First prioritization - external costs and benefits over the life cycle of CCS cases

Economic valuation of environmental impacts

CATO-2 Deliverable WP4.3-D01c

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1 Executive Summary (restricted)

The present study provides an overview of methods to assess and evaluate external effects applied within the context of energy-related and environmental issues. External effects from power generation are usually addressed as part of an analysis in order to compare the effects of several technologies. A methodological framework can also be used to compare the effect of a (policy) measure. The present study reviews a number of methodologies to include external effects (from power generation) in the standard economic assessment.

One of the methodologies used to assess external effects (from power generation) is *multi-criteria analysis* (MCA). MCA enables the researcher to include both quantitative and qualitative criteria to evaluate a (power generation) technology. Quantitative and qualitative scores on criteria are neatly summed up to result in an overall evaluation score of different technology options. Another characteristic is that the methodology can show the different valuations for the assessed criteria by all stakeholders involved. By varying the weight of the criteria along with stakeholder or perspective, MCA results in a ranking of technology options.

MCA has been used until this date predominantly for the assessment of energy policies, e.g. with regard to planning in general, renewable energy, or bio-energy. MCA has several advantages. Firstly, the researcher is able to use all types of input data in the analysis: the input information does not need to be quantitative in nature. Any type of information can be combined: MCA acknowledges the multi-dimensionality of input data. Secondly, MCA allows for policy measures to be assessed with respect to the performance on more than one goal. It can accommodate goals such as sustainability, health and equity. This feature is especially important when issues are adressed where other goals than efficiency (affordability) are highly relevant. This could for example hold for issues of sustainability where the equity across current and all future generations is deemed relevant.

Thirdly, the method can explicate the valuations of different stakeholders for a particular ranking of policy measures based on different weighings being attached to the defined criteria. For example, regarding the evaluation of allowing for oil and gas production in the Waddenzee, Greenpeace and the NAM are likely to have different valuations of the criteria defined under the policy goals of efficiency and affordability on the one hand, and sustainability on the other. Normally, when applying other types of evaluation methodologies, these preferences remain implicit and result in for example a different calculation of the ‘probability times effect’ of oil production permanently damaging the environment.

MCA is a useful tool for setting priorities in energy policies. Therefore, it is possible that MCA may give a view on advantages and disadvantages of including CCS in the policy mix. Comparison between different options within the scope of Carbon Capture and Storage (CCS) technologies may, however, not be easily addressed based on MCA.

Alternatively, the researcher may use the *cost-benefit analysis* (CBA) methodology. CBA is a well-known framework for evaluation of impacts of technologies. It is a monetary evaluation of the expected costs and benefits of a technology. CBA not only analyses the internal direct costs and benefits of the technology, but also the indirect and external costs and benefits. Cost-benefit analysis is a useful and rather straighforward tool in case of monetary *quantification* of external costs and benefits. The extent to which CBA provides a useful tool for evaluation of a specific (power generation) technology depends on the availability of data, methodologies to quantify external costs and benefits, etc.

CBA has been used for various energy and climate related issues, such as the relationship and synergy of policies focused at reduction of GHG emissions and local air pollution, the costs and benefits of nuclear power to the UK, etc. CBA is widely applied in the field of energy and the environment due to several advantages, although it also contains some serious drawbacks. The general beauty of CBA is the clear rationality behind it and the general transparency with regard to its underlying assumptions and methodological framework. In addition, it appeals to decision-makers because of the capability of bringing together all sorts of qualitative and quantitative information into one monetary value. And finally, the discipline with which the CBA lists the different costs and benefit items, covering all internal and external, and direct and indirect effects is considered an amenity.

CBA is useful for evaluating the costs of various energy alterntives based on quantification of external costs and benefits. Therefore, CBA may be a straigtforward way to detemine the costs and benefits of fossil fuel based electricity generation *with* and *without* CCS. The accuracy of the resulting costs and benefits depends not only on the methodology used but also on the accuracy of the cost data, which may be a problem for some external costs.

Besides, there are *methodologies* to assess or evaluate potential impacts during stages of the life cycle of a power plant. If there is a need for monetarisation of impacts, the methodologies used for economic valuation that are distinguished are based on *avoidance costs* or *damage costs*. Traditionally, the policy debate on climate change has focused on the cost of emission mitigation, e.g. the cost of GHG emission reduction. Whereas the costs of emissions of local/regional pollutants may be based on *damage costs* as the impacts are mainly local or regional by nature, and the temporal extent may also be limited, the impacts of GHG emissions are global and long-lasting (up to hundreds of years).

The methodology denoted as 'avoidance costs' focuses on quantification of the *abatement costs* (instead of damage costs). Mitigation costs of GHG emissions use to be based on abatement costs, e.g. in the updated impact pathway approach or ExternE methodology, as a proxy for environmental cost (external cost) analysis. For the determination of damage costs a methodology was developed on behalf of the European Commission to quantify the *energy external costs* (ExternE). The research resulted in the development of a methodology called the *Impact Pathway Approach*. This approach to quantify environmental impacts is described in the ExternE research program (Externalities of Energy). Four main steps are distinguished:

- Emission: specification of the relevant technologies and pollutants.
- Dispersion: calculation of increased pollutant concentrations in all affected regions.
- Impact: using exposure-response functions for calculation of impacts cumulated exposures.
- Cost: valuation of impacts in monetary terms.

Therefore, the methodology denoted as 'damage cost' aims to quantify potential environmental impacts based on quantifiable damage costs incurred by humans, flora and fauna, buildings, etc. from emissions (to air, water, soil) that arise in case of a specific (power generation) technology. Whereas the ExternE methodology originally focused on GHG emissions, (local) air pollution and radio nuclides, recent extensions of the methodology address land use change, cultural heritage, impacts on building materials, biodiversity, visual impact, and noise.

The ExternE methodology may be applied to CCS. 'ExternE' has the advantage that it draws on a relatively long history of quantification of external effects (from power generation). It is used as a corner stone for development of sustainable energy policies. Also, it enables the researcher to take into account long-term effects from power generation, e.g. the effects of GHG emissions. Limitations of the ExternE methodology relate to the geographical area considered, limitations with regard to dispersion and with regard to impact category.

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Document Change Record

(this section shows the historical versions, with a short description of the updates)

Version	Nr of pages	Short description of change	Pages
01			

Table of Content

2 Applicable/Reference documents and Abbreviations

2.1 Applicable Documents

(Applicable Documents, including their version, are documents that are the “legal” basis to the work performed)

	Title	Doc nr	Version date
AD-01	Beschikking (Subsidieverlening CATO-2 programma verplichtingnummer 1-6843	ET/ED/9078040	2009.07.09
AD-02	Consortium Agreement	CATO-2-CA	2009.09.07
AD-03	Program Plan	CATO2-WP0.A-D.03	2009.09.29

2.2 Reference Documents

(Reference Documents are referred to in the document)

	Title	Doc nr	Issue/version	date
CATO-2-WP4.3-D01 part 1	First prioritization - external costs and benefits over the life cycle of CCS cases; Part 1: Preliminary environmental performance assessment of CCS chains		01	2010.09.15
CATO-2-WP4.3-D01 part 2	First prioritization - external costs and benefits over the life cycle of CCS cases; Part 2: In-depth study of specific environmental themes in CCS chains		01	2010.09.15

2.3 Abbreviations

(this refers to abbreviations used in this document)

CASES	Cost Assessment of Sustainable Energy Systems
CBA	Cost benefit analysis
CCS	Carbon capture and storage
CEA	Cost-effectiveness analysis
EDGAR	Emission Database for Global Research
EMEP	European Monitoring and Evaluation Programme
EPA	(United States) Environmental Protection Agency
ESPREME	Estimation of willingness-to-pay to reduce risks of exposure to heavy metals and cost-benefit analysis for reducing heavy metals occurrence in Europe
ETS	(EU) Emissions Trading Scheme
FGD	Flue-gas desulphurisation
GHG	Greenhouse gas
GWP	Global warming potential
IA	Integrated assessment
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
LAP	Local air pollution
LMS	Least mean square

MAC	Marginal abatement cost
MCA	Multi-criteria analysis
MCDA	Multi-criteria decision analysis
MCDM	Multi-criteria decision making
NDSI	Noise depreciation sensitivity index
NEC	National Emission Ceiling
NEEDS	New Energy Externalities Developments for Sustainability
NHT	(Australian) Natural Heritage Trust
NMVOC	Non-methane volatile organic compound
NPV	Net Present Value
PDF	Potentially Disappeared Fraction
PM	Particulate matter
$PM_{2.5}$	PM with diameter less than 2.5 μm
PM_{10}	PM with diameter less than 10 μm
PMCA	Participatory multi-criteria analysis
R&D	Research and development
SCR	Selective catalytic reduction
SIA	Secondary inorganic aerosols
SMART	Simple multi-attribute rating technique
SMCE	Social multi-criteria evaluation
SOA	Secondary organic aerosols
VOC	Volatile organic compound
VSL	Value of statistical life
WSM	Weighted sum method
WTA	Willingness to accept
WTM	Windrose Trajectory Model
WTP	Willingness to pay
YOLL	Years of life lost

3 Introduction

External effects from power generation are usually addressed to obtain a complete picture of potential effects of several technologies. Generally, external costs and benefits are not part of economic assessments of power generation technologies. Therefore, external costs and benefits require a specific framework as an extension of economic assessment. A methodological framework can be used to compare effects of a power generation technology. Two commonly used frameworks are multi-criteria analysis (MCA) and cost benefit analysis (CBA). These frameworks are used to support decision making on (power generation) technology options to evaluate environmental impacts. However, unlike CBA, MCA does not focus on *monetary quantification* of external effects. CBA requires identification and - to the extent possible - the quantification of both costs and benefits of a (power generation) technology. Effects that a technology/option may have can be distinguished in various ways (see Table 3.1).

Table 3.1 *Selected examples of different effects that may be included in a CBA for CCS*

	Direct effects	Indirect effects
Internal effects	- Immediate impacts on the market for which technology was meant, e.g. changes in production cost or in efficiency; - - Impacts from measures to prevent or reduce external effects	Impacts of direct effects on other markets, e.g. for commodities, labour, R&D, as well as substitution effects
External effects	Immediate impacts for man and environment as a consequence of the technology, as well as side effects, such as non-CO_2 emissions or waste	Impacts on man and environment arising from effects on various markets and/or changes in the economy

Firstly, the technology may have both direct and indirect effects. With *direct effects* we refer to all effects on the market for which a technology was meant, including effects on the project itself, but also effects on human health and the environment. *Indirect effects* comprise effects on other markets or the wider economy, and the implications thereof for man and environment.

A second distinction regards external vis-à-vis internal effects. *Internal effects* are effects that have a bearing on the market for which the technology was meant, as well as for other markets. They regard effects that can be valued in the current financial system. *External effects* are unintended effects that impact on for instance man and environment, either as an immediate consequence from the introduction of the technology or through changes in the economy. In general, for these effects no prices exist on the market, or only prices that do not match the compensation that would have to be paid to undo the external effect. An important element of CBA is therefore the economic valuation of external effects. This does not hold for MCA. Whereas CBA is focused on *monetary quantification* of external effects, MCA is not. For an MCA both qualitative and quantitative criteria can be evaluated.

Note that some external effects may be internalised partly by policies. This applies for instance to the CO_2 emissions under the EU Emission Trading Scheme (EU ETS). For these emissions prices exist in a market and for this reason they could be considered internal effects. However, the CO_2 price is not determined as an estimate for the marginal damage of climate change, but rather is the result of supply and demand and to some extent subject to speculations. We will therefore treat CO_2 emissions as an external effect. In order to prevent or reduce certain external effects, abatement or mitigation measures may be taken. The costs of such measures will have an immediate impact on the installation and the market in which it operates, and can therefore be considered as direct internal effects.

The present study provides an overview of the current status of literature and its approaches to quantify external effects of impacts categories of *CO_2 Capture and Storage (CCS) chains* in terms of external costs and benefits. With regard to impact categories, it is noted that currently available methodologies can only partly provide a quantification of impacts. Of the impact categories that can be described quantitatively, some external effects can be evaluated economically (monetary quantification).

Chapter 4 starts with a brief overview of typical impact categories for assessment of (power generation with) Carbon Capture and Storage (CCS). Next, Chapter 5 presents frameworks for (economic) evaluation of technology options. In Chapter 6, the focus is on methodologies for economic valuation of external effects. Finally, Chapter 7 provides a number of conclusions. Additionally, Appendix A contains Abbreviations and Acronyms, Appendix B provides typical emissions to air of power generation and CCS, and Appendix C gives a view of emissions, dispersion, and impact category and valuation used in the so-called *Impact Pathway Approach*.

CATO2 - WP 4.3

This report is part 3 of the first deliverable “First prioritization - external costs and benefits over the life cycle” (CATO-2-WP4.3-D01) of CCS cases of work package 4.3 “Environmental performance of CCS chains”. Other parts of this deliverable are:

- Part 1: Preliminary environmental performance assessment of CCS chains (CATO-2-WP4.3-D01 part 1)
- Part 2: In-depth study of specific environmental themes in CCS chains (CATO-2-WP4.3-D01 part 2).

This WP aims to:

- Assess the environmental performance of CCS technologies over the complete life cycle
- Deepen the insights of all CATO2 partners in the (non-CO_2) environmental aspects of CCS in general and capture in particular by enlarging the amount of available and accessible data
- Provide input that would be required to carry out a strategic environmental impact assessment for CCS in the Netherlands.

4 Frameworks for evaluation of technology options

Chapter 3 shortly introduced frameworks for evaluation of external costs and benefits of technologies. A framework is used as an extension of conventional economic assessment to support decision making on technologies to reduce a certain environmental impact. Common frameworks are multi-criteria analysis (MCA) and cost benefit analysis (CBA). Unlike CBA, multi-criteria analysis does not necessarily focus on *monetary quantification* of external effects, but on quantitative and qualitative effects in general. Paragraph 4.1 and 4.2 present overviews of multi-criteria analysis, and cost-benefit analysis, respectively.

4.1 Multi-criteria analysis (MCA)

Multi-criteria analysis (MCA) enables the researcher to include both quantitative and qualitative criteria to evaluate a (power generation) technology. Quantitative and qualitative scores on criteria are neatly summed up to result in an overall evaluation score of different technology options. Another characteristic of MCA is that the methodology can show the different valuations for the assessed criteria by all stakeholders involved. By varying the weight of the criteria along with stakeholder or perspective, MCA results in a ranking of technology options.

Multi-criteria analysis holds a number of techniques which mainly differ in the type of input data to be handled and the type of inter-criteria information required to perform the analysis. Inter-criteria information refers to the information needed to arrive at a valuation of the criteria. Given these differences, each technique poses its own difficulties in performing a proper MCA. Undertaking a MCA analysis involves the following steps (De Joode and Van der Welle, 2007):

1. Analysing the problem;
2. Defining the goals;
3. Defining the project alternatives;
4. Draft and define the criteria on which one can assess reaching the goals;
5. Evaluate the project alternatives by giving scores;
6. Converting the scores using a common reference valuation;
7. Defining the weights to be attached to each criteria - based on expert judgement, perspective (e.g. economic, environmental);
8. Agregating the scores per alternative;
9. Performing a sensitivity analysis to get insight into the robustness of the ranking of alternatives.

4.1.1 Examples of energy and environment related MCA studies

In the following, total eleven literature sources (articles) are shortly addressed that refer to MCA studies or provide a review of MCA methodologies with a bearing for the present study. Table 4.1 provides an overview of features of these articles.

Kowalski et al. (2009) analysed the combined use of scenario building and participatory multi-criteria analysis (PMCA) in the context of renewable energy from a methodological point of view. Scenarios have been applied increasingly in decision-making about long-term consequences by projecting different possible pathways into the future. Scenario analysis accounts for a higher degree of complexity inherent in systems than the study of individual projects or technologies. MCA is widely used as an appraisal method, which assesses options on the basis of a multi-dimensional criteria framework and calculates rankings of options. In their study, five renewable energy scenarios for Austria for 2020 were appraised against sustainability criteria. A similar process was undertaken on the local level, where four renewable energy scenarios were developed and evaluated against criteria. On both levels, the scenario development consisted of two stages: first an exploratory stage with stakeholder engagement and second a modelling stage with forecasting-type scenarios. Thus, the scenarios consist of a narrative part (storyline) and a modelled quantitative part. The preferences of national and local energy stakeholders were included in the form of criteria weights derived from interviews and participatory group processes, respectively. The most favoured scenario was one focused on the reduction of energy demand and the support of small-scale, privately-owned renewable energy plants.

Especially in the case of renewable energy promotion in Austria, Kowalski et al. (2009) systematically analysed the potentials and limitations of the methodology (1) for capturing the complexity of decision-making about the long-term consequences of changes in socio-economic and biophysical systems and (2) for appraising energy futures. They conclude that assessing scenarios with PMCA is resource intense, but this methodology captures successfully the context of technology deployment and allows decision-making based on a robust and democratic process, which addresses uncertainties, acknowledges multiple legitimate perspectives and encourages social learning.

Cunningham and van der Lei (2009) contend that technology managers increasingly face problems of group decision. The scale and complexity of research, development and alliance efforts in emerging fields of technology mandate as correspondingly sophisticated form of group coordination. Choices made include the selection of projects, the choice of investment alternatives, and the formation of technology licensing agreements. Multi-criteria decision analysis (MCDA) methods are often used to help decision-makers in such situations. They explore an approach closely related to MCDA, known as exchange modelling, incorporating actor preferences, and assumptions about the play of the game, to better examine the resulting preferences of groups. The advantage of this method is that the results provide an improved prescription for strategy, given the constraints of preferences and existing alliance structures. The model is motivated based upon the needs of technology managers in new, converging fields of technology. The model is formally analysed using operations research techniques. They then apply the model to a representative technology management problem in the converging fields of a particular technology.

According to Buchholz et al. (2009), sustainable bio-energy systems are, by definition, embedded in social, economic, and environmental contexts and depend on support of many stakeholders with different perspectives. The resulting complexity constitutes a major barrier to the implementation of bio-energy projects. Their analysis aims to evaluate the potential of MCA to facilitate the design and implementation of sustainable bio-energy projects. Four MCA tools (Super Decisions, Decide IT, Decision Lab, NAIADE) are reviewed for their suitability to assess sustainability of bio-energy systems with a special focus on multi-stakeholder inclusion. The MCA tools are applied using data from a multi-stakeholder bio-energy case study in Uganda. Although contributing to only a part of a comprehensive decision process, MCA can assist in overcoming implementation barriers by (i) structuring the problem, (ii) assisting in the identification of the least robust and/or most uncertain components in bio-energy systems and (iii) integrating stakeholders into the decision process. Applying the four MCA tools to a Ugandan case study resulted in a large variability in outcomes. However, social criteria were consistently identified by all tools as being decisive in making a bio-electricity project viable. Cost differences,which are often used as a decisive criterion for energy planning (e.g., cost–benefit analysis), played only a minor role in the MCA results.

Table 4.1 *Summary of scope, goal, aim, methodology, reasons and other factors and benefits involved in multi-criteria analysis*

	Scope	Goal or use of project	Aim of methodology applied	Methodology	Reason for this methodology	Other factors mentioned	Other benefits of methodology
Kowalski et al. (2009)	Participatory MCA (PMCA) for decision making on energy policy	Provide possible starting points for decisions in the policy arena	Identification of compromise solutions in a transparent and fair way	PMCA with scenarios incl. renewables and energy efficiency	Address complexity and uncertainty and organise information	Conflicts among heterogeneous socio-economic interests	Cognitive learning, learning from others and about decision making
Cunningham and van der Lei (2009)	Analysis tool for assist in complex coordination problems	Examining consequences of restricted access to a network in strategic positioning	Evaluate alliance networks, design new networks, select alliance partners	Multi-criteria decision analysis with exchange modeling	Assist decision makers in preparing for optimal negotiations and exchanges	Present a vision of quantitative decision support given strategic modelling	Provide tools for new empirical applications in technology management
Buchholz et al. (2009)	Identify the potential and limitations of selected MCA tools	Involve stakeholders in bio-energy project in Uganda	Guide stakeholders to find and agree on sustainable solutions	PMCA (Super Decisions) with stakeholders of local / national government, and NGOs	Divergent values on how to assess and decide with lack of data (uncertainty)	Social criteria, not costs play a key role in making bio-electricity systems viable	Only tool allowing inclusion of stakeholders in criteria weighting
Wang et al. (2009)	Addressing complex problems with uncertainty, conflicting objectives, etc.	Review of the published literature on sustainable energy decision-making	Multi-criteria decision-making methods for sustainable energy	Multi-criteria decision analysis (MCDA); criteria selection and weighting	MCDA applicable to complex decision making on energy and climate policy	Rational decisions on energy supply, planning, management and economy	Aggregation methods are rational and aid in sustainable energy decision-making
Diakoulaki and Karagelis (2007)	Broaden the evaluation perspective so as to incorporate all aspects that should guide the decision procedure	Encompass all positive and negative side-effects characterising the electricity generation technologies	Comparative evaluation of scenarios for the development of the power generation sector in Greece	MDCA – method of comparison in pairs of alternatives – and Cost Benefit Analysis (CBA)	Considerable conflicts between economic, technical and environmental aspects	In CBA, monetary values play the role of weights in MCDA	As each method separately often disputed; therefore, combination of MCDA and CBA

Table 4.1 *Summary of scope, goal, aim, methodology, reasons and other factors and benefits involved in multi-criteria analysis*

	Scope	Goal or use of project	Aim of methodology applied	Methodology	Reason for this methodology	Other factors mentioned	Other benefits of methodology
Gamper and Turkanu (2007)	Support complex governmental decision making	Dealing with qualitative criteria and with uncertainties	Aiding public decision making in complex context	MCA in environmental decisions in public domain	MCA greatly facilitates stakeholders' involvement	MCA has to be trusted support tool for decisions	Narrowing scope for randomness and mere decoration
Hajkowicz (2007)	Support making decisions in environmental management context	Evaluate environmental projects in Queensland, Australia	Improve the decision making through better learning, clarification, etc	MCA and unaided approaches for evaluation of alternatives	MCA is a 'glass box' rather than a 'black box'	Understand trade-offs and appreciate the consequences of alternatives	Making choices analytically robust, accountable and auditable
Hermann, Kroeze and Jawjit (2007)	Compare and rank alternative options and to evaluate their (environmental) consequences	Provide detailed information on the overall environmental impact	Evaluate the environmental consequences of alternatives with multiple criteria	Combination of MCA, LCA and environmental performance indicators (EPIs)	Develop a tool enabling actors to carry out an overall environmental assessment	'Cradle-to-gate' approach and prevention of problem shifting	Expand scope towards LCA and aggregating the output into a single index
Løken (2007)	Enabling energy planning with conflicting objectives	Decision support to reach better solutions in energy planning	Decisions made in uncertainty, long time frames, and high capital-intensity	MCDA for use in energy planning	Enable decision making in systems with multiple energy carriers	Maintain synergy when infrastructures are planned independently	Include other criteria, e.g. reliability, land use, human health, etc
Stirling (2006)	Participatory analysis in the appraisal of environmental performance	Enabling decision making with different political interests and conflicts	Improve decision making acknowledging institutional, economic and political power	Various forms of MCA	Participation in decision making for empowerment, quality or justification	Facilitating the building of consensus in a participatory process	MCA should highlight the irreducible plurality of values and interests
Pohekar and Ramachandran (2004)	Provide solutions to increasing complex energy management problems	Provide better understanding of inherent features of decision problem	Improve quality of decisions by making them more explicit, rational and efficient	Multi-criteria decision making (MCDM) methods	Take care of multiple, conflicting criteria to arrive at better solutions	Indications of paradigm shift in energy planning approaches	Suitable for renewable energy planning and energy resource allocation

Wang et al. (2009) observe that MCDA methods have become increasingly popular in decision-making for sustainable energy because of the multi-dimensionality of the sustainability goal and the complexity of socio-economic and biophysical systems. This article reviewed the corresponding methods in different stages of multi-criteria decision-making for sustainable energy, i.e., criteria selection, criteria weighting, evaluation, and final aggregation. The criteria of energy supply systems are summarised from technical, economic, environmental and social aspects. The weighting methods of criteria are classified into three categories: subjective weighting, objective weighting and combination weighting methods.

Several methods based on weighted sum, priority setting, outranking, fuzzy set methodology and their combinations are employed for energy decision-making. It is observed that the investment cost locates the first place in all evaluation criteria and CO_2 emission follows closely because of more focus on environment protection, equal criteria weights are still the most popular weighting method, analytical hierarchy process is the most popular comprehensive MCDA method, and the aggregation methods are helpful to get the rational result in sustainable energy decision-making.

Diakoulaki and Karagelis (2007) examine four mutually exclusive scenarios for the expansion of the Greek electricity system with the aim to encompass all positive and negative side-effects characterising the electricity generation technologies assumed to participate in each scenario and emphasis is given to the particular role of renewable energy sources which represent a major differentiating factor between them. The calculation of economic, technical and environmental performances of the examined scenarios for the year 2010 shows that electricity planning is a complicated task since improvements in one policy target are accompanied by losses in others. In order to resolve this conflict, the scenarios are comparatively evaluated with two decision support techniques, multi-criteria decision analysis and cost–benefit analysis, which are capable of broadening the strict boundaries of a financial analysis while avoiding intuitive solutions that are often applied in practice. Following the two completely different evaluation approaches, it is confirmed that the scenario assuming the highest penetration of renewable energy sources is the best compromise configuration for the Greek power generation sector.

Gamper and Turkanu (2007) contend that public decision making, especially about our natural environment, is inherently exposed to a high conflict potential. The necessity to capture the complex context has led to an increasing request for decision analytic techniques as support for the decision process. MCA is deemed to overcome the shortcomings of traditional decision-support tools used in economics, such as cost-benefit (CBA) or cost-effectiveness analysis (CEA). This is due, among others, to its ability of dealing with qualitative criteria (e.g. sensitive ecological factors), as well as with uncertainties about current or future impacts.

Unlike CBA or CEA, MCA is rarely required by national laws or directives. Nonetheless, a number of recent MCA applications were supported by public authorities who either initiated or directly participated in such analyses. Given the theoretical assumptions about MCA's potential to support complex decision problems, as is often the case for environmental or sustainability policies, the key concern in their paper is to evaluate whether this potential has already been recognised in public decision making. For limitation purposes, the present work focuses on real-life case studies reported during the last decade with an insight in the initiation, the actors involved and the importance of the MCA results in the decision process. They argue that the significance and role played by MCA so far reaches beyond its current legal requirements.

Hajkowicz (2007) compares MCA assisted decisions and unaided decisions in an environmental management context. It involved decision makers in Queensland, Australia, who used MCA techniques to evaluate environmental projects alongside their own intuitive approaches under the

Australian Natural Heritage Trust (NHT) program, i.e. Australia's largest environmental program. The study assessed decision maker learning and perceptions of MCA's overall usefulness. It was found that MCA produced markedly different results to unaided evaluations. Feedback from decision makers typically showed that unaided decisions did not make explicit use of evaluation criteria. Even though most decision makers were unwilling to change their choices following the use of MCA, they found it a helpful input to their decision procedure. Most decision makers supported the adoption of MCA to make future investment decisions.

Hermann, Kroeze and Jawjit (2007) present a new analytical tool which can be used to provide detailed information on the overall environmental impact of a business. It integrates parts of tools such as life cycle assessment, multi-criteria analysis and environmental performance indicators. It avoids disadvantages and combines complementary aspects of these three tools. The methodology is based on environmental performance indicators, expanding the scope of data collection towards a life cycle approach and including a weighting and aggregation step. A case study on the Thai pulp industry illustrates the usefulness of the tool.

Løken (2007) contends that most decision making requires the consideration of several conflicting objectives. MCDA describes various methods developed for aiding decision makers in reaching better decisions. Energy planning problems are complex problems with multiple decision makers and multiple criteria. Therefore, these problems are quite suited to the use of MCDA. A multitude of MCDA methods exists. These methods can be divided in three main groups; value measurement models, goal, aspiration and reference level models, and outranking models.

Methods from all of these groups have been applied to energy planning problems, particularly in the evaluation of alternative electricity supply strategies. Each of the methods has its advantages and drawbacks. However, Løken contends that one method generally is not better suited than the others for energy planning problems. A good alternative might be to apply more than one method, either in combination to make use of the strengths of both methods, or in parallel to get a broader decision basis for the decision maker. Until now, studies of MCDA in energy planning have most often considered energy networks with only one energy carrier.

By reference to the particular field of multi-criteria assessment, Stirling (2006) examines some key themes in the general relationship between participatory deliberation and quantitative analysis in the appraisal of environmental performance. His analysis builds on Fiorino's distinction between normative, substantive and instrumental approaches to appraisal. Although often contrasted, both analysis and deliberation are found to be similarly sensitive to different kinds of 'framing conditions'. After Collingridge, it is argued that both approaches are therefore susceptible to various political and institutional pressures for decision justification. Based on this analysis, it is concluded that there exists an important but neglected characteristic of social appraisal that is equally applicable to both participatory and analytic approaches and which in many ways transcends the importance of this distinction. This concerns the difference between the functions of appraisal in 'opening up' or 'closing down' wider policy discourses. By exploring some detailed implications for participatory multi-criteria assessment, the paper points towards a more balanced emphasis on these two modes of appraisal.

Pohekar and Ramachandran (2004) state that Multi-Criteria Decision Making (MCDM) techniques are gaining popularity in sustainable energy management. The techniques provide solutions to the problems involving conflicting and multiple objectives. Several methods based on weighted averages, priority setting, outranking, fuzzy principles and their combinations are employed for energy planning decisions. A review of more than 90 published papers is presented in their article to analyse the applicability of various methods discussed. A classification on application areas and the year of application is presented to highlight the trends. Validation of results with multiple methods, development of interactive decision support systems and application of fuzzy methods to tackle uncertainties in the data is observed in the published literature.

4.1.2 Methods applied in MCA studies

Wang et al. (2009) give an in-depth analysis of methods used in MCA studies. For instance, they distinguish technical, economic, environmental, and social criteria. They also distinguish five methods for criteria selection:

- *Systemic principle*. The criteria system should roundly reflect the essential characteristic and the whole performance of the energy systems.
- *Consistency principle*. The criteria system should be consistent with the decision-making objective.
- *Independency principle*. The criteria should not have inclusion relationship at the same level criteria. The criteria should reflect the performance of alternatives from different aspects.
- *Measurability principle*. The criteria should be measurable in quantitative value if possible or qualitatively expressed.
- *Comparability principle*. The decision-making result is more rational when the comparability of criteria is more obvious. Additionally, the criteria should be normalised to compare or operate directly when there are both benefit criteria and cost criteria.

Wang et al. (2009) also introduce the following elementary selection methods of criteria used to decision making on sustainable energy:

- *Delphi method*. The Delphi method is a systematic and interactive method, which relies on a panel of independent experts.
- *Least mean square (LMS) method*. The principle of LMS method is that one criteria contributes less importance to results and it can be ignored when its performances of alternatives are almost same or near although the criteria is vital in evaluation.
- *Correlation coefficient method*. Correlation analysis adopts the correlation coefficient to show the interaction between criteria.

With regard to weighting of criteria, Wang et al. (2009) present the following methods:

- *Equal weights method*. The method requires minimal knowledge of the decision maker's priorities and minimal input from the decision maker.
- *Rank-order weighting method*. The rank-order weighting methods are classified into three categories: subjective weighting method, objective weighting method and combination weighting method.
- *Subjective weighting methods*. Finally, Wang et al. (2009) address a number of so-called subjective weighting methods, e.g. the Simple multi-attribute rating technique (SMART), pair-wise comparison, etc.

Furthermore, Wang et al (2009) address a number of methods to determine the preference orders of alternatives:

- *Elementary methods*. This category encompassese 10 different weighting methods.
- *Weighted sum method (WSM)*. WSM is the most commonly used approach in sustainable energy systems.
- *Unique synthesizing criteria methods*. This category encompasses also 10 different weighting methods.
- *The outranking methods*. Compared to the other multi-criteria evaluation methods, the outranking methods have the characteristic of allowing incomparability between alternatives.

This characteristic is important in situations where some alternatives cannot be compared for one or another reason.

Finally, Wang et al. (2009) present a number of aggregation methods. Usually, the decision maker selects the best alternative based on the ranking orders after the calculation in a selected MCDA method. However, the creditability of decision making is necessarily verified so that the results of the ranking orders are computed by a few MCDA methods sometimes. Wang et al. (2009) distinguish two main aggregation methods:

- *Voting methods*. Voting methods (e.g. the so-called Borda and Copeland rules) assign points to the alternatives in the individual preferences.
- *Mathematical aggregation methods*. These methods either do not require the collaboration of the decision-makers and are obtained in mathematical methods over the ranking orders of alternatives, which avoid the preference of decision makers, or require collaboration of the decision maker in which case the final results are obtained through the negotiation of decision makers when there is difference of opinion.

4.1.3 Discussion on advantages and disadvantages

Multi-criteria analysis is a useful tool to assess the various impacts of a technology or technologies in a comprehensive way, both quantitatively and qualitatively. It is, however, not applicable to straighforward comparison of the possible financial impacts - internal and external - of technologies. For such a straightforward financial analysis, cost-benefit analysis is needed.

MCA has three important advantages
Firstly, there is the advantage of being able to use all types of input data in the analysis: the input information does not need to be quantitative in nature. Any type of information can be combined: MCA acknowledges the multi-dimensionality of input data.

Secondly, MCA allows for policy measures to be assessed with respect to the performance on more than one goal. Whereas the focus of CBA is on the goal of efficiency, MCA can accommodate goals such as sustainability, health and equity. This feature is especially important when issues are adressed where other goals than efficiency (affordability) are highly relevant. This could for example hold for issues of sustainability where the equity across current and all future generations is deemed relevant.

Thirdly, the method can explicate the valuations of different stakeholders for a particular ranking of policy measures based on different weighings being attached to the defined criteria. For example, regarding the evaluation of allowing for oil and gas production in the Waddenzee, Greenpeace and the NAM are likely to have different valuations of the criteria defined under the policy goals of efficiency and affordability on the one hand, and sustainability on the other. Normally, when applying other types of evaluation methodologies, these preferences remain implicit and result in for example a different calculation of the ‘probability times effect’ of oil production permanently damaging the environment.

The MCA methodology also beholds some disadvantages. Firstly, since the methodology does not put firm requirements on the criteria to be defined, chances are that some effects may be overlapping or even double counting of effects occurs. This a serious flaw in comparison with CBA which is characterised by a high level of discipline. Secondly, some steps in the analysis can become quite complex to grasp for others than the researcher, for example the principal and stakeholders. This particularly holds for the transformation of scores and the selection of weights. This could prevent succesfull involvement of stakeholders.

Thirdly, in some part of the steps in analysis it is difficult to remove the appearance of subjectivity, in particular when attaching weights to the different criteria. The role of the research team is crucial here. Fourthly, it is unclear how MCA can properly take into account the valuation of time (time preferences). In general, the valuation of effects taken place imediatley after implementation of a proposed policy measure are identical to effects occuring years from now. Fifthly, although MCA results in clear rankings of different options, it does not answer the question whether implementation of a measure will result in a net increase of total welfare, since the unit of analysis in the MCA is not per definition (and is often not) monetary. It therefore seems more suitable for the answering of portfolioproblems, and is in that sense more comparable to cost-effectiveness analysis (OECD, 2006).

4.2 Cost-benefit analysis (CBA)

Cost-benefit analysis, CBA, is a well-known framework for evaluation of impacts of technologies. It is a monetary evaluation of the expected costs and benefits of a technology. Generally denoted as social cost-benefit analysis, CBA not only analyses the internal direct costs and benefits of the technology, but also the indirect and external costs and benefits. Various types of CBA are distinguished by (De Joode and Van der Welle, 2007). Cost-benefit analysis is a useful and rather straightforward tool in case of monetary *quantification* of external costs and benefits. In this respect, it is to preferred over MCA if the financial impacts of a technology or technologies are the primary concern. The extent to which CBA provides a useful tool for evaluation of a specific (power generation) technology depends on the availability of data, methodologies to quantify external costs and benefits, etc. (Table 4.2).

Four types of CBA can be distinguished where mutual differences are caused by the inclusion or exclusion of external and indirect effects, and the general depth of the analysis (i.e. how much effort is put in acquiring the correct quantification of a certain effect):

- An *integral CBA* is the most complete type of CBA: it considers both the internal indirect effects, and all external effects. Also, it involves monetary quantification thereof.
- The *indicative CBA* comes close to integral CBA since this type also includes indirect and external effects. However, an indicative CBA typcially uses indicative values for different impacts (e.g. cost of emissions) instead of searching case-specific values of costs and benefits. Just like in case of integral CBA, it involves monetary quantification.
- The *partical CBA* also shows resemblance with integral CBA, except that it does not quantify indirect internal effects. Besides these indirect internal effects, all other effects are included in the monetary quantification, just like in case of integral CBA.
- The *exploratory CBA* differs much from integral CBA in the sense that it does not perform a monetary quantification of effects. It merely involves a systemic analysis of internal and external direct and indirect effects in a quantitative or qualitative manner.

Cost-benefit analysis involves the following steps (De Joode and Van der Welle, 2007)

1. Analysing the problem;
2. Defining the project alternatives (e.g., technology options);
3. Identifying the effects of the project alternatives;
4. Estimating relevant exogenous developments influencing the effects;
5. Estimating and monetarily quantifying the effects;
6. Producing costs and benefits accounts;
7. Performing a sensitivity analysis.

Cost-benefit analysis is a useful and rather straighforward tool in case of monetary *quantification* of external costs and benefits. In this respect, it is to be preferred over MCA if the financial impacts of a technology or technologies are the primary concern. The extent to which CBA provides a useful tool for evaluation of a specific (power generation) technology depends on the availability of data, methodoliges to quantify external costs and benefits, etc.

Table 4.2 *Overview of types of cost-benefit analysis*

		Effects			
		Internal		External	
Type of cost-benfit analysis	Depth	Direct	Indirect		Monetary quantification
Explorative	Low	Yes	Yes	Yes	No
Indicative	Medium	Yes	Yes	Yes	Yes
Partial	High	Yes	No	Yes	Yes
Integral	High	Yes	Yes	Yes	Yes

Source: De Joode and Van der Welle, 2007.

4.2.1 Examples of energy and environment related CBA studies

Bollen et al. (2009) performed a model-based analysis of possible synergy between greenhouse gas (GHG) emission reduction and PM reduction policies. To the knowledge of Bollen et al., no multi-region model exists, that is global and has a long time horizon, analyses both optimal GHG and PM emission reductions, and allows balancing the costs of abatement with the benefits of avoided damages for GHG and Local Air Pollution (LAP). They use the MERGE model – developed by Manne, Mendelsohn, and Richels (1995) – in its cost-benefit mode. When LAP policy is applied, more than 90% of global PM emissions are reduced. The inclusion of LAP externalities as disutility in consumption, however, proves to have little effect on the level of CO_2 emissions. If one combines GHG and LAP policy, there is little to gain in terms of additional reductions in PM emissions, since LAP policies alone already rid most of these emissions. For CO_2, however, combining GHG and LAP policy achieves extra CO_2 emission reductions i.e. more than follows from the sum of the application of either policy alone (synergy). GHG policy delivers benefits not only in terms of GHG but also for LAP, while purely LAP-oriented policy essentially only brings forward LAP benefits.

Kennedy (2007) analysed the costs and benefits of nuclear power to the UK, based on two research questions, viz.

- What is the scope for new nuclear power generation given the existing generation capacity stock and its likely evolution?
- What is the net economic benefit associated with nuclear relative to a do-nothing case where new investment in electricity generation is likely to flow to gas-fired plant?

The analysis considers resource costs associated with nuclear plant relative to alternatives of gas-fired generation and other technologies. It includes valuation of environmental benefits and security of supply benefits. The net benefit of nuclear generation is negative at low gas prices/high nuclear costs across the range of CO_2 prices. Welfare balance is positive in the central gas price world depending on the CO_2 price, and in high gas price/low nuclear cost worlds across the range of CO_2 prices (including a zero CO_2 price). Under the central gas price and a CO_2 price of € 36 /t (£25/t), the net present value (NPV) benefit over 40 years associated with a 6 GW nuclear programme would be of the order £6 billion.

The monetary valuation of environmental externalities seems to be the dominant paradigm in the comparative environmental appraisal of contending energy options, but the derivation of external costs reproduces many of the most serious problems of the predecessor methodology of comparative risk assessment. These general and fundamental problems might be summed up as ‘a failure to address the multidimensional nature of environmental appraisal’ (Stirling, 1997).

According to Stirling (1997), the main issues of CBA are related to:

- The distribution of environmental effects;
- The autonomy of those affected;
- The choice of indicators;
- The framing and presentation of appraisal.

He concludes that the need to improve the environmental performance of the energy sector is one of the most pressing challenges facing modern industrial society. However, this is not a good reason for the suspension of general criticism of the various available appraisal techniques. Indeed, a lack of constructive attention to the many and profound difficulties in the social appraisal of environmental performance may ultimately act to undermine environmental protection. It is well recognised that environmental decision making should be founded on the best available scientific data and most rigorous theoretical models. It is less well recognised that rigorous policy analysis in a plural society also means systematic and transparent attention to the exploration and accommodation of divergent value judgements.

According to Munda (1996), cost-benefit analysis relies on the following main assumptions:

- Regarding the set of alternatives, the application of a mono-criterion analysis requires the accomplishment of the following properties: the alternatives are all mutually exclusive and the set of alternatives is well-defined and fixed. However, it may happen that the definition of A is progressively elaborated during the course of the decision process. It is also possible to distinguish between the cases where A is *globalized*, i.e., each element of A excludes any other, and *fragmented*, i.e., the decision procedure’s results involve combinations of several elements of A.
- The concept of Pareto optimality implies the following assumptions:
    - All the relevant dimensions underlying costs and benefits must be identified. If relevant dimensions are omitted, then there are potential opportunity costs;
    - Only one alternative considered the best has to be identified. Since the ‘second best’ may have been eliminated during the technical screening, if more than one action has to be found, the elimination of the ‘inefficient’ action may result in an opportunity loss.
- Mutual preference independence must always hold, as a consequence an additive value function permits the assessment of the marginal contribution of each attribute separately and the trade-off ratio between two attributes is independent of the values of the n - 2 other attributes. From an epistemological point of view, preferential independence implies the separability of values. If environmental dimensions are involved, preferential independence implies that among the different eco-systemic aspects there are no phenomena of synergy or conflict. Both consequences do not seem very realistic.
- Since the concept of intensity of preference is used, complete compensability among attributes is allowed. This implies that weights have to be considered as scaling factors and then their meaning is of a trade-off ratio (depending on the scales of measurement of the various attributes). As a consequence the weights used in CBA based on the concept of ‘importance’ are not theoretically compatible with the linear aggregation rule.
- The quality of results of contingent valuation studies depends on how well informed people are, moreover, the problem with these techniques is that respondents may answer ‘strategically’. In order to avoid free rider behaviour people should really pay the amount of money they indicate

(this is needed by the consistency requirements of subjective probability theory); unfortunately in this case, willingness to pay (WTP) depends upon the ability to pay, thus projects which benefit higher income groups would be generally considered to be the best.

- Complete compensability and commensurability imply the inseparability between efficiency, equity and sustainability issues. As a consequence no 'objective value free' optimisation of a mono-criterion type can be done (since it is possible to optimise only one objective per time).
- The optimisation and compensation models do not aim at achieving a better environmental quality, but only at incorporating the environmental impacts in the traditional price and market system. Since the objective is to keep utility constant, complete substitution between environmental quality and economic growth is always allowed, then a weak sustainability philosophy is implied.
- From an intra-generational point of view, the compensation model presents strong distributive impacts; the monetary value of a negative externality depends on social institutions and distributional conflicts. If the people damaged are poor or of future generations, the cost of internalisation will be lower.
- From an inter-generational equity point of view, society has a much longer life expectancy than individuals, thus the value society attaches to natural resources and the environment is likely to deviate from the aggregate of individual values since the simple summation of individual preferences may imply the extinction of species and ecosystems (future generations are not in the market).

Because of the deep uncertainties present in evaluation methods, it is a case of 'post-normal science'. Quality assurance requires 'extended peer communities', which include all those with a stake in the issue who are prepared to engage in dialogue. The criteria of quality in this new context will, as in traditional science, presuppose ethical principles. But in this case, the principles will be explicit and will become part of the dialogue.

According to Simpson and Walker (1987), although cost-benefit analysis is still widely practised, because it addresses real and continuing problems, the technique has been frequently called into question. They identify three major limitations in the technique, and offer suggestions for improvements. While costs and benefits of energy investments have several dimensions, CBA attempts to give all effects an economic value. This often requires arbitrary and subjective judgments which have discredited the technique. It is proposed that CBA should be extended from the single economic dimension to include three others: environmental, technical and the analysis of risk (much like MCA). It is suggested that important subjective judgments should be made by the ultimate (political) decision maker, and not by the analyst.

Spangler (1984) contends that there seems to be an asymmetrical treatment of costs and benefits in our policy analyses regarding technological alternatives. Because of societal pressures on political processes, we seem to work harder at quantifying costs than benefits. An excessive zeal in reducing the adverse effects (or costs) to society from technologies can also lead to a reduction in their benefits out of all proportion to the societal value gained in the reduction of these adverse impacts.

Spangler denotes the tension between 'hard science' and 'intangibles' as the problem of 'apples and oranges'. According to Spangler (1984), there have been a number of attempts to solve the apples and oranges problem by converting the oranges to apples – a sort of challenge not drastically different from the quest to transmute lead to gold. One such approach is through the device of convening a panel of experts to develop judgementally a set of numerical index numbers and weighting factors for the various technological effects. These are then combined in a socioeconomic impact matrix that compares and derives a composite score for various technological options. Cleary et al. (1976) developed such an experimental socioeconomic impact matrix for evaluative index ratings (or scaling factors) of alternative cooling systems for a proposed nuclear power plant using a geometric scale ranging from 1 to 8.

4.2.2 Advantages and disadvantages

CBA is widely applied in the field of energy and the environment due to several advantages, although it also contains some serious drawbacks. The general beauty of CBA is the clear rationality behind it and the general transparency with regard to its underlying assumptions and methodological framework. In addition, it appeals to decision-makers because of the capability of bringing together all sorts of qualitative and quantitative information into one monetary value. And finally, the discipline with which the CBA lists the different costs and benefit items, covering all internal and external, and direct and indirect effects is considered an amenity.

On the downside, the quantification and monetarisation of all effects can become problematic when certain effects are highly uncertain or extremely difficult to measure. These type of effects are generally included in the cost-benefit framework as ‘pro memori’ posts, with the possible danger that these effects are not given the proportional weight they could deserve in the decision-making process into which the CBA results are fed in. Especially external effects, for which no markets exist, are difficult to monetarise. Although techniques exist with which external effects might be estimated (such as revealed or stated preference techniques) they can lead to quite a large range of possible outcomes (Kopp et al., 1997; Lebret et al., 2005).

The fact that the CBA strives for monetarisation of all costs and benefits that culminates into one monetary indicator can give rise to a false appearance of accuracy. Although uncertainty can be reflected in the overall sensitivity analysis it is recommended that when particular type of uncertainties is fundamental in the overall assesment (in the sense that results are largely dependent) effects should be expressed in ranges instead of one number (CE, 2007). This warrants that the uncertainty actually shows up in the final result of the CBA. There is also fundamental critique on the welfare theory that underlies the CBA (Gowdy, 2004; OECD, 2006). Based on welfare theory only judgements on efficiency can be made, not on the equity since this falls outside the scope of the theory. The problem is that it is inherently difficult to compare the utility of the one person with that of the other. CBA also has a drawback in the communication of the results to decision-makers in the sense that it has a high ‘black-box’ character (Koopmans, 2006). On the more practical side, an integral analysis is generally very time-consuming due to the elaborate mapping of costs and benefits.

A major difficulty is the determination of the discount rate to be applied. In order to include the monetary impact of policy actions in the future the time value of money needs to be taken into consideration. All costs and benefits need to be brought forward to one particular moment in time (for example the moment of decision-making). The level of the discount rate determines to which extent costs and benefits realised in the future are taken into account. As a result, long-term effects tend to have a relatively low weight in the total cost-benefit assesment. The discussion on the value to be used for the discount rate is particularly controversial for issues regarding sustainability. For example, it is argued that the discount rate applied to environmental damage should be lower than the discount rate applied in the quantification of other aspects (Koopmans, 2006; CE, 2007). Also, the present value of a marginal tonne of CO_2 reduced depends on the discount rate used (Hanly and Tinch, 2004). The use of discount rate is also critisised from the perspective of intergenerational equity (Lebret et al., 2005; OECD, 2006).

5 Methodologies for economic valuation of external effects

Chapter 2 presented *methodological frameworks* for evaluation of a technology or option. Cost benefit analysis (CBA) includes *monetary quantification* of external effects of a technology, which is why CBA is the framework of choice if monetary quantification is needed. Unlike many multi-criteria analysis (MCA) studies suggest, it does not exclude monetisation per se. With this distinction in mind, there are *methodologies* to assess or evaluate potential impacts during stages of the life cycle of a power plant. If there is a need for monetarisation of impacts, the methodologies used for economic valuation that are distinguished are based on *avoidance costs* (paragraph 5.1) or *damage costs* (paragraph 5.2).

5.1 Avoidance costs

5.1.1 Definition and application

Traditionally, the policy debate on climate change has focused on the cost of emission mitigation, e.g. the cost of GHG emission reduction. Whereas the costs of emissions of local/regional pollutants may be based on *damage costs* as the impacts are mainly local or regional by nature, and the temporal extent may also be limited, the impacts of GHG emissions are global and long-lasting (up to hundreds of years).

The methodology denoted as 'avoidance costs' focuses on quantification of the *abatement costs* (instead of damage costs). Mitigation costs of GHG emissions use to be based on abatement costs, e.g. in the updated impact pathway approach or ExternE methodology, as a proxy for environmental cost (external cost) analysis. The recommended value for CO_2 is €19 per tonne of CO_2 (NEEDS, 2006). This cost figure is based on a marginal abatement cost (MAC) for GHG emissions reductions in Europe required by the Kyoto Protocol for the timeframe 2008-2012[1].

5.1.2 Strengths and weaknesses

Cost data based on marginal abatement cost (MAC) appear to be very useful for the not too distant future, as the damage inflicted by GHG emissions might *in future decades* prove to be higher than the MAC value of CO_2 (and corresponding costs for CH_4 and N_2O) experienced today in the European Emissions Trading Scheme (ETS). Therefore, higher costs than €19 per tonne of CO_2 and corresponding cost levels for other GHGs (CH_4 and N_2O) cannot be excluded. According to (NEEDS, 2006) and (Tol, 2007), however, MAC data (€19 per tonne of CO_2) are also useful for long-term policy analysis (2020, 2030, and 2050). In the words of Richard Tol:

> …. "based on all available evidence, it is hard to argue that climate change impacts justify a carbon price of much more than $50/tC ($13.6/t CO_2). At the same time, it is hard to argue that a $50/tC carbon tax would lead to carbon dioxide concentrations below 550 ppm".

In order to put the above mentioned cost data for CO_2 (€19 per tonne), CH_4, and N_2O and the phrases quoted above in perspective: according to Richard Tol, a cost level of $26/tonne CO_2

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1 Using IPCC global warming potentials (GWPs), this translates into an avoidance cost for methane (CH_4) of €399 per tonne, and for nitrous oxide N_2O of €5890 per tonne).

would be equivalent to a scenario of 500 ppm in the long term which would be concomitant with an increased temperature worldwide of 2.2°C above pre-industrial levels (NEEDS, 2006). This scenario of 500 ppm is more stringent than the one touched upon in the above quote of Richard Tol, which is why the cost of CO_2 is higher ($26/tonne vis-à-vis $13.6/tonne of CO_2).

A more fundamental issue is that avoidance costs are not social costs, which are the standard metric required in the ExternE (and follow-up studies) impact pathway approach. Another reason why avoidance costs do not appear attractive for use in environmental cost analysis is that its use can lead to circular reasoning in policy cost-benefit analysis (when comparing ‘externalities’ against the costs of policies). What is more, because of the different atmospheric lifetimes of different GHGs, conversion of monetary values using one set of avoidance costs of GHG emissions may be incorrect as this does allow to adjust for discounting (unless different sets for CO_2, CH_4 and N_2O are used dependent on the discounting period). For an analysis of the effect of discounting on the costs of greenhouse gases, reference is made to (NEEDS, 2006).

5.2 Damage costs

5.2.1 Definition and application

On behalf of the European Commission a methodology was developed to quantify the *energy external costs*. The research resulted in the development of a methodology called the *Impact Pathway Approach*. This approach to quantify environmental impacts is described in the ExternE research program (Externalities of Energy). Four main steps are distinguished:

- Emission: specification of the relevant technologies and pollutants.
- Dispersion: calculation of increased pollutant concentrations in all affected regions.
- Impact: using exposure-response functions for calculation of impacts cumulated exposures.
- Cost: valuation of impacts in monetary terms.

Therefore, the methodology denoted as ‘damage cost’ aims to quantify potential environmental impacts based on quantifiable damage costs incurred by humans, flora and fauna, buildings, etc. from emissions (to air, water, soil) that arise in case of a specific (power generation) technology.

ExternE includes issues such as the exposure-response functions; especially health impacts from air pollution; the monetary valuation of these impacts (‘value of statistical life’); accidents in the whole energy supply chain; and the assessment of other impacts like global warming, acidification and eutrophication. Models for pollutant dispersion have been developed. Also, case studies have been performed. The latest methodology update was made public in 2005. Some costs parameters used in the first ExternE project have been revised or the methodology has been updated or extended over time (NewExt project, NEEDS, CASES, EXIOPOL, etc).

As shown above, the *Impact Pathway Approach* not only addresses *air emissions and impacts* but also - in principle - emissions and impacts to *water, land and soil*. The latter emissions and impacts, however, have not been investigated as thoroughly. Follow-up projects - NewExt, NEEDS, CASES, EXIOPOL - comprise *inter alia* emissions and impacts to water, land and soil.

Appendix C provides a view of emissions, dispersion, impact category and valuation used in the *Impact Pathway Approach*.

5.2.2 Strengths and weaknesses

There are three major issues to the *Impact Pathway Approach* underlying the determination of damage costs, namely:

- Geographical;
- Dispersion; and
- Impact category.

Geographical
When considering a Life Cycle Analysis (LCA), the use of the current ExternE methodology often implies a very important simplification. All emissions are being considered, or deliberately set, as originating from one source. While this assumption can be fair for emissions that have an impact on a global scale on a long term, local impacts in a different stage of the life cycle (for instance, emissions from coal mining in Australia) are considered as emissions from, for instance, a single source in Europe. As upstream emissions have local impacts, this assumption is open for discussion whether the single source simplification should be used at all or alternative methods are to be preferred. Moreover, no harmonised region-specific methodology exists for different world regions.

Within the NEEDS and CASES studies, a webtool has been developed, EcoSenseWeb. For case studies, this tool gives the user the means to make calculations of external costs for single sources in Europe. Since the whole of North-west Europe, North Africa and part of Russia is included, a detailed assessment of external effects covering these areas during the operational phase of a power plant is feasible. RiskPoll is a program that uses the *Impact Pathway Approach* but is more general in its approach compared to the detailed data involved in EcoSense. It is not constrained in its use by geography, so in principle results can be used from RiskPoll to check the order of magnitude of specific results from site dependent sources of emissions. It also can be useful to determine the external costs of emission in an area where only general characteristics are available.

Limitations with regard to dispersion
Some emissions and impact categories require the use of dispersion models. In order to be complete in the external impacts, modelling the dispersion of emissions also involves dispersion of the emissions with disposition into the water. External effects of aquatic emissions in general are not taken into account in the current literature. Aquatic emissions to seawater, for instance as a consequence of transport of coal over oceans and seas, is currently not modelled.

Nevertheless, an enormous effort has been made to come up with detailed, well researched and cross-verified methodologies to address dispersion of emissions. For many emissions those insights are valuable and very useful.

Impact category
In each stage of a Life-cycle analysis a specific set of important impact categories is appropriate. In principle the number of impact categories included in the external valuation can be enormous. The ExternE project and its successor projects are already taking into account in their studies the damage costs of health impacts, as well as effects on land, soil and materials. But as already introduced in the beginning of this report, not every impact category or end-point can be expressed quantitatively and/or in monetary value.

6 Overview of typical impact categories assessed

An overview of environmental impacts of power production is given as an illustration in Table 4.1. This overview is not complete, in the sense that when performing a life-cycle analysis (LCA), each stage in the total life cycle should address environmental impacts for all impact categories that are relevant. Table 6.1 provides an overview of relevant impact categories and options for evaluation of the external effects as addressed in the ExternE research projects.

Table 6.1 *Overview of environmental impacts in ExternE from the use of power plants and feasibility to quantify and/or monetise direct external and direct internal effects respectively (QL = qualitative, QN = Quantitative)*

Impact category	**Direct external effects**		
	Impacts power plant	**Quantitative or qualitative**	**Economic valuation of impact?**
Land use	Occupied area and surrounded regulated zone	QN	QN
Cultural heritage	Amenity loss	QL	QL
Building material	Precipitation of material	QN	QN
Biodiversity	Disturbance ecosystems/dispersion species	QN	QN
Visual impact	Impacts of elements (e.g. stack) considering surroundings	QL	QL
Gaseous emissions and immission	CO_2, NO_x, SO_x, hydrocarbons, PM, VOC, heavy metals	QN	QN
Waste management	Solid waste handling, quality and quantity of waste flows	QN	QN
Noise, light and odour nuisance	Noise zoning Light emissions/immission Odour emissions/	QN	QL

Source: adjusted after consulting Koornneef et al, 2008.

Some impact categories are quantifiable, some impact categories are not. To a certain extent there can be made an economic valuation of a quantitative impact.

7 Conclusions

The present study provides an overview of the current status of literature and its approaches to quantify external effects of impacts categories of *CCS chains*. External effects from power generation are usually addressed as part of an analysis in order to compare the effects of several technologies. A methodological framework can also be used to compare the effect of a (policy) measure. The present study reviews a number of methodologies to include external effects (from power generation) in the standard economic assessment.

Multi-criteria analysis (MCA) enables the researcher to include both quantitative and qualitative criteria to evaluate a (power generation) technology. Quantitative and qualitative scores on criteria are neatly summed up to result in an overall evaluation score of different technology options. Another characteristic of MCA is that the methodology can show the different valuations for the assessed criteria by all stakeholders involved. By varying the weight of the criteria along with stakeholder or perspective, MCA results in a ranking of technology options.

MCA has been used until this date predominantly for the assessment of energy policies, e.g. with regard to planning in general, renewable energy, or bio-energy. MCA has several advantages. Firstly, the researcher is able to use all types of input data in the analysis: the input information does not need to be quantitative in nature. Any type of information can be combined: MCA acknowledges the multi-dimensionality of input data. Secondly, MCA allows for policy measures to be assessed with respect to the performance on more than one goal. It can accommodate goals such as sustainability, health and equity. This feature is especially important when issues are adressed where other goals than efficiency (affordability) are highly relevant. This could for example hold for issues of sustainability where the equity across current and all future generations is deemed relevant.

Thirdly, the method can explicate the valuations of different stakeholders for a particular ranking of policy measures based on different weighings being attached to the defined criteria. For example, regarding the evaluation of allowing for oil and gas production in the Waddenzee, Greenpeace and the NAM are likely to have different valuations of the criteria defined under the policy goals of efficiency and affordability on the one hand, and sustainability on the other. Normally, when applying other types of evaluation methodologies, these preferences remain implicit and result in for example a different calculation of the 'probability times effect' of oil production permanently damaging the environment.

MCA is useful for setting priorities in energy policy. Therefore, it is possible that MCA may give a view on advantages and disadvantages of including CCS in the policy mix. Comparison between different options within the scope of CCS technologies may, however, not be easily addressed based on MCA.

Cost-benefit analysis (CBA) is a well-known framework for evaluation of impacts of technologies. It is a monetary evaluation of the expected costs and benefits of a technology. Generally denoted as social cost-benefit analysis, CBA not only analyses the internal direct costs and benefits of the technology, but also the indirect and external costs and benefits. Cost-benefit analysis is a useful and rather straighforward tool in case of monetary *quantification* of external costs and benefits. The extent to which CBA provides a useful tool for evaluation of a specific (power generation) technology depends on the availability of data, methodologies to quantify external costs and benefits, etc.

CBA has been used for various energy and climate related issues, such as the relationship and synergy of policies focused at reduction of GHG emissions and local air pollution, the costs and benefits of nuclear power to the UK, and the costs and benefits of investment in different power generation technologies in general.

CBA is widely applied in the field of energy and the environment due to several advantages, although it also contains some serious drawbacks. The general beauty of CBA is the clear rationality behind it and the general transparency with regard to its underlying assumptions and methodological framework. In addition, it appeals to decision-makers because of the capability of bringing together all sorts of qualitative and quantitative information into one monetary value. And finally, the discipline with which the CBA lists the different costs and benefit items, covering all internal and external, and direct and indirect effects is considered an amenity.

CBA is useful for evaluating the costs of various energy alterntives based on quantification of external costs and benefits. Therefore, CBA may be a straigtforward way to detemine the costs and benefits of fossil fuel based electricity generation *with* and *without* CCS. The accuracy of the resulting costs and benefits depends not only on the methodology used but also on the accuracy of the cost data, which may be a problem for some external costs.

Besides, there are *methodologies* to assess or evaluate potential impacts during stages of the life cycle of a power plant. If there is a need for monetarisation of impacts, the methodologies used for economic valuation that are distinguished are based on *avoidance costs* or *damage costs*. Traditionally, the policy debate on climate change has focused on the cost of emission mitigation, e.g. the cost of GHG emission reduction. Whereas the costs of emissions of local/regional pollutants may be based on *damage costs* as the impacts are mainly local or regional by nature, and the temporal extent may also be limited, the impacts of GHG emissions are global and long-lasting (up to hundreds of years).

The methodology denoted as ‘avoidance costs’ focuses on quantification of the *abatement costs* (instead of damage costs). Mitigation costs of GHG emissions use to be based on abatement costs, e.g. in the updated impact pathway approach or ExternE methodology, as a proxy for environmental cost (external cost) analysis. For the determination of damage costs a methodology was developed on behalf of the European Commission to quantify the *energy external costs* (ExternE). The research resulted in the development of a methodology called the *Impact Pathway Approach*. This approach to quantify environmental impacts is described in the ExternE research program (Externalities of Energy). Four main steps are distinguished:

- Emission: specification of the relevant technologies and pollutants.
- Dispersion: calculation of increased pollutant concentrations in all affected regions.
- Impact: using exposure-response functions for calculation of impacts cumulated exposures.
- Cost: valuation of impacts in monetary terms.

Therefore, the methodology denoted as ‘damage cost’ aims to quantify potential environmental impacts based on quantifiable damage costs incurred by humans, flora and fauna, buildings, etc. from emissions (to air, water, soil) that arise in case of a specific (power generation) technology.

Just like other methodologies, the ExternE methodology gives much attention to emissions of GHG, air pollutants, and radio nuclides. Other impacts that have been added to the three main categories of emissions to the air (‘air pollutants’, GHGs, and radio nuclides) are:

- Land use change;
- Cultural heritage;
- Building materials;

- Biodiversity;
- Visual impact and noise.

The ExternE methodology may be applied to CCS. 'ExternE' has the advantage that it draws on a relatively long history of quantification of external effects (from power generation). It is used as a corner stone for development of sustainable energy policies. Also, it enables the researcher to take into account long-term effects from power generation, e.g. the effects of GHG emissions. Limitations of the ExternE methodology relate to the geographical area considered, limitations with regard to dispersion and with regard to impact category.

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Appendix A - Typical emissions to air of power generation and CCS

TNO/UU (2008) inventoried the impacts of different CO_2 capture technologies on trans-boundary air pollution emissions relevant for the National Emission Ceiling (NEC) for the Netherlands in 2020. The study found that emission factors presented in the literature for energy conversion technologies with CO_2 capture are most often based on assumptions, and not on measurements, since very few actual full-scale installations exist. In addition, data in the literature are often not consistent with respect to year of costs, time horizon, interest rates, lifetime, reference technology, fuel quality and fuel prices. Yet, a number of conclusions could be drawn on the NEC (National Emission Ceiling) emissions of power generation technologies with different types of CO_2 capture technology.

Other impacts of CO_2 capture are the safety of CO_2 transport and storage (leakage) and toxic wastes from chemical solvents that will be produced in large quantities. Also the impact of emissions of amines and degradation products to air form the CO_2 capture unit can be significant. These are not studied in detail in this project.

Box A.1 ***Literature findings on emissions to air of power generation and CCS (TNO/UU, 2008)***

SO_2

In general, SO_2 emissions are expected to be very low for power plants with CO_2 capture, since for CO_2 capture deep flue gas desulfurization has to be performed. The sulphur content of natural gas is very low and thus SO_2 emissions are expected to be negligible for gas-fired power plants with and without CO_2 capture. For all coal-based power generation technologies, application of CO_2 capture results in a decrease of the emission of SO_2 per kWh. Sulphur has to be removed to avoid degradation of the solvent in post combustion CO_2 capture processes. In case of pre-combustion and Oxyfuel CO_2 capture the efficient treatment of the syngas and flue gas, respectively, is expected to result in low SO_2 emissions.

NO_x

In the post-combustion concepts NO_x emissions are believed to be largely unaffected by the (amine based) capture process, although consensus seems to be absent. The NO_2 part of NO_x, being 10%, is assumed to be removed since it causes degradation of the amines. Hence, the NO_x emissions per kWh seem to increase almost proportionally to the increase in primary energy demand related to adding CO_2 capture. In literature lower, equal and higher NO_x emissions per kWh are reported when applying pre-combustion CO_2 capture. NO_x emissions from Oxyfuel concepts are in general expected to be very low, particularly for plants based on natural gas. However, the literature is ambiguous about this subject for coal-fired plants. In addition, in the Netherlands, a performance standard rate for NO_x is mandatory for power plants, currently (2010) set at 40 g/GJ fuel input, but decreasing to 37 g/GJ by 2020. A high energy penalty of CCS power plants based on post-combustion or pre-combustion will thus result in higher NO_x emission levels.

NH_3

Only for post-combustion CO_2 capture concepts NH_3 emissions are estimated to significantly increase (with more than a factor 20). This is assumed to be caused by solvent degradation (i.e. an amine based solvent) that is used in the post-combustion capture concept. However, the uncertainty regarding this estimate is considered to be high. In this respect, improvements in the (amine) solvent are currently a subject of research, development and testing.

PM
The emission of particulate matter (PM) from natural gas fired cycles in general can be considered negligible. PM must be removed for a stable capture process and is subsequently expected to be removed by the post-combustion capture process. PM emissions are expected to increase per kWh as a result of the efficiency penalty related to CO_2 capture. In the literature assumptions on this subject vary considerably, however. The application of pre-combustions CO_2 capture may reduce PM2.5 emissions from an Integrated Gasification Combined Cycle (IGCC) plant. In the literature, PM emissions are estimated to be lower per kWh also for coal-fired oxyfuel concepts, compared to conventional pulverized coal-fired power plants.

NMVOC
Pre-combustion CO_2 capture can increase or decrease the non-methane volatile organic compound (NMVOC) emissions. Quantitative estimates for this reduction are absent in the literature. It is largely unknown whether and to what extent NMVOC emissions are affected by the CO_2 capture process in the Oxyfuel and post-combustion concepts. Quantitative estimates for NMVOC emissions were not found in the pertaining literature.

The effect of biomass co-firing in power plants with pre- or post-combustion CO_2 capture is not well investigated, although it seems likely that both SO_2 and NO_x emissions will be lower, since the sulphur content and the flame temperature will be lower for biomass than for coal. For other emissions it is not possible to make an educated guess. In case of Oxyfuel concepts, effects of biomass co-firing on the performance and emission profile are currently also unknown.

Appendix B - Emissions and dispersion in ExternE

B.1 Emissions

In the *Impact Pathway Approach* the emissions are distinguished in three broad categories:

- air pollutants;
- greenhouse gases;
- radio nuclides.

The air pollutants that are included in the model are: Major parts: SO_2, NO_x, PM_{10}, $PM_{2.5}$, NH_3, and NMVOC. Minor emissions considered are Cd, Hg, As, Pb, Cr, Cr-VI, Ni, and H_2-CO (formaldehyde). The greenhouse gases that are evaluated are: CO_2 (carbon dioxide), CH_4 (methane), and N_2O (nitrous oxide). The radio nuclides included are the following (Table B.1).

Table B.1 *Radio nuclides included in the ExternE evaluation*

Aerosols	Radioactive aerosols, unspecified, to air
C-14	Carbon-14
Cs-137	Cesium-137
H-3	Tritium
I-129	Iodine-129
I-131	Iodine-131
I-133	Iodine-133
Kr-95	Krypton-85 (noble gas)
Ra-222	Radon-222
Th-230	Thorium-230
U-234	Uranium-234
U-238	Uranium-238
Sr-90	Strontium-90
Ru-106	Ruthenium-106
Pb-210	Lead-210
Po-210	Polonium-210
Ra-226	Radon-226

B.2 Dispersion

Dispersion of radio nuclides is not modelled like airborne pollutants. But exposure modelling in a number of representative locations is available in literature and these results were used to evaluate the effects from the release of radio nuclides due to normal operation.

Dispersion of minor emissions is not modelled. An averaged concentration is assumed based upon which external costs are estimated by applying general monetary values.
Country specific values for heavy metals, based on ESPREME and NEEDS calculations have been introduced. ESPREME (Internet Source 1) was a EU-project especially set-up for this purpose. Pathway for emissions to air via soil and water for As, Cd and Pb is included. However, the values per tonne are applicable to emissions to air only. It should be noted that the values for Cr and Cr-VI are to be used alternatively and not simultaneously.

The impact area is calculated on 3 different resolutions. The local impact around the facility is determined at a 10*10km grid, covering 100km^2. A 50*50km grid is used to for region impact assessments, i.e. European wide and a Northern Hemispheric impact assessment uses a 0.5 degrees resolution.

- The meteorological model for dispersion of primary particles is the Industrial Source Complex Model, developed by the US-EPA. A Gaussian plume model is used for the local scale assessment on a 10*10 km grid centered on the site of the plant. This model covers no chemical reactions; hence it covers primary pollutants only. Impacts on human health can be evaluated on a local scale..
- Source Receptor matrices are used for regional modelling based on EMEP/MSC-West Eulerian dispersion model. Grid cells have a 50*50km area. Meteorological data for the years 1996, 1997, 1998 and 2000 were averaged and used for typical conditions and 2003 condition were used for the years 2010 and 2020, because of the relatively warm conditions in that year. Impacts consist of primary and secondary pollutants on the human health, crop, building material and eco systems.
- For intercontinental transport in the Northern Hemisphere and from the Northern African countries also Source Receptor matrices were being used. Meteorological data has been used from the year 2001. Emissions are based on EDGAR (2000, Emission Database for Global Research) (Internet Source 2) and within EMEP area (European monitoring and Evalution program) (Internet Source 3) EMEP emissions are used. Impacts consist of prim[a]ry and secondary pollutants on human health.

The ExternE Methodology update 2005 report describes the dispersion as follows:

> "The principal greenhouse gases, CO_2, CH_4 and N_2O, stay in the atmosphere long enough to mix uniformly over the entire globe. No specific dispersion calculation is needed but the calculation of impacts is extraordinarily complex, see the documentation published by the Intergovernmental Panel on Climate Change (IPCC).[4]
>
> For most other air pollutants, in particular PM_{10} (particulate matter with diameter less than 10 µm), NO_x and SO_2, atmospheric dispersion is significant over hundreds to thousands of km, so both local and regional effects are important. ExternE uses therefore a combination of local and regional dispersion models to account for all significant damages. The main models for the local range (< 50 km from the source) have been the Gaussian plume models ISC for point sources such as power plants, and ROADPOL for lines sources (emissions from transport).
>
> At the regional scale one needs to take into account the chemical reactions that lead to the transformation of primary pollutants (i.e. the pollutants as they are emitted) to secondary pollutants, for example the creation of sulphates from SO_2. Here ExternE uses the Windrose Trajectory Model (WTM) to estimate the concentration and deposition of acid species. WTM is a user-configurable Lagrangian trajectory model, derived from the Harwell Trajectory model. The modelling of ozone is based on the EMEP MSC-W oxidant model EMEP is the official model used for policy decisions about trans-boundary air pollution in Europe.
>
> Several tests have been carried out to confirm the accuracy of the results. For example, we have checked the consistency between ISC and ROADPOL, and we have compared the concentrations predicted by WTM with measured data and with calculations of the EMEP program.

Whereas only the inhalation dose matters for the classical air pollutants (PM_{10}, NO_x, SO_2 and O_3), toxic metals and persistent organic pollutants also affect human health through food and drink. For these a much more complex IPA is required to calculate ingestion doses. During the NewExt phase of ExternE (see ExternE, 2005) two models were developed for the assessment of external costs due to the emission of the most toxic metals (As, Cd, Cr, Hg, Ni and Pb), as well as certain organic pollutants, in particular dioxins.

One of these models ('WATSON') is a multi-zonal model that links the regional air quality model of EcoSense to a soil and water multimedia model of the Mackay level III/IV type. The other model is based mostly on transfer factors published by EPA (1998), with some supplemental data of IAEA (1994 and 2001). These transfer factors account in a simple manner for the transport of a pollutant between different environmental compartments, for example the uptake by agricultural crops of a pollutant from the soil. The uncertainties of these models are large, but at least one has approximate values for the pollutants of concern here. The results published by ExternE are based on both of these models."

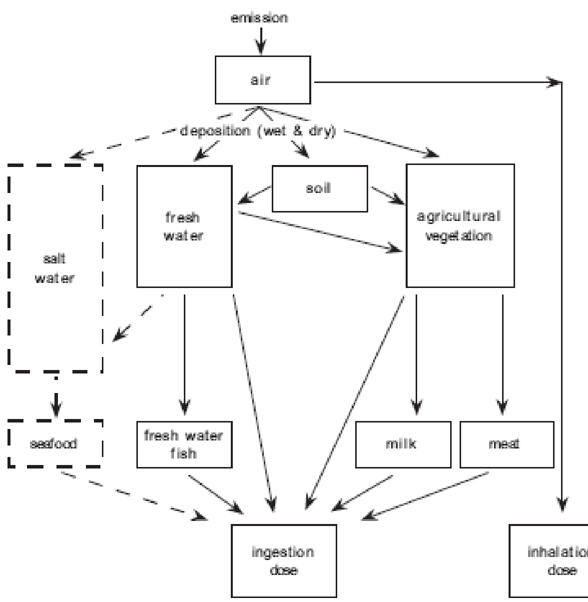

Figure 4.3 Pathways taken into account for health impacts of air pollutants. Direct emissions to soil or water are a special case where the analysis begins at the respective "soil" and "water" boxes. The impacts from seafood have not yet been calculated.

Figure B.1 *ExternE pathway overview*
Source: ExternE, 2005.

C.3 Impact categories

Land use change

Not assessed in EcoSense is land use change due to mining or in (tropical) areas through feedstock supply. The geographic location for which the ExternE methodology was developed focuses on the European continent and Northern African countries and only considers local impact categories i.e. land-use change due to the construction of a power plant. Land use change in the EcoSense program is taken into account under the impact of biodiversity change.

Cultural heritage

The damage costs of cultural heritage are not yet implemented in EcoSense or RiskPoll. Research to this aspect within ExternE has been done; currently methodologies are available to result in damage costs for cultural heritage. In the ExternE methodology 2005 two approaches are described. Although methods have been described, they are in need for a complete inventory of cultural heritage, or buildings at risk due to amenity loss in order to provide a complete result for the affected geographic region,

Building materials

For impacts on building materials a damage cost calculation can be performed. These costs are related to a certain required maintenance and maintenance frequency of materials used for buildings due to the precipitation of rain, hydrogen ions, temperature and NO_x, SO_2, NH_3 emissions (see Table B.2). For several materials concentration response functions are available including their maintenance costs per m^2. The materials effected involved in the assessment are:

Table B.2 *Maintenance cost of materials included in ExternE*

Material
Galvanised steel
Limestone
Mortar
Natural Stone
Paint
Rendering
Sandstone
Zinc

Source: ExternE 2005

Biodiversity

Loss of bio diversity due to electricity production is evaluated in two ways:
1. Bio-diversity Losses due to land-use changes;
2. Bio-diversity Losses due to acidification and eutrophication.

The first aspect involves the land-use change due to construction of the facility (when building a facility land use can be changed from natural forest area to industrial area, having an effect on the number of species) while the second aspect involves the acidification and eutrophication of the soil due to emissions of SO_2, NO_x and NH_3. The approach to measure bio-diversity loss is the potentially disappeared fraction (PDF) and calculates the restoration costs.

For each 50 *x* 50 km grid cell the share of natural soil is available, from the regional modeling dispersion model, the deposition of the emissions and finally a ‘pressure index’ per country is used as a sensitivity indicator of the soil. The evaluation is based on minimum restoration costs.

That is to say, the costs to improve a land use type from one with a lower number of species to one with a higher number of species.

The approach to calculate monetary values was addressed in the NEEDS project but reviewed during CASES (CASES, 2008a and b; Internet Source 4):

> "The NEEDS approach to the assessment and valuation of biodiversity or ecosystem damages due to energy-related externalities is based on a number of assumptions:
>
> 1. A change in the potentially disappeared fraction (dPDF) is an acceptable indicator for ecosystem damage.
> 2. The PDF change (dPDF) per kg pollutant used in the approach is 1) a reasonably accurate description of 'true' ecosystem damages in the Netherlands; and 2) it is valid for all other European countries.
> 3. Pollution-induced ecosystem damage only takes place on natural lands (no ecosystem or biodiversity damage on agricultural and urban lands).
> 4. There is a direct (linear and positive) relationship between background levels of acidification and eutrophication, and marginal unit damage.
> 5. Restoration cost is a reasonable proxy for willingness-to-pay; and transferring restoration cost to other countries by adjusting it with purchasing power standards is a valid methodology.
>
> With respect to the first two assumptions, it should be mentioned that the current NEEDS method only takes damage of terrestrial ecosystems into account. Damages to aquatic ecosystems have not been taken into account.
>
> In the mid-1990s, a fairly comprehensive study in Norway on the damage of acidification to fish stocks found a willingness-to-pay to reduce the emissions of SO_x of 4.0 to 7.7 €/kg for sulfur deposition above critical loads. We can compare this to the NEEDS estimate of SO_2 damage to terrestrial ecosystems in Sweden **(…)** to reflect that we are only considering deposition above critical loads (…) the NEEDS estimate for terrestrial ecosystem damage is € 0.67/kg SO_x. This would suggest that the value of damages to aquatic ecosystems could be substantially higher than damages to terrestrial ecosystems. In our conclusions on aquatic damages we do stress, however, the uncertainties in the valuation studies and the difficulties of transferring country-specific estimates to other European countries.
>
> Another aspect of the first two assumptions, specifically the validity of the relationships between deposition of airborne pollutants and PDF change across Europe, could benefit from additional future research. We have, however, not addressed this relationship in the current study. We have also not addressed the third and fourth assumption, that is, we have not studied biodiversity impacts on agricultural and urban lands and we did not address the relationship between background levels of acidification and eutrophication and marginal damage."

In this specific report a valuation method from the study in NEEDS, restoration costs, was compared to another method introducing a Willingness-to-pay value. Addressing the Willingness-to-pay method, using a meta-analysis of available literature and calculating regression parameters, the conclusion of the above evaluation is:

> "In summary, the willingness-to-pay approach to valuing ecosystem damage instead of the restoration cost approach increases the unit value of ecosystem damage due to SO_x deposition in Germany from € 0.26/kg to € 0.48/kg. The (…) function can be used for all countries (or even the sub-country level), provided information is available on population density, the shares of different ecosystems, and the average size of ecosystem areas in these countries (or at the sub-country level). Note that a big difference with the NEEDS approach is that country values are not dependent on per capita income, but on ecosystem characteristics and population density."

Visual impact

At the moment no reliable method is included in a software program to calculated a monetary value for visual intrusion. The studies available are rare and to site-specific. During the CASES study (CASES 2008a and b) it was concluded:

> "European studies that value aesthetic effects of wind parks are largely from the Nordic countries (Norway, Denmark and Sweden) and from southern Europe (France and Spain). Damage costs are highly project- and site-dependent, and are also very sensitive
> to the alternative or reference scenario ('how would electricity be generated without the wind turbine?'). We certainly believe that aesthetic effects of wind parks can in principle be monetized with a sufficient degree of certainty to be used in cost-benefit analyses. But before we implement functions and values in EcoSense we need more primary valuation studies. The relatively few studies available, and the 'bundle' of environmental goods valued (purposely or not) in valuation studies of aesthetic effects of hydropower, makes it difficult to foresee accurate benefit transfer. More original studies of good quality, and with a clear understanding of which (bundle of) environmental effects to value, are needed first. More studies are also needed for a robust valuation of the external costs of transmission lines."

Gaseous emissions and immissions

1. Global warming

The impact of the greenhouse gasses CO_2, CH_4 and N_2O are evaluated. The costs due to greenhouse gases are evaluated by damage, so including the year of release. For the evaluation the FUND2.9 model was used, assessing the impact of climate change over a long period, from 1950 to 2300.

Damage due to emissions of greenhouse gases and from that the resulting climate change has been assessed in 'EcoSenseWeb' by use of the model 'FUND2.9'. The model values the impact on a number of areas, namely agriculture, silviculture, non-managed ecosystems, sea-level rise, human chance of mortality, energy use and water stocks.

2. NEC emissions

CE (2008) carried out a social cost-benefit analysis of possible new objectives for NEC-emissions in 2020. The study included a valuation of external effects, mostly based on the ExternE (2005) methodology. It assessed external effects, impacts and the valuation of impacts. Next, typical damage figures were calculated, which were used to also calculate the effects in the years until and after 2020. The study considered four physical effects caused by the emissions of particulate matter ($PM_{2.5}$), NO_x, SO_2, NH_3 and NMVOC. Note that emissions of NO_x, SO_2, NH_3 and NMVOC result in secondary aerosols (Table B.4.).

Table B.4 *Relation between emissions and environmental effects*

	$PM_{2.5}$	NO_x	SO_2	NH_3	NMVOC
Acidification		√	√	√	
Eutrophication		√		√	
Particulate matter	√	√ [a]	√ [a]	√ [a]	√ [a]
Ozone near surface		√			√

a NO_x, SO_2, NH_3 and NMVOC result in secondary aerosols.
Source: CE, 2008.

These environmental effects have an impact on:

- Health (morbidity, mortality);
- Nature and ecosystems (split into acidification, eutrophication and ozon related effects);
- Productivity of agriculture;
- Buildings and cultural heritage.

These relevant relations are summarised below (Table B.5).

Table B.5 *Relation between environmental effects and impacts*

Impacts	Acidification	Eutrophication	Particulate matter (PM)	Ozone (O_3) near surface
Health, mortality			√	√
Health, morbidity			√	√
Nature and ecosystems	√	√		√
Productivity of agriculture	√	√		√
Buildings and cultural heritage	√		√	

Source: CE, 2008.

The relations between environmental effects and impacts were based on modelling work. Therefore, possible impacts could be related to emissions, using indicators shown in Table B.6.

Table B.6 *Relation between emissions and impacts, and relevant indicators*

	$PM_{2.5}$	NO_x	SO_2	NH_3	NMVOC
Health (mortality)					
Primary PM	Chronic YOLL [a]				
SIA [b]		Chronic YOLL	Chronic YOLL	Chronic YOLL	
SOA [c]					Chronic YOLL
O_3 [d]		Negligible	Negligible		Acute YOLL
Health (morbidity)					
Primary PM	Miscellaneous				
SIA [b]		Miscellaneous	Miscellaneous	Miscellaneous	
SOA [c]					% Mortality
O_3 [d]					Miscellaneous
Other					
Nature and ecosystems		Ha unprotected, excess	Ha unprotected, excess	Ha unprotected, excess	
Productivity agriculture		Production damage	Production damage	Production damage	Production damage
Buildings/cultural		Acid	Acid	Acid	

heritage	deposition	deposition	deposition

a YOLL = years of life lost.
b SIA = secondary inorganic aerosols.
c SOA = secondary organic aerosols.
d O_3 = ozone.
Source: CE, 2008.

3. Heavy metal emissions

For heavy metals country-specific values, based on ESPREME and NEEDS calculations, have been introduced. The pathway for emissions to air via soil and water for As, Cd and Pb is included. However, values per tonne are applicable to emission to air only (Table B.7). Note that the monetary values for Cr and Cr-VI are to be used alternatively and not simultaneously.

Table B.7 *Country-specific values for damage from heavy metal emissions*

Pollutant	Impact
Cd	Cancer
As	Cancer
Ni	Cancer
Pb	IQ loss
Hg	IQ loss
Cr	Cancer
Cr-VI	Cancer
Formaldehyde	Cancer

Source: NEEDS, 2009.

The valuation of impacts was based on the ExternE (2005) methodology. For *mortality* an average number of €50,000 for was used for chronic YOLL (years of life lost). An alternative approach would have been to use the so-called value of a statistical life (VSL) or the value of prevented fatality (VPF), often rated at €1million, based on the willingness to pay (WTP).

For *morbidity* several types of cost are considered, including resource costs (direct costs, e.g. for medical care), opportunity costs (lost productivity and spare time) and disutility costs (damage caused by pain, worries, trauma of relatives, based on willingness to pay, WTP, or willingness to accept, WTA). ExternE (2005) provides a detailed list of these costs. End-points included in the analyses are summarised below (Table B.8).

Table B.8 *Health effects included in EternE*

	Unit
Chronic bronchitis (27 and older)	Case by case
Hospital for respiratory defects (all ages)	Per intake
Hospital for heart problems (all ages)	Per intake
Days with limited activities (15-64 yrs)	Per day
Medicine use against respiratory defects, 20 yrs and older	Per day
Chronic lower respiratory defects, 15 yrs and older	Per day

Source: CE, 2008

4. Light, noise and odour nuisance

A number of impacts, on health and psychosocial level, due to noise exposure are described in literature. One state-of the art review from De Kluizenaar et al (2001) reports exposure –response functions for eight concrete stress-related health effects and sleep disturbances. It calculates expected values in days as a function of L_{den}; an expression of the noise level that can be calculated from the day (7h-19h), evening (19h-23h) and night (23h-7h) period. L_{den} denotes noise in dB(A) according to the ratio:

$$L_{\text{den}} = 10 \cdot {}^{10}\log \frac{12 \cdot 10^{\frac{L_{\text{day}}}{10}} + 4 \cdot 10^{\frac{L_{\text{evening}}+5}{10}} + 8 \cdot 10^{\frac{L_{\text{night}}+10}{10}}}{24}$$

Table B.9 shows a number of noise impacts distinguished.

Table B.9 *Noise impacts*

End-point	Expected value [a] (per 1000 adults exposed)
Myocard infarction (MI), fatal, Years of life lost (YOLL)	0.084 $\cdot L_{DEN} - 5.25$
Myocard infarction (non-fatal), days in hospital	0.504 $\cdot L_{DEN} - 31.5$
Myocard infarction (non-fatal), days absent from work	8.960 $\cdot L_{DEN}$ - 56
Myocard infarction, expected cases of morbidity	0.028 $\cdot L_{DEN}$ - 1.75
Angina pectoris, days in hospital	0.168 $\cdot L_{DEN}$ - 10.5
Angina pectoris, days absent from work	0.684 $\cdot L_{DEN}$ - 42.75
Angina pectoris, expected no. of morbidity days	0.240 $\cdot L_{DEN}$ - 15
Hypertension, days in hospital	0.063 $\cdot L_{DEN}$ - 4.5
Sleep disturbance, road traffic	0.62 $\cdot (L_{Aeq,23\text{-}07h}$ - 43.2) [b]
Sleep disturbance, rail traffic	0.32 $\cdot (L_{Aeq,23\text{-}07h}$ - 40.0) [c]
Sleep disturbance, air traffic	0.48 $\cdot (L_{Aeq,23\text{-}07h}$ - 32.6) [d]

Notes: [a] Threshold is 70 dB(A) L_{DEN} except for [b] 43.2 dB(A), [c] 40 dB(A) and [d] 32.6 dB(A); Other assumptions: MI, 7 years of life lost per fatal heart attack in average; base risk of MI: 0.005; survival probability of MI: 0.7; MI, morbidity: 18 days in hospital per MI, 32 days absent from work; Angina pectoris, base risk: 0.0015; days in hosp.:14 per severe episode; 20 days of morbidity per episode; $L_{Aeq,23\text{-}07h}$ as assessed outside at the most exposed façade.

Source: ExternE, 2005.

The valuation of amenity losses from noise have been described and researched in different literature. Almost always the noise source of research has been from road traffic, aircraft or rail noise. Industrial noise was valued with road traffic noise in one study of Oosterhuis and van der Pligts (1985). They used hedonic pricing to calculate a value. They found a Noise Depreciation Sensitivity Index (NDSI) value of 0.4% for the combined impact of the sources. That means the change in the average percentage in property prices per decibel.

The studies known do not provide enough information to come up with a general applicable method for practical use in software. Therefore the above results are not taken into account in the software tools Ecosense or RiskPoll.

C.4 Valuation

For valuation the specific assumptions and categories involved are that extensive that an overwhelming extension of this report would be the result.

Above that, for the purpose of providing an overview of the available evaluation frameworks for impact categories of power production the exact valuation parameters in the monetisation process of external effects, are of secondary interest.

As a consequence, for the original valuation parameters one is referred to the CASES website (Internet source 5), or for the most up to date numbers, to the literature appendix of (CE, 2010).