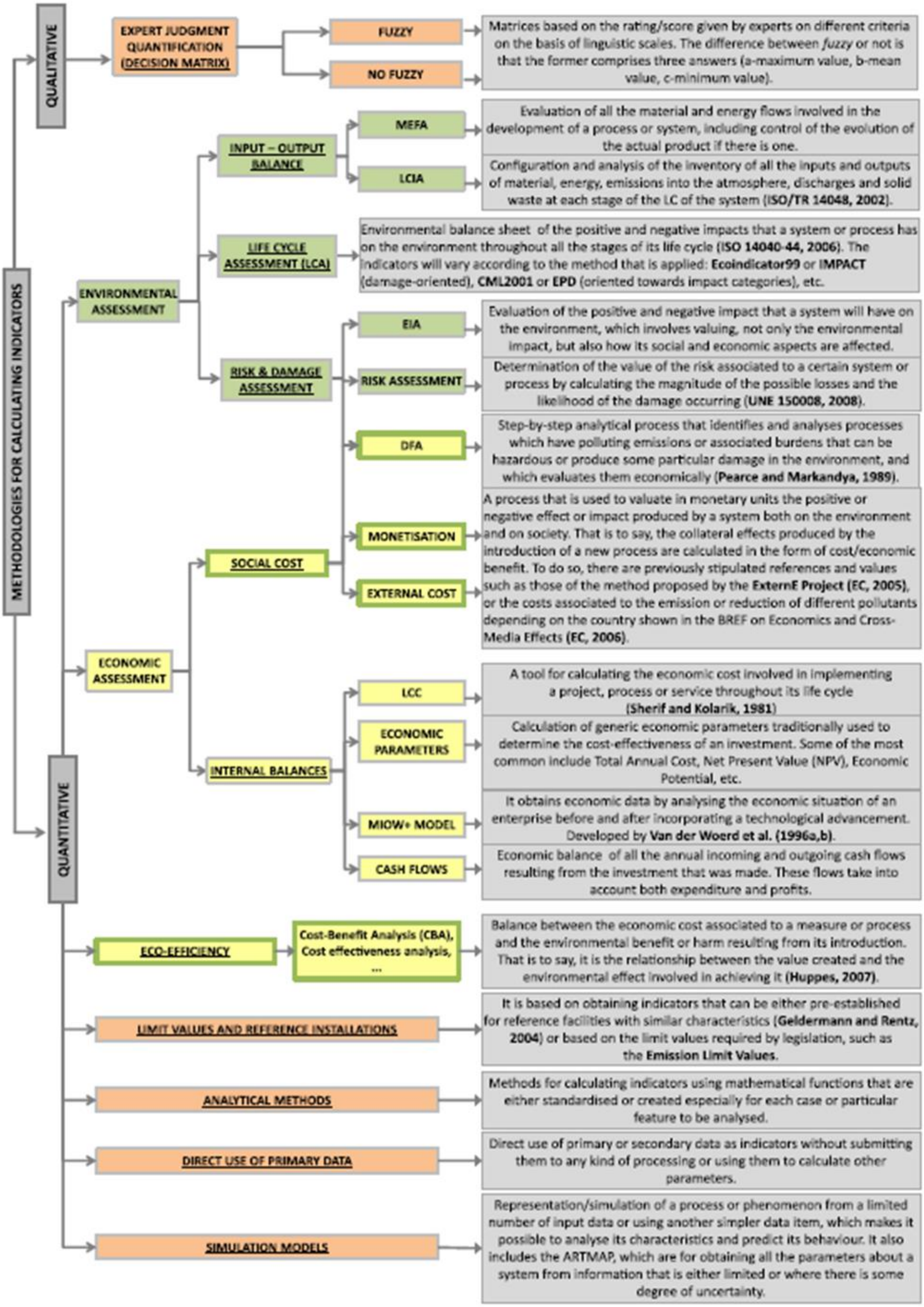
Appendix 2. Classification of methods for MCDA

Methods for criteria selection:



Taken from [40]

Classification for technology assessment methods



Appendix 3. Economic valuation of environmental impact

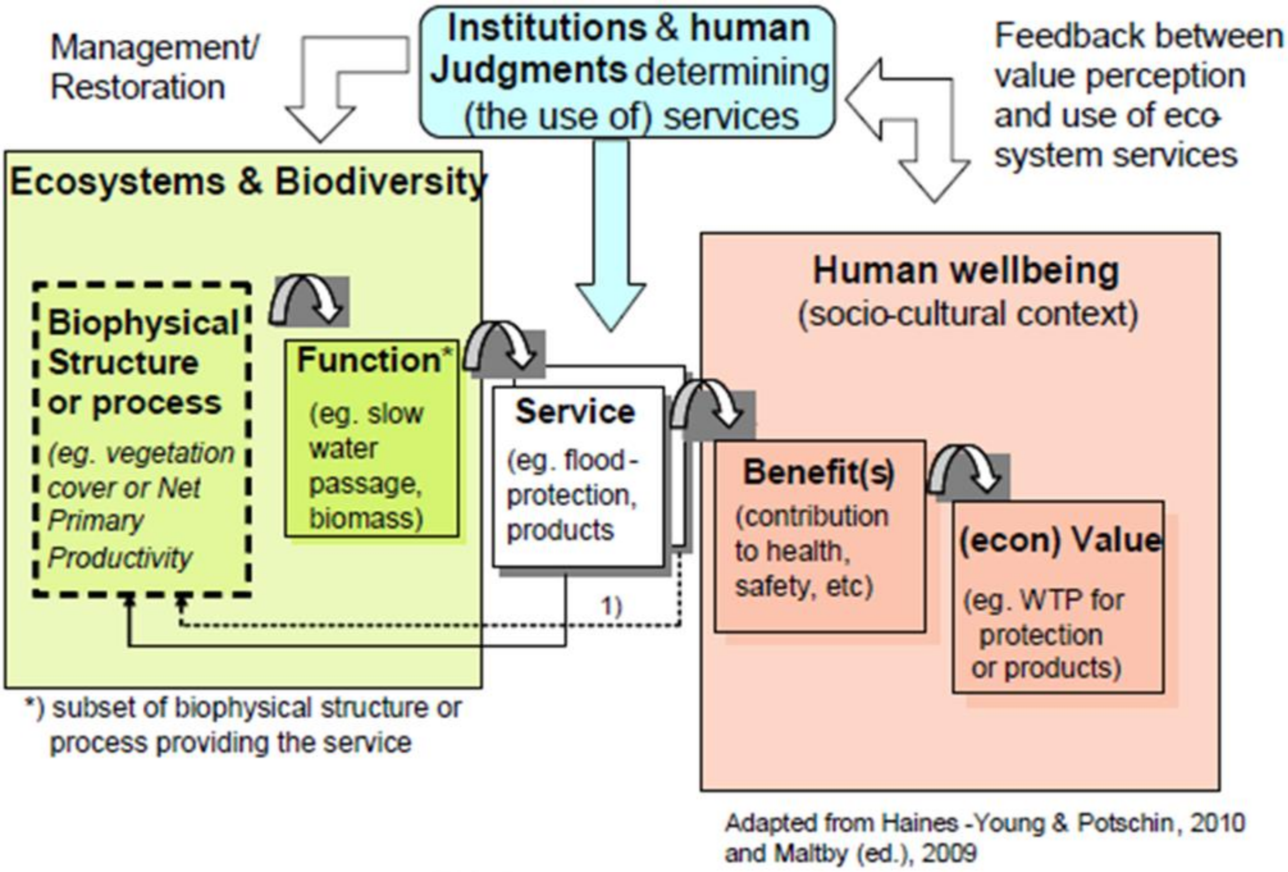


Figure 4: **The pathway from ecosystem structure and processes to human well-being**

[77]

Appendix 4. Damage cost for pollutants from NEEDS project

Unit damage cost for air pollutants in €$_{2000}$ per elementary flow [NEEDS 2008]

		Emissions in 2010				Emissions in 2020			
		health	biodiversity	crop yield	material damage	health	biodiversity	crop yield	material damage
Emissions to air									
NH_3	€/t	9485	3409	-183		5840	3440	-183	
NMVOC	€/t	941	-70	189		595	-50	103	
NOx	€/t	5722	942	328	71	6751	906	435	131
PPM_{CO} (2.5-10 µm)	€/t	1327				1383			
$PPM_{2.5}$ (< 2.5 µm)	€/t	24570				24261			
SO_2	€/t	6348	184	-39	259	6673	201	-54	259
Cd	€/t	83726				83726			
As	€/t	529612				529612			
Ni	€/t	2301				2301			
Pb	€/t	278284				278284			
Hg	€/t	8000000				8000000			
Cr	€/t	13251				13251			
Cr-VI	€/t	66256				66256			
Formaldehyde	€/t	200				200			
Dioxin	€/t	37,0 E09				37,0 E09			
Aerosols, radioactive	€/kBq	2,57E-04				2,57E-04			
Carbon-14	€/kBq	1,40E-03				1,40E-03			
Tritium	€/kBq	5,10E-07				5,10E-07			
Iodine-131	€/kBq	2,61E-03				2,61E-03			
Iodine-133	€/kBq	3,76E-07				3,76E-07			
Krypton-85	€/kBq	2,75E-08				2,75E-08			
Noble gases, radioactive	€/kBq	5,53E-08				5,53E-08			
Thorium-230	€/kBq	3,86E-03				3,86E-03			
Uranium-234	€/kBq	1,03E-03				1,03E-03			
Uranium-235	€/kBq	8,40E-04				8,40E-04			
Uranium-238	€/kBq	9,01E-04				9,01E-04			
Emissions to water									
Carbon-14	€/kBq	9,38E-06				9,38E-06			
Tritium	€/kBq	1,09E-07				1,09E-07			
Iodine-131	€/kBq	8,17E-03				8,17E-03			
Krypton-85	€/kBq	2,75E-08				2,75E-08			
Uranium-234	€/kBq	2,55E-05				2,55E-05			
Uranium-235	€/kBq	9,20E-05				9,20E-05			
Uranium-238	€/kBq	2,53E-04				2,53E-04			

Appendix 5. Factors for different monetization methods

ExternE[11]

EXTERNAL COSTS			nuclear power plant	heavy oil condensing power plant	light oil gas turbine	hard coal condensing power plant	hard coal IGCC	lignite condensing power plant
TOTAL	Human Health	Euro Cent	0.13186	1.73192	1.36203	1.20215	0.77436	0.87770
TOTAL	Loss of Biodiversity	Euro Cent	0.00905	0.12202	0.10058	0.12539	0.07915	0.08875
TOTAL	Crop N deposition & crops O3	Euro Cent	0.00187	0.02190	0.02241	0.02167	0.01516	0.01248
TOTAL	Crops SO2	Euro Cent	-0.00012	-0.00172	-0.00139	-0.00083	-0.00055	-0.00062
TOTAL	Materials: SO2&Nox	Euro Cent	0.00279	0.02848	0.03238	0.01372	0.01104	0.00602
TOTAL	Other pollutants - human health	Euro Cent	0.02339	0.05597	0.03212	0.05314	0.06090	0.04930
TOTAL	Radionuclides generic	Euro Cent	0.00239	0.00017	0.00019	0.00013	0.00013	0.00006
TOTAL	Climate Change - generic	Euro Cent	0.04283	0.43810	0.91704	1.71984	1.75624	1.93560
EU27	**TOTAL EXTERNAL COSTS**	Euro Cent	0.21406	2.39685	2.46537	3.13521	2.69643	2.96929

natural gas combined cycle	natural gas, gas turbine	hydropower, run of river 10MW	hydropower, run of river <100MW	hydropower, run of river >100MW	hydropower, dam (reservoir)	hydropower, pump storage	wind, on-shore	wind, off-shore	solar PV, roof
0.40304	0.61991	0.04317	0.03084	0.02775	0.05371	0.04693	0.05654	0.04878	0.56033
0.05195	0.07878	0.00165	0.00118	0.00106	0.00226	0.00185	0.00382	0.00313	0.03324
0.01257	0.01874	0.00072	0.00052	0.00046	0.00080	0.00054	0.00084	0.00067	0.00662
-0.00021	-0.00034	-0.00002	-0.00001	-0.00001	-0.00002	-0.00001	-0.00005	-0.00004	-0.00046
0.00740	0.01114	0.00047	0.00033	0.00030	0.00052	0.00032	0.00112	0.00097	0.01078
0.02101	0.01395	0.00277	0.00198	0.00178	0.00353	0.00267	0.01892	0.02300	0.08172
0.00002	0.00002	0.00001	0.00001	0.00001	0.00002	0.00001	0.00007	0.00005	0.00038
0.89736	1.34227	0.01272	0.00909	0.00818	0.01548	0.01048	0.02124	0.01720	0.18193
1.39313	2.08447	0.06150	0.04393	0.03953	0.07629	0.06279	0.10249	0.09376	0.87454

solar PV, open space	solar thermal, parabolic trough	natural gas CHP with extraction condensing turbine	hard coal CHP with extraction condensing turbine	natural gas combined cycle CHP with backpressure turbine	hard coal CHP with backpressure turbine	biomass (straw) CHP with an extraction condensing turbine	biomass (woodchips) CHP with an extraction condensing turbine	MCFC (natural gas)	SOFC (natural gas)	MCFC (biogas)
0.54994	0.07239	0.37040	1.05808	0.40504	1.14449	1.31900	0.42776	1.36135	0.53914	2.28457
0.03352	0.00551	0.04752	0.11039	0.05184	0.11934	0.29380	0.04882	0.09719	0.04489	0.14190
0.00705	0.00136	0.01149	0.01908	0.01253	0.02063	0.01037	0.01337	0.02479	0.01474	0.02617
-0.00038	-0.00004	-0.00019	-0.00073	-0.00021	-0.00079	-0.00038	-0.00020	-0.00132	-0.00046	-0.00236
0.00933	0.00118	0.00677	0.01207	0.00739	0.01306	0.01182	0.00694	0.03136	0.01172	0.05392
0.10768	0.01938	0.01978	0.04872	0.02149	0.05926	0.23631	0.03647	0.08722	0.01995	0.13447
0.00032	0.00002	0.00002	0.00012	0.00002	0.00013	0.00029	0.00028	0.00018	0.00005	0.00271
0.18052	0.02042	0.81928	1.51416	0.89390	1.63642	0.14623	0.12028	0.39432	0.30630	0.68758
0.88796	0.12020	1.27506	2.76188	1.39199	2.99254	2.01744	0.65371	1.99510	0.93633	3.32896

Evolution of these parameters in time until 2030 is available on project website.

[11]http://www.feem-project.net/cases/documents/deliverables/D_06_01%20private%20ext%20and%20full%20costs%2008_08_21%20values.xls

EPS Method [50]

Damage category	Impact category	Indicator unit	Weighting factor (ELU/indicator unit)
Human health	Life expectancy		85,000
	Severe morbidity	PersonYr	100,000
	Morbidity		10,000
	Severe nuisance		10,000
	Nuisance		100
Ecosystem production capacity	Crop growth capacity	kg	0.15
	Wood growth capacity	kg	0.04
	Fish and meat production capacity	kg	1
	Soil acidification	H^+ eq	0.01
	Production capacity for irrigation water	kg	0.003
	Production capacity for drinking water	kg	0.03
Abiotic stock resources	Depletion of element reserves		
	Depletion of fossil (natural gas, oil, coal) reserves	ELU[a]	1
	Depletion of mineral reserves		
Biodiversity	Species extinction	NEX[b]	1.10E+11

[a] ELU: Environmental Load Unit, the unit of the weighted and aggregated impacts; One ELU is equal to an environmental damage cost of one EUR.
[b] NEX: Normalized Extinction of Species.

Ecotax [50]

Impact category	Reference and unit of the characterization method	Weight in EUR per unit of reference (converted from SEK: 1 EUR = 10 SEK)	
		Min	Max
Abiotic resources	MJ eq		
Coal		0.0012	0.0012
Oil	kg CO_2 eq	0.002	0.006
Natural gas	kg CFC-11 eq	0.0006	0.0069
Global warming potential (GWP)	kg C_2H_2 eq	0.063	0.063
Ozone depletion potential (ODP)	kg SO_2 eq	120	120
Photochemical oxidation (POCP)	kg PO_4 eq	4.8	48
Acidification potential (AP)	kg 1,4-dichlorobenzen eq	1.5	1.5
Eutrophication potential (EP)	kg 1,4-dichlorobenzen eq	2.86	2.86
Fresh water aquatic ecotoxicity	kg 1,4-dichlorobenzen eq	6.086	12.437
Marine aquatic ecotoxicity	kg 1,4-dichlorobenzen eq	1.333E-06	0.0606
Terrestrial ecotoxicity		17.647	17.647
Human toxicity		0.15	0.15

Stepwise2006 [50]

Impact category	Characterized unit at midpoint	Ecosystems EUR/characterized unit	Human well-being EUR/characterized unit	Resource productivity EUR/characterized unit	Single score EUR/characterized unit
Human toxicity	kg C_2H_3Cl eq		0.21	0.064	0.27
Respiratory inorganics	kg PM2.5 eq		52	16	68
Ionizing radiation	Bq C-14 eq	7.1E-06	1.6E-05	4.8E-06	2.0E-05
Ozone layer depletion	kg CFC-11 eq	1.1E-03	78	24	102
Ecotoxicity aquatic	kg TEG eq water	0.12			7.1E-06
Ecotoxicity terrestrial	kg TEG eq soil	0.082	0.0016	−3.70E-04	0.0011
Nature occupation	m^2 agri land year	0.0077			0.12
Global warming	kg CO_2 eq	0.1	0.2	0.06	0.083
Acidification	m^2 UES	0.013		2.8E-04	0.0077
Eutrophication aquatic	kg NO_3 eq			0.004	0.1
Eutrophication terrestrial	m^2 UES	9.3E-05		0[a]	0.013
Respiratory organics	person ppm h				0.26
Photochemical ozone, veg.	m^2 ppm h				3.7E-04
Mineral extraction	MJ extra				0.004
Non-renewable energy	MJ primary				0

PM: particulate matters, CFC: chlorofluorocarbon, TEG: triethylene glycol, UES: unprotected ecosystem.
[a] The damage characterization factor for non-renewable energy is 0 EUR/MJ primary, i.e. zero impact on economic production. This is explained by the fact that the current dissipation of non-renewable energy carriers will not have any influence on the future energy requirement for provision of energy, assuming that the future energy system will be renewable-based (Weidema et al., 2008).