Integrated Decision Support for the Sustainability Assessment of Low Carbon Energy Options in Europe

Geïntegreerd beslissingsondersteunend systeem voor de duurzaamheidbeoordeling van laag- koolstof energie-opties in Europa

Thesis

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They say that “the journey matters more than the destination itself”. In my case this is partly true as reaching my destination and completing my PhD, is both a great reward and relief at the same time. It was a long journey indeed, but like Odysseus’ journey to reach Ithaca, it was not easy and it had many ups and downs, many challenges both at a professional and personal level. Since I started my PhD, and after 14 years, while working in different projects and organizations, I have succeeded to reach my destination and finalize my PhD thesis. This objective would not have been achieved without the great support I have had during all of these years by many people to whom I am deeply grateful.

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PhD Brief Summary

The PhD research aims at developing and applying a hybrid weighting methodology for the elicitation of local stakeholders' preferences regarding an integrated set of sustainability and resilience evaluation criteria during the assessment of low-carbon energy technologies. The overall methodology has been applied and tested for the integrated sustainability evaluation of selected low-carbon energy technologies in Europe from a local stakeholders' and local governments' perspectives. The researcher developed and applied a hybrid weighting methodology based on different Multiple Criteria Analysis (MCA) techniques to test the consistency of stakeholders' preferences. The methodology was piloted based on a small-scale European local stakeholders' survey within the framework of Covenant CapaCITY, an Intelligent Energy Europe project, but also through another survey among 32 main European local governments. It became evident that the local stakeholders and governments who participated placed high priorities on aspects such as CO_2eq emissions reduction, ecosystem damages reduction, and resilience to climate change during the evaluation of low-carbon energy technologies. Considering the overall energy technologies integrated assessment, wind off-shore, solar photovoltaic, hydropower, and wind on-shore achieved the highest scores and better reflected the priorities of local stakeholders considering a large set of multiple sustainability and resilience criteria.

Samenvatting promotieonderzoek

Dit promotieonderzoek is gericht op de ontwikkeling en toepassing van een hybride evaluatiemethode die wordt gebruikt om de voorkeuren van lokale belanghebbenden te achterhalen met betrekking tot een aantal geïntegreerde criteria voor de weging van duurzaamheid en weerbaarheid die een rol spelen bij de beoordeling van koolstofarme energietechnologieën. De methode is in zijn geheel toegepast en getoetst ten behoeve van de geïntegreerde evaluatie van de duurzaamheid van bepaalde koolstofarme energietechnologieën in Europa vanuit het perspectief van lokale belanghebbenden en lokale overheden. Om de samenhang van de voorkeuren van de belanghebbenden te bepalen heeft de onderzoeker een hybride beoordelingsmethode ontwikkeld en toegepast die is gebaseerd op verschillende multicriteria-analysetechnieken (MCA). Deze methode is getoetst op basis van een kleinschalige lokale enquête onder Europese belanghebbenden in het kader van Covenant CapaCITY, een project van Intelligent Energy - Europe, maar ook door middel van een andere enquête onder 32 grote lokale Europese overheden. Het bleek dat de deelnemende

lokale belanghebbenden en overheden bij de evaluatie van koolstofarme energietechnologieën een hoge prioriteit gaven aan aspecten zoals reductie van de uitstoot van koolstofdioxide-equivalenten, beperking van de schade aan ecosystemen en weerbaarheid tegen klimaatverandering. Gezien de uitkomst van de totale geïntegreerde beoordeling van energietechnologieën behalen het winnen van windenergie op zee, het door middel van fotovoltaïsche cellen winnen van zonne-energie, het winnen van energie uit waterkracht en de winning van windenergie op land de hoogste scores en zij vormen rekening houdende met een groot aantal meervoudige criteria voor de weging van duurzaamheid en weerbaarheid de beste afspiegeling van de prioriteiten van de lokale belanghebbenden.

Contents

Chapter 1: Introduction

1.1 Motivation and background

In recent decades, particularly after the oil crises of 1973 and 1979, the global political and economic interest has been focused on the energy sector. The main reason is that the new economy is based on the free flow of energy resources and therefore economic development and social prosperity are linked directly to the energy use and consumption. A very large proportion of energy is consumed for electricity production. Electricity today in the western world is a basic resource which was considered granted and exists in great quantity leading many times to electricity overconsumption. The combination of rapid population growth, economic development and attempts of meeting the basic needs in developing countries has resulted in a dramatic increase of electricity consumption and consumption of primary energy resources that are used in electricity production.
To the extent that energy needs and the needs of electricity production covered mostly by conventional fuels, high growth rates of energy demand will inevitably lead to shortages of energy resources. For example, the verified deposits of recoverable oil, according to forecasts, and the current rate of oil consumption, are enough only for about 50 more years (IEA, 2008).

Moreover a pressing and important component of the energy system which has been emerged is the issue of environmental impacts. At the same time fossil fuels combustion is the single most important cause of greenhouse gas emissions. Electricity production has great contribution to emissions of greenhouse gases that cause global warming. In addition, electricity production has significant contribution to emissions of specific pollutants such as nitrogen oxides (NOx), sulphur dioxide (SO2) and particulates (TSP), responsible for air pollution and acid rain resulting in serious health problems and degradation of ecosystems. The multitude of environmental problems and their severity caused worldwide the attention of official agencies and governments resulting in the UN manifestation in 1987 about the concept of sustainable development or sustainability. According to the definition given by the UN in Our Common Future (1987), "sustainable development is the development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs".

Policy decisions and evaluations for climate change mitigation and energy supply security often face a high degree of complexity and multi dimensionality that characterizes this type of multidisciplinary policy problems. In this context, of the fast changing global energy landscape and the central role that electricity production is playing in the economic and social life, the era of serious environmental problems like climate change and the global interest in sustainable development, European Union (EU) and its Member States (MSs) are called to get adapted to the new conditions and requirements. According to EU directives of the Commission, all MSs should adopt policies that lead to the achievement of specific GHG emissions reduction goals and commitments.

Specifically, the commitment of EU under the Kyoto Protocol is 8% reduction of greenhouse emissions for the period 2008 to 2012 compared to 1990 levels. The energy and climate policy framework of EU consists of a series of regulations and initiatives that aim at different objectives and affect various actors in the energy and climate field. These policies aim to achieve specific objectives set by the United Nations Framework on Climate Change Convention, which assigns Greenhouse Gas (GHG) emissions reduction targets for all Member States. In December 2008, EU leaders reached agreement over an energy and climate change "package" to deliver the bloc's ambitious objectives of slashing greenhouse-gas emissions by 20%, boosting renewable energies by 20% and increasing the energy efficiency to 20% of the primary energy consumption by 2020. The package has multiple objectives and is designed to increase EU's share to combat climate change, reduce the Union's dependency on imported fuels, promote green technologies and create new jobs (CEC,2009a, 2009b).

As this PhD thesis is being finalized climate negotiations for the new climate change agreement are under way. The new agreement will be adopted at the 21st conference of the Parties (COP21) that will be held in Paris in December 2015 and implemented from 2020. The new agreement is expected to have the form of a protocol, a binding agreement or another legal instrument such as "an agreed outcome with legal force", which will be applicable to all Parties. The negotiations for the new legal agreement took place through the process of the so called "Durban Platform for Enhanced Action". The EC has spelled out the EU's vision for the new global climate agreement to be agreed and adopted in Paris in December 2015. The Communication, "The Paris Protocol - a blueprint for tackling global climate change beyond 2020", is part of the EU's Energy Union package. According to the EU's vision for the new global climate agreement, collective commitments based on scientific evidence should put the world on track to reduce global emissions by at least 60% below 2010 levels by 2050. In relation to that, the EU road map towards a low carbon economy have set ambitious targets for the year 2030 for tackling climate change. These include a 40% GHG emissions reduction compared to 1990 emission levels and an increase in renewable energy share by 27% (European Commission, 2011).

In the EU wide context, a unified emissions trading scheme (EU ETS) was established as from 2005 based on an EU Emissions Trading Directive (CEC, 2003), followed up by an additional Directive (CEC, 2004) that enables direct links of the EU ETS with the Kyoto Protocol project mechanisms (namely Joint Implementation and Clean Development Mechanism). The climate and energy package laid down certain conditions and requirements which were introduced for further improvement and amendment of EU ETS specifically for its third phase which starts in 2013 (CEC, 2009a). Also the Directive 2001/81/EC on emission ceilings for certain atmospheric pollutants sets targets for MSs to reduce SO2 emissions by a certain percentage in 2020 compared to 1990 levels. For the same year there are reduction targets for NOx emissions, particulate matters and ammonia (NH3).

In addition, EU policy focuses also on the promotion of renewable energy sources by adopting various Directives as the Directive on the promotion of electricity produced from renewable energy sources (CEC, 2001) and the recently amended Directive based on the agreed energy and climate package which includes new targets for renewable energy sources for EU (CEC, 2009b). The Directive 2001/77/EE "To promote electricity production from renewable energy sources in the internal electricity market" provides to MSs indicative targets of certain percentage coverage of renewable energy of their gross energy consumption by 2020.

The development of Renewable Energy Sources (RES) is one of the most important interventions to reduce CO2 emissions and adverse environmental impacts from electricity production. There is high and important potential of renewable energy globally, and thus its exploitation is deemed as an essential key factor to achieve certain climate, environmental and energy objectives (Vatenfall, 2007). Particularly in the context of climate change mitigation, RES considered some of the most effective technologies to reduce CO2 emissions in the electricity generation sector. In addition to RES there are other mitigation technological options under investigation, within the electricity sector, such as Carbon Capture and Storage (CCS) and nuclear power.

Moreover, considering the Fukoshima disaster aftermath in 2012, the increasing reliance on fuel imports (European Commission, 2014), the recent crisis in Ukraine with the risks involved for the EU security of energy supply, and the likely impacts of a changing climate to the European energy system (Dowling, 2013), the issue of resilience of future energy technologies is becoming a major priority for the EU.

Cities and municipalities in Europe are also increasingly concerned about climate change mitigation and are therefore taking actions within their own boundaries. Local governments joining the Covenant of Mayors adopt – or even go beyond - European GHG emission reduction targets (Covenant of Mayors, 2013). Current and future low carbon energy technologies, including renewable energy technologies, play a major role in the fight against climate change and for EU to achieve its targets. Particularly at the local level, low carbon energy technologies could provide other benefits such as creation of local jobs, diversity of energy supply, and air pollution reduction.

Detailed research has been conducted towards the assessment of abatement technologies, but many questions still remain open for investigation. There are several techno-economic approaches to assess climate mitigation technologies at the electricity sector that provide quantitative results such as (projected) costs (Gross et al. 2007, IEA, 2007, World Bank, 2007, Bakos et al. 2008, Blesl et al., 2010, IEA, 2010). Techno-economic approaches address technical, financial, investment and risk issues relevant to the electricity technologies under investigation without though addressing aspects such as emissions, externalities or GHG emissions savings.

Emissions of NOx and SO2 emissions cause significant environmental impacts and effects on human health. The need to account for these effects in a reliable and valid way and include them in the energy planning and climate mitigation decision making is growing the last years. The various environmental and non- market effects caused by the electricity industry lead to changes in social welfare and constitute an external economic cost or benefit that is not reflected by the current market price mechanism. These costs and benefits called "external costs" or "externalities" in the neo-classical economic theory and welfare economics literature. Thus, in the context of sustainable development and climate mitigation, the issue of integrating the energy externalities into the energy planning, constitutes an important factor. A number of studies and projects have emerged, which investigate the externalities of energy, attempting to quantify electricity technologies' emissions and monetize their respective external costs. In particular, they have developed several approaches and methods and have made systematic efforts to assess the environmental impacts of electricity production expressed in monetary units (EC, 1995, 2005, Hirschberg et al., 2007, Cases 2008).

At this point, the criticism of the unambiguous use of a single tool for analyzing and comparing different mitigation technologies and measures, which is the cost - benefit analysis (CBA), has been intensified the last years (Munda 1996,). In addition, neoclassical economic valuation methods have received criticism with regard to their validity and scope. The limitations of using only traditional methods for economic evaluation of all environmental values and externalities has been stated by a large part of the scientific community (Vatn and Bromley, 1994, Stirling, 1998, Soderholm and Sundqvist, 2003), highlighting the need for development of more integrated and holistic approaches that have the ability to include the multiplicity of aspects and impacts of climate mitigation technologies. Furthermore, most of these studies do not address GHG emissions and climate change as externality of energy. However there are few attempts to assess GHG emissions mitigation efforts and air pollution reductions in a combined approach (Aman et al., 2007).

There is also an emerging load of studies focusing on the assessment of abatement potential of certain electricity technologies in combination with the estimation of their respective costs (Burgemneier et al. 2006, Ordorica - Garcia, et al., 2006, Vatenfall, 2007, Bakker et al., 2009, IEA/OECD, 2008). The above techno-economic studies which normally measure the quantifiable performance of certain abatement technologies in terms of abatement costs provide useful information on abatement costs of mitigation technologies. However they do not consider other important factors relevant to policy implementation. Socio-political and public acceptance issues, other macroeconomic aspects, stakeholders' preferences and factors of relative importance are not taken into account. In particular, in the context of comparing and assessing alternative mitigation technologies in energy planning, techno-economic and mitigation potential studies do not consider issues such as environmental benefits of substituting conventional fuels, technological viability and other socio - economic criteria, namely employment, security of energy supply, energy efficiency, public acceptance, etc. Few dispersed studies attempt to capture these aspects but they lack the ability of investigating them in combination to cost and mitigation potential issues (Ragwitz et al. 2005, Dincer 2007, Hirschberg et al. 2007, Evans et al. 2009).

1.2 Formulation of the problem

Integrated approaches are now required to include all diverse dimensions of sustainable development and the multiple impacts and aspects of low carbon energy technologies.

Since the publication of the Brundtland report in 1987 and the earth summit in Rio in 1992 the concepts of sustainable development and sustainability have been interpreted, used, and contested in various contexts both in policy and academia. Furthermore, since the conceptualization of sustainable development in the Brundtland report, numerous approaches and frameworks have been developed to measure and assess the achievement of sustainable development goals, ranging from guidelines to more specific indicator based frameworks (Ness et al., 2007). For a comprehensive review and elaborated classification of different sustainability assessment methodologies, see Ness et al. (2007) and Singh et al. (2012).

According to Ness et al. (2007), many of the integrated assessment tools that have been reviewed integrate environmental and social aspects of sustainability. According to Weaver and Rotmans (2006) the dimensions of integration that can take place in sustainability assessment processes and in transitions towards sustainability (Rotmans et al., 2001) are:

- integrated objectives that embrace multiple sustainability concerns and values
- knowledge and information across multiple domains and sources
- sustainability values and principles throughout the process
- stakeholders, policy makers and experts
- quantitative and qualitative tools, methods, information
- proposal design and assessment (integration into policy development process)
- social learning, self - evaluation and reflexivity
- internally integrated sustainability assessments to form a coherent assessment regime
- keeping a large number of options.

The main phases of an integrated sustainability assessment (ISA) are scoping, envisioning, experimenting and learning and monitoring and evaluation (Weaver and Rotmans, 2006). Moreover, according to Rotmans (2006) in practice, Integrated Sustainability Assessment encompasses analysis of the dynamics of sustainable development, forecast of trends and developments, assessment of the sustainability impact of policy and technological options, monitoring of the long term process of sustainability using (model based) indicators and incorporation of participatory methods in the integrated sustainability assessment process.
Multiple criteria analysis/assessment (MCA) or Multiple Criteria Decision Analysis (MCDA) approaches have been classified under the integrated assessment category (Ness et al., 2007; Singh et al., 2012) since they integrate multiple objectives while including multiple stakeholders in the assessment process. MCA has been widely used for sustainable energy

planning, as a useful tool in facilitating decision making among different stakeholder groups, in expanding the range of possible outcomes, and in assessing the performance of technologies against a set of evaluation criteria (Pohekar, S.and Ramachandran, 2003; Kowalski, et al., 2009; Braune, et al., 2009).

MCA evaluation approaches have been applied increasingly the last two decades for energy and climate policy evaluation in various decision making contexts (Roy, 1996, Lahdelma et al., 2000, Belton and Stewart, 2002). In particular MCA approaches have been applied for incorporating public values in energy future scenarios evaluation (Keeney et al., 1990), evaluating alternative integrated energy plans (Hobbs and Horn, 1997, Hobbs and Meier, 2000), indirect valuation of energy externalities (Diakoulaki and Grafakos, 2004), participatory design of renewable energy policy instruments (Madlener and Stagl, 2005), integrated assessment of energy analysis (Giampetro et al., 2006), evaluation of energy projects for electricity generation (Mavrotas et al., 2003), defining national priorities for greenhouse gases emissions reduction in the energy sector (Georgopoulou et al., 2003).

The application of MCA methods within the climate mitigation policy field has been also increased. MCA methods highlighted as a useful tool for climate policy for first time by UNEP (1994). Borges and Villavicencio (2004) applied MCA method for the development of Peruvian GHG emissions reduction strategies in accordance to UNEP MCA analytical framework. Bell et al. (2003) investigated the use of Multi-criteria methods in integrated assessment of climate mitigation policy. In addition, MCA methods have been applied for the control of GHG emissions from international civic aviation sector (Solomon and Hughey, 2007) and the assessment of climate policy interactions (Konidari and Mavrakis, 2007, Oikonomou et al. 2010, 2011a, 2011b, 2013; Grafakos et al., 2010a). MCDA approaches attempt to integrate multiple aspects of sustainability while assessing relevant to climate mitigation energy technologies such as renewable and sustainable energy (Afgan and Carvalho, 2000, Afgan and Carvalho, 2002, Haralambopoulos and Polatidis, 2003, Cavallaro, 2005, and Carbon Capture and Storage (Shackley and McLachlan, 2006) technologies.

There are some studies investigating the European energy security of supply (Chevalier, 2005, Constantini et al., 2007) and vulnerability of European energy system on fuel imports (Gupta, 2007, World Energy Council, 2008, Bhattacharyya, 2009, Roupas et al., 2009, 2011). Although the concept of system resilience has been contextualized in different fields (Holling 1973, Tyler and Moench, 2012, Collier et al., 2013) there are only few studies that explicitly address system resilience in the energy sector (O'brien and Hope, 2010; Gaudreau and Gibson, 2010; Molyneaux et al., 2012; McLellan et al., 2012). It is evident in the literature that sustainability and resilience are considered and treated in the assessment of energy options and systems in a disconnected manner. Moroever, various literature acknowledge the desirability of integrating sustainability and complex systems (Fiksel, 2006; McLellan, et al., 2012). While there are already attempts to integrate these two components (O'brien and Hope, 2010, Milman and Short, 2008; Molyneaux et.al, 2012), there is still a lack in the literature on explicitly integrating sustainability and resilience indicators within one framework for the assessment of energy options and technologies. Based on this background, **the first research question of the PhD thesis is "how can the assessment of low carbon energy technologies be improved in an integrated way that sustainability and resilience aspects are incorporated"?**

Criteria weights elicitation techniques have been developed within the framework of MCA to integrate stakeholders' preferential information into the decision making process (Keeney et al., 1990, Poyonen and Hamalainen, 2001, Belton and Stewart 2002). During energy and climate evaluations, stakeholders and decision makers implicitly or explicitly express their perceived relative importance between criteria by assigning weighting factors to them. Stakeholders' objectives and policy priorities should be taken into account and even get incorporated into the decision making process in a structured, systematic and transparent way. This process can render decisions more defensible and acceptable (Kowalski et al., 2009; Grafakos et al. 2010a, 2010b). The inclusion of stakeholders' preferences in the evaluation process of climate mitigation technologies is an issue that has not been explored systematically, mainly, due to its distinctive and multidisciplinary character.

In addition several studies have shown that well-articulated and preconceived preferences regarding unfamiliar and complex issues cannot apply. Instead in these settings, respondents construct their preferences during the process of elicitation. Preference construction process should be considered when some of the decision elements are unfamiliar and where there are conflicts among the choices to be made (Lichtenstein and Slovic, (2006). Energy planning and sustainability evaluation of energy systems are complex issues that also entail difficult decisions and trade off considerations. Moreover preferences change under different contextual conditions (Norton et al., 1998), while different methods (procedure) and different descriptions (framing) can give rise to systematically different responses (Gregory and Slovic, 1997). Hence, this indicates that respondents need a method to help them to articulate their preferences, and any attempt to derive their preferences should be based on an active procedure of preference construction (Lichtenstein and Slovic, 2006). According to Bell et al. (2003) the combination of different methods during preferences' elicitation could

a) provide a form of consistency test and b) lead to more reliable and acceptable elicitation of preferences. Different methods can yield different results. As Bell et al. (2003) argued such inconsistencies are an opportunity to reflect on results from different framings of the issue at hand, whereas that opportunity is lost when a single method is used. Furthermore, as has been shown some respondents may react negatively to the chosen approach, lessening acceptance of the process.

The development of an evaluation framework that can adequately deal with complex characteristics, structure and analyze climate and energy issues at hand, and assist stakeholders to construct their preferences, is indispensable. In particular, MCA application for climate mitigation problems lack a simple, transparent, interactive and structured way to support stakeholders to construct and elicit their views and objectives while further incorporating them in the evaluation process (Hamalainen and Alaja, 2008, Grafakos et al., 2010a, 2010b). **The second research question of this PhD thesis "how can stakeholders' preferences be incorporated in the evaluation of low carbon energy options in a constructive and iterative way.**

The integration of techno-economic approaches and MCDA provides a holistic and comprehensive framework capable of assessing low carbon energy technologies that achieve great carbon emissions reduction while at the same time meet multiple other sustainability and resilience criteria. An integrated approach to the assessment of different low carbon energy technologies in order to support policy-making is deemed necessary. As a result, the scientific community has now turned its interest to the complementarity of different decision support tools and integrated approaches.

At the European level, the New Energy Externalities Development for Sustainability (NEEDS) project applied a MCDA of future energy technologies in four countries, namely France, Germany, Italy and Switzerland (Hirschberg et al., 2007) for the year 2050. The MCA for NEEDS aimed to assess energy technologies, considering the varied national stakeholders' preferences for the trade-offs between different criteria (Makowski et al., 2009). The stakeholders' elicitation process engaged a wide range of energy experts and national stakeholders (Makowski et al., 2009).

At the national level, future energy policy options were evaluated in the United Kingdom (Stagl, 2006) through MCA with the participation of experts, stakeholders and the general public. In Greece, an assessment of sustainable technological energy priorities for 2021 was carried out (Doukas et al., 2007) with a working group of participants from relevant national energy stakeholders, while in Norway, future energy supply infrastructure (Loken et al.,

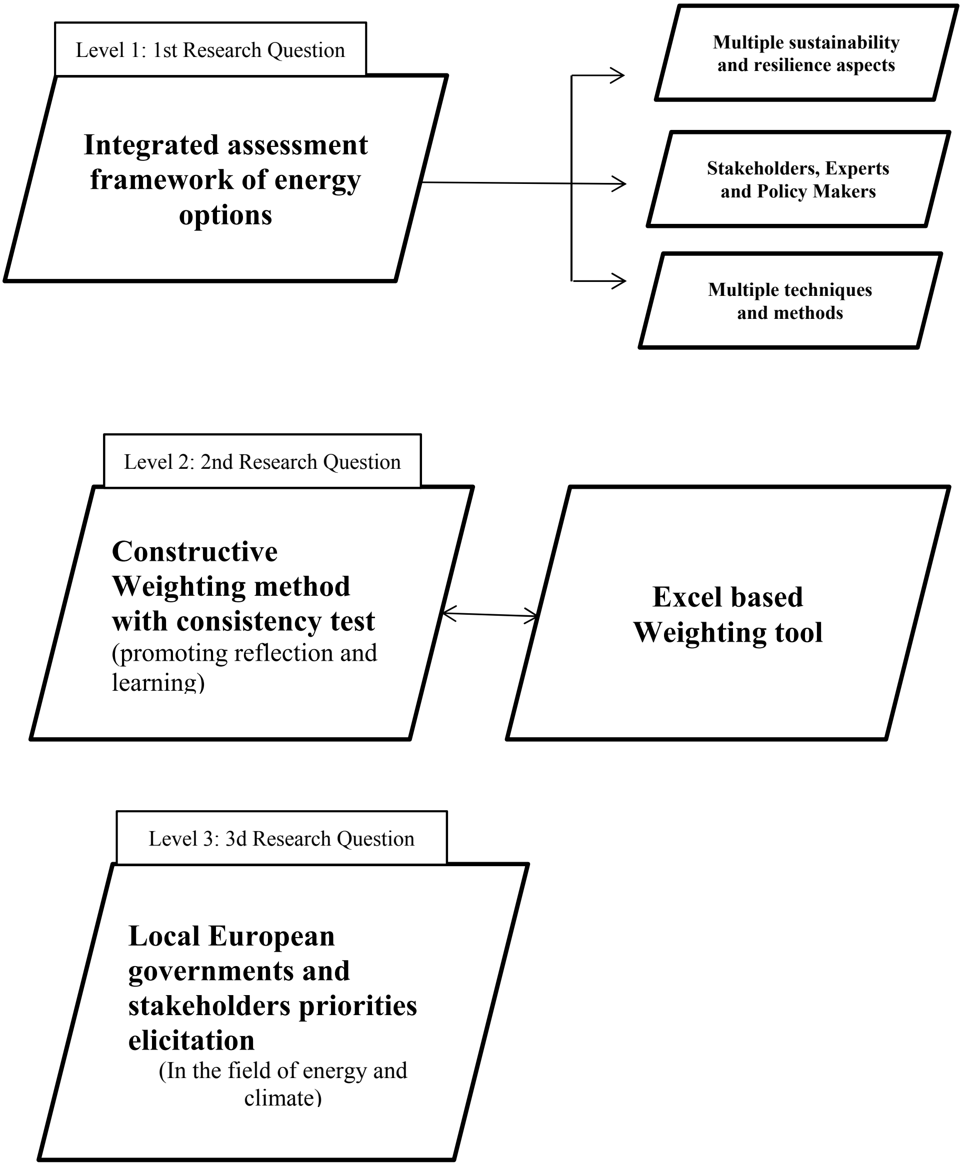
2009) were evaluated. In this case, preference elicitation interviews were carried out among six individuals in the energy sector. In Austria, the ARTEMIS Project evaluated renewable energy scenarios –at the national level and in two local communities - for the year 2020. The study involved different stakeholders and energy experts through workshops and interviews that were carried out for scenario development and criteria weighting (Madlener et al., 2007). It is clear that assessing future energy technologies while integrating and mapping local stakeholders' perspectives at a wider scale (i.e. European level) is lacking. On one hand, a European-wide MCA study, such as in the case of NEEDS project, looked at the preferences of national stakeholders. On the other hand, there are various distinct local/regional MCA studies that cannot be applied as a unified framework in mapping local governments and stakeholders preferences at the European level. **The third research question of the PhD thesis is "which are the priorities of European local governments' and other local energy stakeholders with regard to the evaluation of low carbon energy technologies?"**

More specifically, and based on this background, the **main research objective** of this PhD thesis is the development of an integrated decision support system for the assessment of low carbon energy technologies at the local level in Europe, which incorporates sustainability and resilience aspects. This decision support system is applied at a local decision and policy making context for eliciting European Local governments' preferences on the evaluation criteria for the assessment of low carbon energy technologies.

The **specific research sub-objectives** of this thesis are:

- The development of an integrated analysis and assessment framework of low carbon energy options by incorporating:
    - different techniques and methods,
    - multiple sustainability and resilience aspects relevant to low carbon energy technologies,
    - different views from stakeholders, experts and policy makers
- The development of a constructive weighting method combining different techniques to derive consistent verbal and ratio expressions of stakeholders' preferences.
- The elicitation of European local governments' preferences on multiple sustainability and resilience evaluation criteria of low carbon energy technologies assessment.

Figure 1: Contribution of PhD thesis



The contribution of the PhD thesis can be seen in 3 distinct levels:

1. The thesis develops an integrated assessment framework of energy technologies by 3 means of integration: a) incorporating multiple sustainability and resilience aspects, b) including stakeholders, experts and policy makers in the assessment process and c) integrating different techniques and methods. Answering to the 1st Research Question will provide this first level contribution.
2. The thesis develops a constructive weighting methodology by combining different weighting techniques that can be adjusted according to the context (e.g. number of criteria) while providing the means to stakeholders to reconsider and revise their preferences based on the introduction of a consistency test. Furthermore, this methodology has been "translated" in an excel based weighting tool that can be used to elicit stakeholders' preferences in different contexts (individual or group decision making). Answering to the 2nd Research Question will provide this second level contribution.
3. By applying the overall integrated assessment framework, for first time, to the best of my knowledge, European local governments' priorities are systematically elicited regarding their preferences in the evaluation of low carbon energy options. Answering to the 3d Research Question will provide this third level contribution.

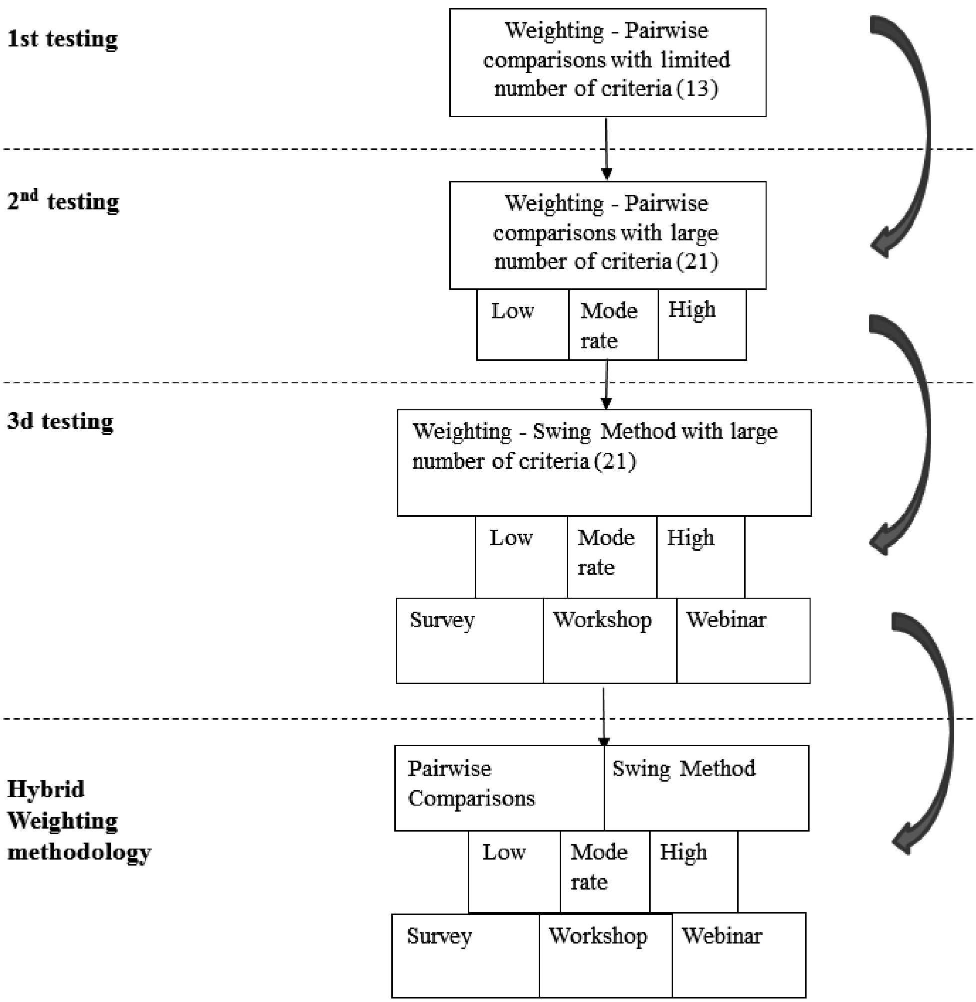
Learning and Iterative process

Moreover the thesis follows a cyclical process of developing, testing and learning approach towards the development of the hybrid constructive weighting methodology. In particular, the development of the weighting methodology follows the testing stages below:

- 1st testing stage: Initial (1st) testing of the weighting methodology by employing a pairwise comparisons for the elicitation of stakeholders' weights of limited number of criteria (13). It should be noted that the 1st testing of the weighting methodology was conducted in the context of energy and climate policy interactions (Annex 1).
- 2nd testing stage: Based on the lessons learned from the first testing, the 2nd testing stage employs the pairwise comparisons for the elicitation of stakeholders' weights for a large number of criteria (21) while introducing an approach of breaking down the list of criteria in three different groups of level of importance (low, moderate, high) in order to reduce the cognitive burden of respondents. The second testing stage leads to additional learning outcomes.

- 3d testing stage: Based on the lessons learned from the previous stage, the 3d testing stage employs the swing weighting method for the elicitation of respondents' weights for a large number of criteria (21) using three different elicitation techniques namely survey (individual), webinar (group) and workshop (group). The 3d testing stage leads to new learning outcomes in order to further refine the overall hybrid constructive weighting methodology.

Figure 2: Learning, testing and iterative process of the PhD thesis



Thesis structure

It should be highlighted at this stage that the PhD thesis is the volume of a coherent and structured document with a flow of sequential chapters, but at the same time is a compilation of interlinked but different peer reviewed journal article publications. In order to enhance the coherency of the PhD thesis as an overall book, the author has included in the main body of the PhD thesis only the chapters and publications that are related to the integrated evaluation of energy technologies, while the 1st testing of the weighting methodology in the context of energy and climate policy options was moved to Annex 1.

The PhD thesis structure is as follows:

Chapter 2 focuses on the theoretical underpinnings of MCA approaches regarding sustainability issues within the energy decision making context. Furthermore chapter 2 presents an extensive literature review regarding MCA applications in the field of low carbon energy technologies evaluation at different levels (European, national and local) and weighting methods developed and applied for stakeholders' preferences elicitation. Furthermore chapter 2 presents recent studies that aim to conceptualize resilience aspects in the energy systems assessment context.

Chapter 3 presents the integrated MCA assessment methodology that was developed for the evaluation of low carbon energy technologies. Furthermore, the chapter presents the development of the constructive weighting technique that was developed in order to support local stakeholders and decision makers to elicit their preferences with regard to the evaluation criteria on low carbon energy technologies. Furthermore the modified "3S" criteria validation approach is discussed along with all the data collection methods and techniques that have been used in the research.

Chapter 4 presents the low carbon energy technologies impact assessment and the development of the MCA impact matrix. In particular the results of the experts' impact assessment survey of low carbon energy technologies against selected non quantified evaluation criteria are also presented and discussed.

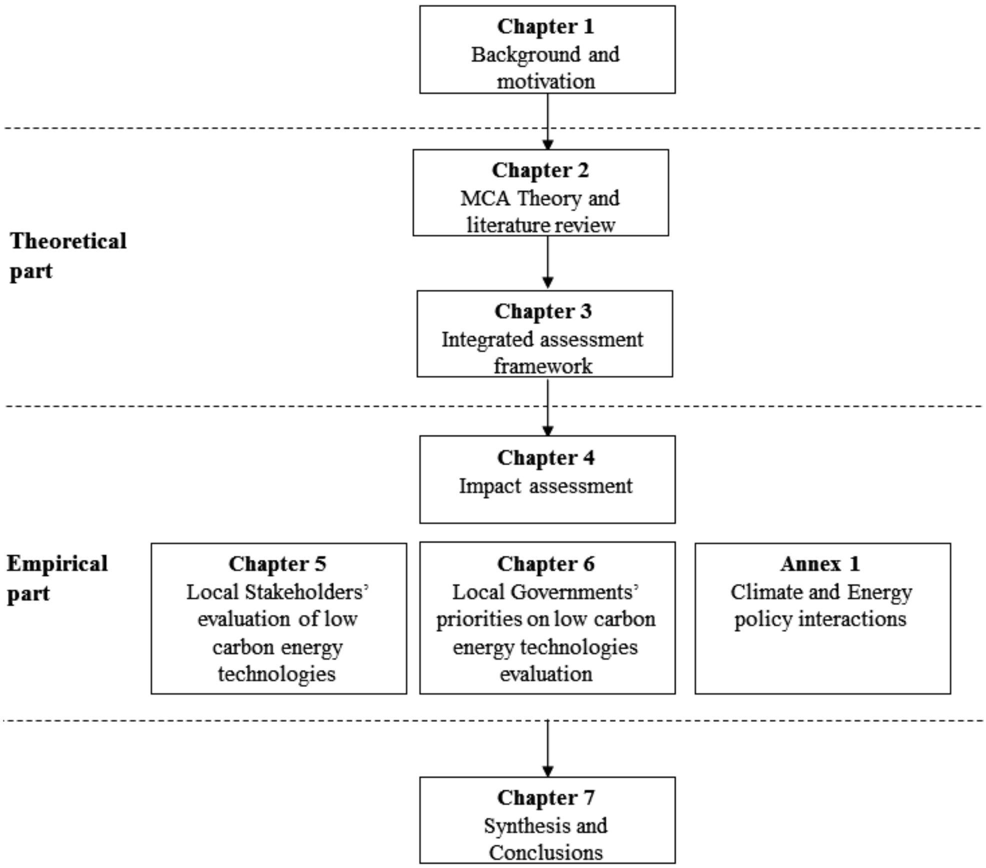
Chapter 5 focuses on the first application of the overall integrated MCA assessment methodology for the elicitation of European local stakeholders' preferences and the evaluation of low carbon energy technologies from a local stakeholders' perspective.

Chapter 6 presents the results of the second application of the integrated MCA assessment methodology for the elicitation of European Local Governments preferences and the evaluation of low carbon energy technologies from a local governments' perspective. This chapter also discusses to which extent the outcomes are validated by the priorities local governments have identified during the development of their Sustainable Energy Action Plans.

Chapter 7 focuses on the discussion about the outcomes of and lessons learned from the different applications of the proposed integrated MCA methodology along with future research directions. The chapter also draws some concluding remarks of the PhD thesis and discusses some policy and research related recommendations in the field of low carbon energy options in Europe.

Annex 1 presents and discusses the results of the application and testing of the constructed weighting methodology on a decision problem of climate and energy policy interactions in Europe. Outcomes and lessons learned from this application were fed to the further development of the constructed weighing methodology.

Figure 3: Structure of the thesis



Chapter 2: Theoretical background and literature review

(parts of this chapter have been published in:

i) Grafakos, S, Ensenado, E., and Flamos, A., 2015, Developing an Integrated Sustainability and Resilience Framework of Indicators for the Assessment of Low Carbon Energy Technologies at the Local Level, *International Journal of Sustainable Energy*

ii) Grafakos S., Flamos, A., Zevgolis D., and Oikonomou V., 2010, Multi Criteria Analysis weighting methodology to incorporate stakeholders' preferences in energy and climate policy interactions, *International Journal of Energy Sector Management*, Vol. 4, No. 3, pp. 434-461)

2.1 Decision aid tools for sustainability assessment

2.1.1 Introduction

The long identified need to secure a balance between economic, environmental and social targets, having found its most comprehensive phrasing in the report of the UN Development Programme (the so-called Brundtland report), has subsequently influenced several international conventions and EU policy documents. Thus, the international community is forced to seek for a common understanding of the emerging constraints and for effective routes towards sustainable development, despite their differing interests, responsibilities and capabilities.

The reconciliation of economic, environmental and social values is in fact the ultimate goal of sustainable development which is setting the targets and boundaries of the new policy framework in the EU. However, such a reconciliation of many different values in policy making is not an easy task. The inherent complexity of the systems concerned, the uncertainty regarding the consequences of alternative policy choices, the conflict between contradictory values, and the multiplicity of people concerned about policy decisions, advocate for the use of powerful decision-aid tools. In particular, MCDA appear as an appealing tool capable of systematically and effectively handling all the above difficulties. In the following paragraphs the main characteristics of sustainability problems will be reviewed, the degree MCDA is compatible with these characteristics will be investigated.

2.1.2 Characteristics of sustainability problems

The consideration of sustainable development as an evolutionary process encompassing three discrete dimensions is by definition giving a multi-criteria character to the task of tracing policies for sustainability. The economic, environmental and social dimensions are specifying the overall target of sustainable development and can be further decomposed into several criteria following the structure of a typical 'value tree'. Any policy choice is expected to satisfy one or more criteria by at the same time being in contradiction with other criteria. Conflicts exist not only between the three major dimensions of sustainability but also within the same dimension. It is very common that by effectively coping with one environmental aspect, other aspects become worse.

In front of these conflicts policy makers have to articulate their preferences for finding the most satisfactory balance between contradictory goals. Preferences refer to both, the level of performances in a single criterion, and also to the relative importance of each of the criteria reflecting the multiple aspects contributing to sustainability. Besides the difficulties that are present in any decision situation, preference elicitation in sustainability problems has to face additional sources of trouble, especially as regards the environmental criteria that have to be taken into account.

It is clear that among the three dimensions of sustainable development -the economic, the social and the environmental one- the main emphasis today should be given to the environmental dimension, which was the one most undervalued until today. The alarming threat of climate change, the severe impacts of atmospheric pollution on human health and natural ecosystems, the contamination of soil, underground and surface waters, are only some of the environmental problems arising from human activities and needing particular attention in order to be effectively solved. The problems encountered when dealing with sustainability/environmental issues are the following:

High complexity: Ecological processes and systems are highly complicated, without the underlying mechanisms and their interrelations being fully detected and completely understood. The gaps in the scientific knowledge about natural-ecological phenomena and about the type and severity of environmental impacts are usually larger than in other disciplines, so that uncertainty and ambiguity in the elicitation of human preferences is greater. Besides, there exist multiple positive and negative synergistic effects that further impede the articulation of preferences and their aggregation through simple aggregation models (Munda, 1996).

Value pluralism: Environmental goods are most of the times involving a broad variety of values. In neoclassical economics these values are distinguished as use and non-use values, while ecological economists proceed to a much more detailed taxonomy including economic, ecological, social, scientific, aesthetic, religious, ethical, educational, cultural, life supporting and recreational values (Gregory and Slovic, 1997; Rosenberger, 2001). These values are often in conflict with each other and within themselves, so that it is difficult for the human mind to recognize, capture and describe his/her attitude in a single preference statement. Furthermore, each value factor is conceived in a different way by the many stakeholders concerned or affected by changes in environmental goods. This is mainly because sustainable development should not only deal with measurable and/or contrastable dimensions of a system, but also with its higher dimensions, where power relations, hidden interests and other constraints affect human attitude (Martinez – Alier et al, 1998).

Non-tradability: Environmental goods are not completely substitutable to each other and with economic goods. This is either because of 'objective' scientific thresholds imposing certain limits to the use of environmental resources, or because of 'subjective' deontological or desirability thresholds setting restrictions on our actions and choices (Rosenberger, 2001). As a consequence, many environmental goods cannot be traded-off for gains in other goods, or can be traded only to a certain limit, above which objective or subjective thresholds will be violated.

Incommensurability: Environmental repercussions are difficult to measure, not only because of technical/monitoring inefficiencies. The variety of environmental goods, most of which are outside the market mechanism, entails the absence of a common unit of measurement (Rosenberger, 2001; Munda, 1996). In addition, due to the plurality of values associated with each good, there is often not a commonly agreed cardinal scale on which different impact levels are gauged (e.g. impact on visibility, aesthetic nuisance). In such cases, preferences are expressed by means of ordinal impact scales or qualitative value judgments. These value judgments cannot be considered as unique and stable but are influenced by the evaluator's individual attitude, culture, impulses and motivations (factors that are not necessarily rational) and the overall decision context. In this sense, they may well be revised in response to new insights, exchange of ideas with other people and contextual changes.

Communality: Due to the common property rights applying to most environmental goods, there is a need to actively involve a large number of stakeholders (Toman, 1998). Such participatory processes help also in the consideration of the plurality of values relevant to environmental issues and in the development of the necessary debate to achieve a deeper understanding of the open questions and of the solutions at hand (Rosenberger, 2001). Therefore, the involvement of stakeholders is essential to take place at an early stage of the decision process.

Distributional aspects: Even a participatory decision process is usually not possible to include all interested stakeholders and mostly it is not easy to cope with information gaps and to solve the ethical problems arising when trying to secure intra- and intergenerational equity. In the absence of 'perfect' markets and –for certain goods- in the absence of real markets, it is difficult to avoid biases and effectively integrate relevant distributional effects into the analysis (Munda, 1996; Joubert et al., 1997). The solution of an environmental problem might disproportionately favour a certain group of people, which have the economic or political power to serve their own interests. In addition, several environmental problems affect not only the present but also or exclusively forthcoming generations.

All the above-described characteristics impose specific restrictions in the valuation and decision making process of sustainability problems. Thus, it is necessary to be aware of the properties of the tools to be used in order to avoid serious biases and inconsistencies.

2.2 Background on Multiple-Criteria Decision Analysis

2.2.1 Introduction

In modern societies, decisions are hard to make and decision makers feel often uncomfortable to select one among possible courses of actions. The main difficulties faced by decision makers are the following:

- **Complexity:** Decisions address problems that are encountered within a complicated environment including several interrelated systems and sub-systems defined upon a multiplicity of parameters. Decision makers have to broaden their analytical perspective in order to take into account all these parameters, since slight changes in one of them might affect in an often unpredictable way the decision's outcome.
- **Uncertainty:** Uncertainty is an inherent characteristic in most decision situations and stems from the lack of relevant information for all different aspects considered, the variability of systems and parameters, the limited scientific knowledge about physical phenomena, and the hesitations of the decision maker about his aspirations.
- **Multiplicity of goals:** Decision makers are usually trying to simultaneously satisfy multiple objectives, i.e. they seek for a solution that is best performing in a number of decision criteria. The problem here is that no such solution exists because of the conflict characterizing most of the considered criteria. Therefore, the decision maker has to

specify how much he is willing to abstain from one criterion in order to achieve a better performance in another.

- **Multiplicity of stakeholders:** The multiplicity of aspects related with modern problems is ensuing the strong interest of several different groups of actors that feel directly or indirectly affected by the outcome of the decision. Thus, it is often necessary to involve stakeholders in the decision making process in order to enrich the evaluation perspective and secure the wide approval of the decision taken and its practical implementation.

MCDA is aiming at providing a formal approach helping decision makers to effectively handle complex decision situations in which the level of conflict between criteria is such that intuitive solutions can not be satisfactory. MCDA is particularly suited if, in addition to the conflict between criteria, there is significant ambiguity in measuring performances and/or in articulating preferences. Finally, MCDA can help in resolving disagreement if stakeholders have different views on the relative importance of the considered criteria. It is important to stress, that MCDA is not a tool providing the right solution in a decision problem, simply because no such solution exists. Instead, it is an aid to decision making that helps decision makers organize the available information, think on the consequences, explore their own wishes and tolerances and minimize the possibility for a post-decision disappointment (Belton and Stewart, 2002).

In the last 30 years, MCDA methods have known a remarkable progress in the framework of Operational Research and Decision Sciences. This progress is manifested not only in the impressive number of communications in scientific journals and conferences, but merely in the increasing use of relevant approaches in real-life problems in the public or private sector. Although, each decision situation has its own particular characteristics, relevant problems can be classified into broad groups on the basis of the type of the decision to be made. On the other side, there is a multiplicity of methods differing in the modeling procedure, in the techniques used for the elicitation and elaboration of preferences, in the logical and arithmetic approach to aggregate preferences across criteria and in the treatment of uncertainty. However, in all decision situations and independently of the MCDA method used, the approach followed includes the same main steps to arrive at the decision. These basic elements of the MCDA methodology will be briefly described in the following paragraphs.

2.2.2 Problems and problematiques

The strength of MCDA is better reflected in problems of a strategic nature encountered in many different fields of economic activity. These problems refer to non-repeated decision situations with a medium-to long-term planning horizon and usually have more serious and often non-reversible consequences. Similar types of problems are technological choices, establishment of action plans and policies in different sectors, siting decisions, project evaluation and approval, financing decisions etc. However, there are also routine decisions needing the consideration of multiple conflicting criteria, such as provider selection, evaluation of applicants, diagnosis and restoration of disturbances etc. The main difference between these two broad categories from the methodological point of view is that in the former uncertainties are much higher, while there is usually a greater involvement of stakeholders, thus more difficulties to arrive at a consensus.

Besides the above discrimination between strategic and routine problems, multiple criteria decision situations differ in their overall problematique according to the type of decision pursued. Roy (1996) distinguishes four major typologies of decision types:

- ***Choice:*** selecting only one action among several alternatives.
- ***Ranking:*** placing alternatives in a preference ordering for selecting those ranked at the higher places.
- ***Sorting:*** grouping alternatives into broad hierarchical categories, each one including a number of non-distinctive alternatives.
- ***Description:*** analyzing alternatives and their consequences in a formalized manner that helps decision makers gain a deeper understanding of the problem.

A fourth problematique is the ***Portfolio*** analysis, which is aiming at identifying the best combination of alternative actions by taking into account not only the alternatives' individual characteristics but also their interactions and synergies.

Finally, a completely different problematique is followed in Multi-Objective Programming (MOP) models, where alternatives are not a priori defined but result as combinations of continuous decision variables when optimizing a system (defined through a number of constraints) with respect to specific objectives. Both, constraints and objectives are expressed as functions –usually linear- of the considered decision variables. The outcome of the optimization procedure is a set of non-dominated solutions among which the decision maker(s) is called to make the final choice.

The analysis hereafter will be restricted to discrete alternatives which are a-priori defined (probably from a MOP model) and evaluated with respect to a number of evaluation criteria.

2.2.3 Structural elements of MCDA problems

The most essential elements in a MCDA problem are certainly the set of alternative actions and the set of criteria along which these actions have to be evaluated. However, there is a number of structural and external characteristics that go far beyond an arithmetic definition of these basic elements. Several approaches are suggested in order to look in a consistent and systematic way at these characteristics. One of the most convenient and comprehensive ways is the **CAUSE** checklist (Criteria, Alternatives, Stakeholders, Uncertainty, Environment) (Belton and Stewart, 2002).

Criteria represent the decision maker(s) or other stakeholders' points of view about the properties of the solution they are searching out. As stated by Bouyssou (1994), "building a criterion implies that one has chosen a point of view along which it seems adequate to establish comparisons". There are two main approaches to determining the set of criteria reflecting the two ways of building a MCDA problem. A top-down approach is compatible with 'value-focused thinking' where criteria are built in a hierarchical structure, known as 'value tree' and leading from primary goals to main (fundamental) objectives, which in turn are further broken down to specific criteria (Keeney and Raiffa, 1976, Keeney, 1992). Whereas the top level goals and objectives are usually vague concepts and values, the lowest level criteria refer usually to concrete aspects which allow for a more or less unambiguous ordering of the alternatives. Instead, the bottom-up approach suits to 'alternative-focused thinking', where criteria are identified through a systematic elicitation process and may subsequently grouped in broader categories. In both cases, a coherent set of criteria presents the following properties (Belton and Stewart, 2002):

- ***Value relevance:*** Criteria are linked to fundamental goals of the stakeholders enabling them to specify preferences.
- ***Understandability:*** The concept behind each criterion is clear and there is a common view about the preferred direction of the alternatives' performances.
- ***Measurability:*** Alternatives' performances are possible to be determined on either a quantitative or a qualitative measurement scale.
- ***Completeness:*** The set of criteria is covering all important aspects of the problem considered, by at the same time being concise and operational.

- ***Non-redundancy:*** Criteria are not reflecting the same concept (in another phrasing) in order to avoid double-counting and thus attributing a greater importance to a single aspect.

Alternatives are usually thought as ‘given’, in the sense that they are a priori and strictly defined (e.g. evaluation of applicants for a job). However, alternatives may result from the systematic exploration of the objectives pursued in the considered decision situation (e.g. location of a new facility). Especially in problems of strategic nature, the main challenge is to detect interesting alternatives –not obvious or apparent at first sight- on the basis of the main concerns expressed during problem identification. In its work “Value-focused thinking” Keeney (1992) emphasises the importance of generating alternatives through creative thinking focusing on the values of the people concerned. In other occasions, where decision makers are in front of a large number of a priori defined alternatives, a first crucial step is to identify a manageable set of ‘good’ or ‘interesting’ or ‘representative’ alternatives. To this purpose, screening or sorting techniques can facilitate the search for the most preferred alternative(s). Finally, it may happen that alternatives are implicitly defined as combinations of discrete actions. In such cases the decision maker(s) seek(s) to determine the most attractive combination (portfolio) of the available actions.

Decision maker(s) or other **stakeholders** involved in the decision situation are those identifying the nature of the problem and driving the solution procedure towards the preferred direction. Although the two terms may be used interchangeably, decision makers are those assigned with the responsibility to take the final decision, whereas stakeholders is a much broader notion encompassing any single individual or group of people with an interest or concern in the examined problem. Based on this distinction, it can be said that it is up to the decision maker(s) to take into account the stakeholders’ point of view depending on their overall managerial behaviour, the type of the problem considered and the strength of stakeholders to assist or to hamper the solution’s implementation. However, the involvement of stakeholders in the MCDA procedure is useful in capturing several aspects of the problem and getting a better insight to its potential consequences.

Uncertainty is another crucial element of MCDA problems. The main source of uncertainty is related with the limited knowledge about the external parameters that may influence the performances of the considered actions. This type of external uncertainty can be handled by the construction of scenarios denoting possible outcomes in the evolution of the uncertain parameters, as well as by the exploitation of probabilities in the treatment of stochastic events. In addition, decision makers have to handle internal uncertainty that is related with their hesitations during the problem structuring process (which alternatives, how important are the criteria etc.). In should be noted that the problem's solution depends greatly upon the way both external and internal uncertainties are taken into account and the techniques used to incorporate them into the analysis.

Environment refers to all those parameters defining the context in which the decision is taken. They may include fiscal, legislative or cultural aspects that may broaden or restrict the scope of the analysis and impose other constraints in the structuring and decision making procedure. Assuming that all other elements are the same, the problem's solution might differ if the decision is taken in another location and/or another time period.

2.2.4 The steps in MCDA approaches

A MCDA approach is developed in a step-wise procedure. The steps described below are closely connected to each other in the sense that no clear start and end points exist, while backtracks and loops are often necessary before arriving at the final decision.

Problem identification: This first step is to identify the issue under consideration, to agree on the focus and the scope of the analysis and to recognise external constraints such as physical or legislative environment, time and resources available etc. In the presence of multiple stakeholders a common understanding of the problem should be achieved through the elicitation of ideas and the sharing of concerns and values. In these cases the generation of ideas is facilitated through a structured conversation process that is often supported by experienced co-ordinators (facilitators) able to better stimulate thinking and also by specific software. The aim is to look at all aspects of the considered problem, which can be organised by identifying links and building clusters of common concepts.

Problem structuring: After the identification of the problem's nature, the decision maker or group of stakeholders should strive to formally express the detected aspects in order to determine its main elements. In order to emphasise the significance of this step for the subsequent analysis it is often quoted that "a well structured problem is a problem half solved". Following an alternative-led or value- focused thinking the set of alternatives and criteria will be identified and the degree of uncertainty faced will be recognised and –if necessary- incorporated in the analytical procedure to be followed.

Preference modelling: This task aims at capturing the stakeholders' preferences in front of the particular problem as defined in the specific decision context. The difficulty here is that preferences cannot be considered as definite and a priori stored within human mind, but they are modelled during the decision aid process by means of specific techniques acting often as a learning procedure and enabling decision makers to think and realise their aspirations. One has to distinguish two types of preferential information:

- ***Intra-criterion preferences:*** judgements refer to the value attached to different levels of performances and to differences between them. Depending on the aggregation method applied, this kind of preferential information is derived either through a scoring procedure aiming at defining partial value functions in each particular criterion, or as indifference, preference or veto thresholds.
- ***Inter-criterion preferences:*** judgements refer to the relative importance attached to the information carried by each single criterion. Depending on the aggregation method applied, weights either represent scaling factors relating scores and their differences in one criterion to scores in another criterion, or are simply denoting the influence that each criterion has in building up the total preference relation. In each case weights have a different meaning and are derived through different techniques.

Aggregation: The aim in this step is to combine alternatives scores and preferential information in order to arrive at a final solution that takes into account all evaluation criteria. A multiplicity of multi-criteria methods (briefly described in 1.5) have been developed, each based on different ways of deriving preferential information and on different aggregation rules.

Consensus and decision making: Having arrived at the solution sought (rankorder, classification or efficient combination of variables), stakeholders have to think if this solution is a satisfying one. Thus, each single stakeholder may realise ambiguities or false expression of his/her own values and possibly ask for a reconsideration of the problem's structure and/or his/her initial judgements. Moreover, in the presence of multiple stakeholders, it is rather unusual to avoid disagreements regarding the proposed solution. A structured discussion –often supported by specific computational techniques- aiming at discovering main sources of divergence and at justifying or rejecting judgements is usually of great help in getting a better insight in the whole problem enabling the revision of particular structural elements and preferential aspects. Thus, it is possible to gradually arrive at a commonly accepted solution that has more chances to be adopted by all stakeholders and successfully implemented.

2.2.5 MCDA methods

Although the strength of the MCDA methodology lies in the dynamic connection of all the steps described in the previous section, a formal description of the developed methodological tools gives more emphasis on the modelling part that is related with elicitation of preferences and aggregation. Depending on the theoretical background and the key-assumptions adopted in these two steps, MCDA methods can be divided into two broad categories, as follows:

Multi-Attribute Value or Utility Theory

MAVT/MAUT methods are aiming at associating a unique number ('value' or 'utility') denoting the overall strength of preference for each alternative if all criteria are taken into account. The difference between 'value' and 'utility' is that in the latter case there is uncertainty about the performances of alternatives which is formally included in the analytical procedure by considering the behaviour of decision makers against risk. The brief description hereafter will be restricted to the more general notions of value theory assuming that performances are deterministically defined.

In order to identify the total value of the alternatives under the considered set of evaluation criteria, two types of preferential information are provided by the decision maker. As already mentioned, intra-criterion preferences are trying to translate the performances of the alternatives in each single criterion into values denoting the relative significance assigned to different levels of performance. On the other side, inter-criterion preferences are given in the form of weights which relate performances in one criterion to the performances in all other criteria.

The rationale behind intra-criterion preferential information in MAVT methods is that human preferences are not necessarily linearly related with the performances measured on a 'natural' or 'objective' scale. Furthermore, in the case of a criterion where such natural measurement scales do not exist, it is the decision maker who has to construct a scale by assigning values to the examined alternatives according to his/her own view about their relative – not quantified - performances. Hence, each alternative $\boldsymbol{a}$ is associated with a value $\boldsymbol{v_i(a)}$, translating its performance in criterion $\boldsymbol{i}$ in terms of the particular decision maker's preference system.

The basic property of these partial value functions is that –considering criterion ***i*** -alternative ***a*** is strictly preferred to alternative ***b*** if $v_i(a)>v_i(b)$, while indifference between the two alternatives holds only if $v_i(a)=v_i(b)$.
Partial value functions are defined with a strict reference to the worst and best performance, which are usually assigned with 0 and 1, respectively. Worst and best performances refer to either the considered set of alternatives (local scale) or to potentially achievable scores (global scale). In comparison with the natural measurement scale in the considered criterion, partial value scales are:

- ***Monotonically increasing:*** if the highest performance on the natural scale is the most preferred.
- ***Monotonically decreasing:*** if the lowest performance on the natural scale is the most preferred.
- ***Non-monotonic:*** if the most preferred performance is an intermediate point on the natural scale.

In the case of monotonic non-linear value functions, the decision maker(s) have to define its exact form. A common approach to elicit this intra-criterion information is the **bisection method**, where the decision maker identifies the point on the natural scale he/she believes is half the distance between the two reference points (0 and 1). The procedure continues by consecutively finding the midpoint between two reference points with known values.
If no natural measurement scale exists, then the decision maker should construct a qualitative scale. These constructed scales are defined by their extreme values (best and worst, on a local or global scale) and the intermediate scores assigned to the examined alternatives. Prior to aggregation, qualitative scales are normalized to the same interval in which all other partial value functions have been defined.
The transition from partial to global value functions (taking into account the whole set of criteria) implies the use of an aggregation formula together with the inter-criterion preferences provided by the decision maker. The simplest and most commonly used aggregation model is the additive one:

$$V(a) = \sum_i w_i \bullet v_i(a)$$

V(a) is the total value associated with each alternative ***a***, and w_i is the weight reflecting the relative importance attached to each criterion ***i*** by the decision maker. The preference and indifference conditions defined at the level of single criteria apply also to total value functions, which can thus be exploited for constructing a complete preorder of the examined alternatives.

Weights in MAVT/MAUT methods play the role of scaling factors in the sense that they relate scores in one criterion, to the scores of all other criteria. This means that by assigning weights of relative importance, decision makers implicitly determine how much units in one criterion they are willing to give up, in order to improve the performance of another criterion by one unit. So, if the weight of criterion ***i*** is double the weight of criterion ***j***, then the decision maker values 10 units on criterion ***i***, the same as 20 units on criterion ***j*** (Belton and Stewart, 2002). In order for the decision makers to more clearly realize their preferences in terms of the necessary trade-offs between criteria, weights are defined on the initial natural scales and by taking into account the absolute level of performances and absolute differences in scores. Different weights elicitation methods that have been developed for helping decision makers in articulating weights in a systematic and –more or less- consistent way will be described in more detail in Section 3.

Outranking methods

Outranking methods proceed to a pairwise comparison of alternatives in each single criterion in order to first determine partial binary relations according to the intra-criterion preferential information provided by the decision maker. These partial binary relations are then synthesized over all criteria by taking into account the inter-criterion preferences expressed in the form of weights of relative importance.

The main difference to MAVT/MAUT methods is that in outranking approaches preferences are modelled with respect to pairs of alternatives and thus they are denoting the evidence that *'an alternative **a** is at least as good as alternative **b**'*. Furthermore, comparisons of performances are made on the initial scale, either a natural cardinal scale or a qualitative ordinal one. Thus, it is not values of alternatives but the strength of preferences between pairs of alternatives that are determined on a normalized scale, from 0 to 1, the former denoting no preference (including indifference) and the latter strict preference. Because of the vague determination of preferences, the key-feature of the outranking methods is that they allow for two or more alternatives to remain incomparable if no enough arguments exist to support that one alternative is better than (outranks) the other(s).

The two most known outranking approaches are the ELECTRE family developed by Roy and his collaborators (1985, 1996) in the Paris Dauphine University (with ELECTRE III being the most widely used) and PROMETHEE developed by Brans and Vincke, (1985), (Brans et al.,

1986) in the Free University of Brussels. Both methods require simpler hypotheses and less effort to model preferences compared to MAVT/MAUT methods, but their outcomes do not always allow for rigid conclusions to be drawn, especially if several alternatives remain incomparable to each other. Despite their differences in the procedural steps, in the terminology used and in the exploitation of the partial preference functions, both ELECTRE III and PROMETHEE methods are based on the extension of the usual notion of criterion. The former proposes the 'quasi-criterion', and the latter is further enriching the extension problematique by suggesting additional types of 'pseudo-criteria'. The common rationale behind the intra-criterion preferential information in outranking methods is that in front of pairwise comparisons, human preferences do not abruptly pass from the state of indifference to that of preference. Hence, by means of thresholds associated with each pseudo-criterion the state of indifference is extended, while a distinction is made between weak and strict preference.

In the case of the most representative 'pseudo-criterion' (used in both methods), indifference and preference thresholds are defined in each criterion, either as absolute values q_i, p_i, respectively, or as functions $q_i[g_i(\boldsymbol{a})]$, $p_i[g_i(\boldsymbol{a})]$ of the performance $g_i(\boldsymbol{a})$ of the examined alternative ***a***.

In the case of the PROMETHEE method, for any pair of alternatives ***a*** and ***b*** and assuming that $g_i(\boldsymbol{a}) > g_i(\boldsymbol{b})$, partial preference functions $p_i(\boldsymbol{a,b})$ in a criterion ***i*** (to be maximized) are calculated as follows:

Alternative ***a*** is **indifferent** to alternative ***b*** with respect to criterion ***i***:

$$p_i(\boldsymbol{a,b}) = 0 \quad \text{if} \quad g_i(\boldsymbol{a}) \leq g_i(\boldsymbol{b}) + q_i$$

Alternative ***a*** is **weakly** preferred to alternative ***b*** with respect to criterion ***i***:

$$0 < p_i(\boldsymbol{a,b}) < 1 \quad \text{if} \quad g_i(\boldsymbol{b}) + q_i < g_i(\boldsymbol{a}) < g_i(\boldsymbol{b}) + p_i$$

Alternative ***a*** is **strictly** preferred to alternative ***b*** with respect to criterion ***i***:

$$p_i(\boldsymbol{a,b}) = 1 \quad \text{if} \quad g_i(\boldsymbol{a}) \geq g_i(\boldsymbol{b}) + p_i$$

It can be seen from the above formulas that the performance of alternative ***a*** should exceed that of alternative ***b*** by a certain amount $\boldsymbol{q_i}$ in order to support the assertion that ***a*** is weakly preferred to ***b***. In a similar way, to support the assertion that a is strictly preferred to b, this difference should exceed an amount $\boldsymbol{p_i}$, with $\boldsymbol{p_i > q_i}$. It is clear that if $g_i(\boldsymbol{a}) < g_i(\boldsymbol{b})$ then no preference is possible to be supported for any rational decision maker and $p_i(\boldsymbol{a,b})=0$.

In ELECTRE III, instead of partial preference functions, partial Concordance Indices are calculated in a rather similar way. These indices denote the degree of credibility of the assertion that alternative ***a*** is preferred to ***b***. In addition to the Concordance indices determined on the basis of indifference and preference thresholds, a Discordance Index D_i(***a,b***) is calculated, provided that a veto threshold is assigned to criterion ***i***. This index shows the degree the assertion '*alternative **a** is equal or better than alternative **b**',* is strongly disputed. This happens if in one or more criteria the performance of alternative ***b*** exceeds that of ***a*** by an amount greater than the corresponding veto threshold.

Once partial preference functions (or partial concordance and discordance indices) have been calculated for all pairs of alternatives in each criterion, one has to proceed to their aggregation by taking into account the weight of relative importance associated to each criterion. Total preference functions P(***a,b***) (or total Concordance Indices, C(***a,b***)) result as the weighted average of partial ones:

$$P(a,b) = \sum_i w_i \bullet p_i(a,b) \qquad \text{with } \Sigma w_i = 1$$

At a final step total preference functions (or the combination of Concordance and Discordance indices) are exploited -following a different technique in each method- in order to construct outranking relations and establish preorders of the examined alternatives. Due to the imprecise nature of the preferential information, the resulting preorders are in all cases non-complete, meaning that some of the alternatives might appear as incomparable to each other. This result is in many occasions very useful since it indicates strong conflicts in the criteria in which incomparable alternatives show the one high and the other a low performance and forces decision makers to think harder on their preferences. However, in the case of the PROMETHEE method a further refinement of the initial preorders is possible in order to obtain a complete preorder i.e. to remove incomparabilities.

It should be noted that in outranking methods weights of importance have a different meaning than in MAVT/MAUT methods. They do not represent trade-offs between criteria scores, since they are used to combine preference relations and not scores assigned to individual alternatives. Therefore, they should be interpreted rather as measures of the degree each criterion influences a final statement of whether or not 'alternative ***a*** is equal or preferred to ***b***'. It is clear that if this statement is valid in the most important criteria then there are more arguments to accept the overall validity of such an assertion.

2.2.6 MCDA strengths

MCDA advocates emphasize the following advantages, especially as regards their use in sustainability problems:

- MCDA is a **multi-disciplinary approach** that is capable to better capture the complexity of natural systems, the plurality of values associated with environmental goods and the variant perceptions of sustainable development (Toman, 1998). The experts and scientists participating in a MCDA procedure have the possibility and the responsibility to go beyond their own discipline and to take into account perspectives and information that are possibly fields from other disciplines.
- MCDA provides an **open and flexible assessment framework** that can be easily adapted to the particularities of the problem under consideration. The whole decision making process and especially the problem structuring and the preference elicitation phase of MCDA approaches are capable to shed light into the particular decision context and thus, to secure a more flexible and 'democratic' assessment framework leading to a solution that may not be the 'best' for any one group of stakeholders without being the 'worst' (Faucheux and Froger, 1995; Joubert et al., 1997; O'Connor, 2000).
- MCDA is acting as an **interactive learning procedure** that motivates stakeholders to think harder about the conflicts addressed by taking into account other points of view and opposing arguments (Martinez-Alier et al., 1998, Omann, 2000). The decision is structured into manageable sub components, new scientific insights find more easily their way into the policy debate and stimulate constructive revisions of existing positions (Hobbs and Horn, 1997; Toman, 1998). Such a transparent and constructive procedure enables stakeholders to better understand the problem at hand and eventually to arrive at a better and commonly accepted solution (Lahdelma et al. 2000).
- MCDA applications can **consider a large variety of criteria** independently of the type of data (quantitative or qualitative) and the measurement scale ***(weak commensurability)***. Hence, it allows for a comprehensive analysis including all various aspects of sustainability and not only marketed goods or monetized costs and benefits (Oman, 2000).

- MCDA is to a great extent **exempt from the biases and distributional problems** associated with WTP or WTA estimates. Individuals feel more liberated to express their preferences in the form of importance weights and decide on the necessary trade-offs without being restricted by their ability to pay (Joubert et al., 1997). Although a too precise specification of weights is considered as utopian and creating false certainties a better approximation of human preferences is facilitated (Munda, 1996). Furthermore, MCDA, is more effective to deal with (intra - generational) equity issues by including relevant criteria e.g. the improvement in income equity or/and by allowing stakeholders and affected groups of the society to participate at the decision process (Joubert, 1997).

In addition to the above listed strong points, which are common in all MCDA approaches, outranking methods present further advantage because of the non-compensatory approach followed in the elaboration of the stakeholders' preferences. Actually, outranking approaches are building upon the incommensurability characterizing most real decision situations, while using thresholds that are capable to more effectively operationalize the concept of sustainable development. The so implied weak comparability of the considered actions appears as valuable information for policy makers dealing with complicated and ambiguous decision situations.

On the other side, the main shortcomings associated with MCDA approaches are the difficulties to find and motivate the appropriate stakeholders in each single decision situation and the increased co-ordination abilities needed for facilitating the elicitation of preferences and the exchange of ideas (Hobbs and Meier, 2000). Last, but not least is the uncertainty about the use of MCDA results and the extent they are taken into account in real decisions and in policy implementation (Turner et al., 2000). This weakness turns to be one of the most noteworthy arguments for CBA explaining its extensive use in practical policy making and offering the possibility to directly influence the market mechanism, which is still the dominating driving force in human societies.

2.2.7 MCDA and Integrated Sustainability Assessment (ISA)

Numerous approaches and frameworks have been developed to measure and assess the achievement of sustainability goals, ranging from guidelines to more specific indicator based frameworks (Ness et al., 2007). Ness et al. (2007) and Singh et al. (2012) provide a comprehensive review and elaborated classification of different sustainability assessment methodologies. According to Ness et al. (2007), many of the integrated assessment tools that have been reviewed integrate environmental and social aspects of sustainability. According to Weaver and Rotmans (2006) there are different dimensions of integration that can take place in sustainability assessment processes such as integrated objectives and multiple sustainability concerns and objectives, integration of knowledge and information across multiple domains, integration of sustainability values and principles, integration of different stakeholders, experts and policy makers, quantitative and qualitative information and tools.

The general Multi Criteria Decision Analysis methodology which has been applied here is in line with the structure of most MCDA approaches, which consists of the following steps (Belton and Stewart, 2002, Gamper and Turcanu, 2007) as has been described in the previous sections: decision context and type of , recommendation, definition of decision actions or development of alternatives, elaboration of evaluation criteria, assessment of alternative decision actions' impact with respect to these criteria, preference elicitation, consistency check and aggregation of preferences. Multiple criteria analysis (MCA) approaches have been classified under the integrated assessment category since they integrate multiple objectives while including multiple stakeholders in the assessment process (Ness et al., 2007; Singh et al.,2012). Furthermore, Weaver and Rotmans, (2006) have defined the main phases of an integrated sustainability assessment (ISA) which are scoping, envisioning, experimenting, learning, monitoring and evaluation (figure 4).

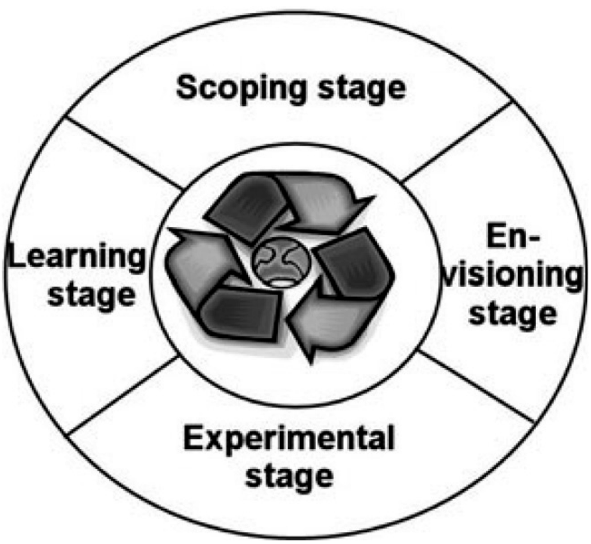


Figure 4: ISA cycle (Weaver and Rotmans, 2006)

By looking more carefully on the processes of ISA and MCA we realise that they are aligned to a large extent sharing many common features. However ISA incorporates further some iterative, cyclical and learning aspects that are not emphasized in traditional MCA approaches. Considering this alignment of the two processes we can enrich further the traditional MCA process with some important ISA components in order to achieve a more integrated sustainability multi-criteria assessment of low carbon energy options and technologies.

Scoping stage

The scoping stage of ISA process entails a clear definition of the unsustainability problem at hand. This stage also involves the understanding of different values and norms of relevant stakeholders with regard to the policy problem. Moreover this stage defines the integrated systems analysis by defining the geographical, temporal and functional boundaries of the system under investigation. In this stage the consideration of previous assessment attempts and their deficiencies and gaps should be identified. An important element of scoping stage is the identification of stakeholders and selection of a participatory "vehicle" of the methodology. Inputs from stakeholders at this stage are essential for refining the overall framework and conceptual model.

Envisioning stage

The envisioning stage involves a common understanding of sustainability in the context of the problem at hand and in consultation with the stakeholders. Therefore the principles and objectives underlying this common interpretation of sustainability should be identified, justified and validated. These principles could range from socio-cultural to institutional ones depending on the specific context and problematique. Options should be also developed/identified along with their potential impacts (beneficial or adverse). Moreover, this stage also involves the use of an appropriate participatory method to organize stakeholders involvement and use of their inputs for defining a narrative assessment of the impacts of the different options.

Experimenting stage

This stage involves the selection and use of mix of quantitative and qualitative tools to perform the ISA experiments. Identification and formulation of tools' weaknesses and deficiencies is important. After choosing the appropriate tools and methodologies the actual assessment should be conducted and testing the the sustainability impacts of the options under investigation. Important element of this stage is the use of stakeholders' inputs regarding their knowledge and expertise on sustainability impacts of the different options .

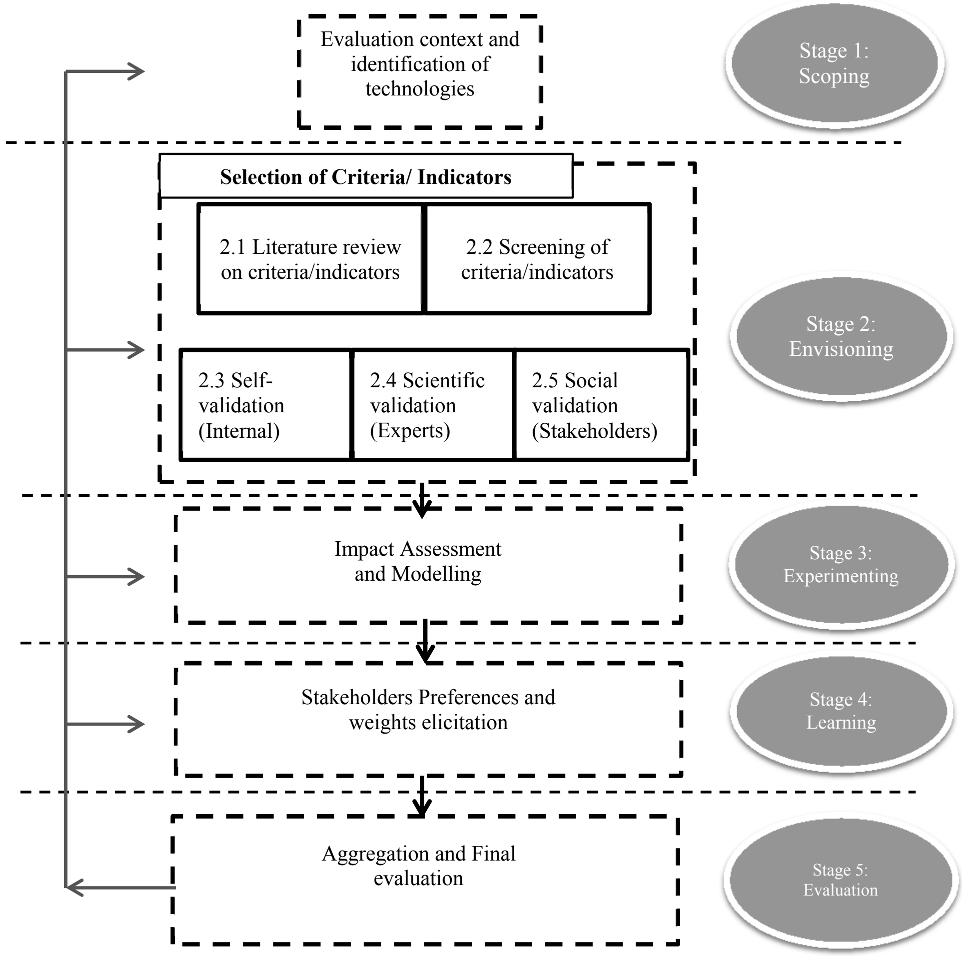
Learning, evaluating and monitoring stage

In this stage learning experiences and lessons during the ISA process need to be explicitly identified. Learning outcomes become inputs for improvement and refinement of the new ISA cycle following an iterative process. In particular in this stage we need to know how the learning process resulted in a reframing of the problem or to the assessment of the ISA tools used and which experiments were successful or not (Rotmans et al., 2001). During this stage also indicators are identified to reflect the reframing of the perceptions of stakeholders involved. With regard to the stakeholders evaluation, elicitation of stakeholders' views and evaluation of level and nature of stakeholders' involvement in terms of possible refinements for the next round are necessary elements.

An important opportunity for ISA concerns unstructured emerging and complex problems where policy and relevant stakeholders have not taken a firm view or where new elements might cause stakeholders to re-evaluate their initial positions. This is also in line with the preference construction theory that should be considered when some of the decision or policy elements are unfamiliar (Lichtenstein and Slovic, 2006) but also with the evidence that preferences may change under different contextual conditions (e.g. framings, methods) (Gregory and Slovic, 1997; Norton, et al., 1998).

Considering the above background of ISA and the steps of MCA described in previous sections, an overall MCA assessment framework of energy technologies was developed which is aligned with the main stages of ISA. The main components and stages of the MCA assessment framework are illustrated at figure 5.

Figure 5: Integrated MCA sustainability assessment framework for energy technologies aligned with the Integrated Sustainability Assessment (ISA) stages



2.3 Evaluation frameworks and criteria for energy options

2.3.1 MCDA approaches in Energy and Climate policy evaluation

MCDA evaluation approaches have been applied increasingly the last two decades for energy policy evaluations in various decision making contexts. In particular MCDA approaches have been applied for incorporating public values in energy future scenarios evaluation (Keeney et al., 1990), evaluating alternative integrated energy plans (Hobbs and Horn, 1997; Kaya and Kahraman, 2011), assessment of renewable and sustainable energy technologies (Afgan and Carvalho, 2001; Haralambopoulos and Polatidis, 2003; Cavallaro, 2005; Gamboa and Munda, 2007; Doukas et al., 2007) indirect valuation of energy externalities (Diakoulaki and Grafakos, 2004), participatory design of renewable energy policy instruments (Madlener and Stagl, 2005), integrated assessment of energy analysis (Giampetro et al., 2006), evaluation of energy projects for electricity generation (Mavrotas et al., 2003), strategic planning in electricity generation (Kaldellis et al., 2013a), defining national priorities for greenhouse gases emissions reduction in the energy sector (Georgopoulou et al., 2003). For an extensive review of MCDA applications in energy planning see Hobbs and Meier (2000).

Despite the absence of MCDA methods in the evaluation of climate policy interactions, the application of MCDA methods within the climate policy field has been increased. The most common use of MCDA in climate policy evaluation appears for Clean Development Mechanism projects evaluation (Diakoulaki et al., 2007, Flamos et al. 2005, Nussbaumer, 2009, Sutter 2003). MCDA methods highlighted as a useful tool for climate policy for first time by UNEP (1994). Borges and Villavicencio (2004) applied MCA method for the development of Peruvian GHG emissions reduction strategies in accordance to UNEP MCA analytical framework. Bell et al. (2001, 2003) investigated the use of Multi-criteria methods in integrated assessment of climate policy, whereas Brown and Corbera (2003) examined the implications of forest carbon projects for different aspects of equity and development by applying a participatory stakeholder MCDA. In addition, MCDA methods have been applied for the assessment of climate impacts in agricultural land use (Abildrup et al., 2006), the assessment of Carbon Capture and Storage technologies (Shackley and McLachlan, 2006), the control of GHG emissions from international civic aviation sector (Solomon and Hughey, 2007) and the assessment of climate policy interactions (Konidari and Mavrakis, 2007, Oikonomou et al. 2010, Oikonomou et al. 2011a, Oikonomou et al. 2011b).

A review of the energy planning and climate mitigation literature showed that MCDA methods have been used extensively in the assessment of different energy options at different levels. MCDA approaches have been applied in the assessment of energy and climate change mitigation options mainly at the micro (project) level, but also at the meso (local/regional) (e.g. Haralambopoulous and Polatidis 2003; Beccali et al. 2003; Mavrotas et al. 2003; Cavallaro and Ciraolo 2005; Flamos et al. 2005; Gamboa and Munda 2007; Burton and Hubacek 2007; Begic and Afgan 2007; Loken et al. 2009) and macro (national/international) levels (e.g. Madlener et al. 2007; Makowski et al. 2009; Stagl 2006; Doukas et al. 2007; San Cristobal 2011).

MCDA has been applied, for example, in evaluating alternative energy plans and electricity generation projects, in assessing renewable energy technologies and energy analysis, and in integrating public views in future energy scenarios and participatory design of policy instruments, among others (Grafakos et al., 2011; Oikonomou et al., 2011a, 2011b). Reviews of MCDA applications in energy planning and climate mitigation can be found in Pohekar et al. (2004), Kowalski et al. (2009) Braune et al. (2009), and Grafakos et al. (2010a). Braune et al. (2009) found that there is a strong application for MCDA methods in renewable energy systems (RES) which could be explained by the increased interest and policy commitment of national and local governments as well as by a shift in the public perception of renewable energy systems.

In Europe, MCDA methods have been extensively applied in climate change mitigation and energy planning in micro (project), meso (local/regional) and macro (national/European) levels. Tables 1 and 2 summarize the studies that have applied MCDA approaches in meso and macro levels for assessing future and current energy options in Europe. Furthermore the table provides information on the level of inclusion of stakeholders in the phases of (1) criteria and indicators selection and validation and (2) criteria weighting.

Table 1. MCDA applications in energy and climate change mitigation planning in Europe at the local/regional level.

Level	Study	Thematic area	MCA methodology	Current vs future energy options	Weighting method	Criteria selection	Actors involved in weighting process	Real Application
Chios Island, Greece	Haralambopoulous, D.A. and Polatidis, H. (2003)	Renewable energy projects	Promethee II	Current	Direct weights	By researchers	Weight factors reflecting the analysts' previous experience	Proposed methodology
Sardinia Island, Italy	Beccali, et al. (2003)	Renewable energy technologies	Electre III	Current	SIMOS approach	By researchers	Three different scenarios by the researchers.	Proposed methodology
Salina Island, Italy	Cavallaro, F. and Ciraolo, L. (2005)	Wind energy plants	Naiade method	Current	Does not incorporate a traditional weighting technique	By researchers	Does not incorporate a traditional weighting technique	Yes
Catalonia, Spain	Gamboa, G. and Munda, G. (2007)	Wind farm locations	Social multi-criteria evaluation	Current	Equal weights	By researchers and stakeholders	Equal weights were assigned	Yes
Metropolitan Borough of Kirklees, United Kingdom	Burton, J. and Hubacek, K. (2007)	Small-scale energy technology applications	MACBETH	Current	Direct allocation	By researchers	Five (5) professionals in the energy sector.	Yes
Norway (local case study)	Loken, E., Botterud, A., and Hoken, A. (2009)	Future energy-supply infrastructure	Equivalent attribute technique (EAT)	Future	Swing	By researchers	Six (6) professionals in the energy and research industry.	Proposed methodology
Crete, Greece	Tsoutsos, T., et al., (2009)	Sustainable energy planning	Promethee	Current	Direct allocation	By researchers	Local authorities, local communities, potential investors, academic institutions, environmental groups, and government and European Union.	Yes
Urnasch, Switzerland	Trutnevyte, E. Stauffacher, M., and Scholz, R. (2011)	Future energy systems	Analytic heirarchy process (AHP)	Future (2035)	AHP	By researchers and stakeholders	Energy consumers, experts and academics, and energy industry actors	Yes
Thassos, Greece	Mourmouris, J.C. and Potolias, C. (2013)	Renewable energy sources	REGIME	Current	Direct allocation	By researchers	Criteria weights based on the (1) combination of environmental, social, and economic characteristics of the technologies and (2) local and regional characteristics of the area under investigation.	Proposed methodology
Crete, Greece	Kaldellis, J., Anestis, A., and Koronaki, I. (2013a)	Strategic electricity generation planning	Delphi approach	Current	Direct allocation through delphi	By researchers	A total of 30 experts (from the academe, national energy research centers, and power corporation).	Yes

Table 2. MCDA applications in energy and climate change mitigation planning in Europe at the national/international level.

Level	Study	Thematic area	MCA methodology	Current vs future energy options	Weighting method	Criteria selection	Actors involved in weighting process	Real Application
Bosnia and Herzegovina	Begic, F., and Afgan, N. H. (2007).	Selection of energy system	ASPID	Current	Direct allocation	By researchers	Weighting factors were allocated to the different indicators by the researchers.	Yes
Turkey	Topcu, Y.I. and Ulengin, F. (2004)	Future electricity resources	Promethee I and II	Future	Pairwise comparisons	By researchers	Criteria weighting was carried out by the researchers.	Proposed methodology
Greece	Diakoulaki, D., Karangelis, F., (2006)	Alternative power generation scenarios	Promethee	Current	Direct allocation	By researchers	Four different weighting sets were used by researchers.	With attributes of real-world application
United Kingdom	Stagl, S. (2006)	National energy policy	Simple multi-criteria evaluation	Future (2050)	Direct allocation	By stakeholders	Members of the general public by way of citizen panels and through (1) small group settings and (2) plenary for comparison of evaluations.	Yes
Austria	Madlener, R., et al. (2007); Kowalski, et al. (2009),	Energy scenarios	Promethee	Future (2020)	SIMOS	Selected by researchers and stakeholders	National case study stakeholders include government bodies, private firms, power distributers, NGOs and research institutes, while local case study stakeholders were energy experts, mayors, and citizens.	Yes
Greece	Doukas, H., Andreas, B., and Psarras, J. (2007)	Sustainable technological energy priorities	Linguistic variables	Future (2021)	Direct allocation	By stakeholders	Decision makers	Proposed methodology
Spain	San Cristobal (2011)	Selection of renewable energy project	VIKOR, Analytic Heirarchy Process	Current	Pairwise comparisons	By researchers	Three groups of stakeholders: government, banks, and development companies.	Proposed methodology
Turkey	Kaya, T. and Kahraman, C. (2011)	Energy planning	modified fuzzy TOPSIS	Current	Pairwise comparisons	By researchers	Three (3) energy planning experts.	Proposed methodology
Lithuania	Sliogeriene, et al., (2013)	Energy generation technologies	AHP and Additive Ratio Assessment (ARAS) method	Current	AHP	By experts	A group of 25 experts (managers and lawyers of energy enterprises, financial specialists, and scientists).	Yes
Europe	Makowski, et al. (2009), Carrera, D. and Mack, A. (2010), Schenler, et al. (2009)	Assessment of electricity supply options	Web-based MCDA	Future (2050)	Hierarchical weighting	By stakeholders	Stakeholders, ranging from energy suppliers and consumers to non-government organizations and government authorities.	Yes

The New Energy Externalities Development for Sustainability (NEEDS) project applied a MCDA of future (2050) energy technologies in four European countries, namely France, Germany, Italy and Switzerland (Hirschberg et al. 2007) for the year 2050. The MCA for NEEDS aimed to assess energy technologies, considering the varied national stakeholders' preferences for the trade-offs between different criteria, and to examine the sensitivity of the sustainability assessment results in reference to the stakeholders' preferences (Makowski et al. 2009). The full set of criteria and indicators selected for the project was derived from a comprehensive review as well as feedback from national stakeholders (Hirschberg et al. 2008). A stakeholders' survey provided the necessary feedback in finalizing the conclusive selection of criteria and indicators. The stakeholders' elicitation process engaged a wide range of energy experts and national stakeholders (Makowski et al. 2009). The preferences of the stakeholders, which were conveyed through relative importance of the criteria, were obtained via a web-based MCA.

The ARTEMIS Project entailed the evaluation of renewable energy scenarios for Austria –in the national level and in two local communities - for the year 2020. The study involved different stakeholders and energy experts through workshops and interviews that were carried out for scenario development and criteria weighting. Drawn from systems theory as well as from the integrative sustainability concept, the indicator set for assessing energy options was improved through a participatory process. (Madlener et al. 2007).

At a national level, MCA was applied to evaluate future energy policy options in the United Kingdom (Stagl 2006). Experts, stakeholders, and the general public were consulted in the process through surveys, focus group discussions, and workshops. In one of these workshops, the criteria for assessing energy options were discussed with the participants. Workshop participants expressed their preferences for the criteria up for selection.

In Greece, an assessment of sustainable technological energy priorities for 2021 was carried out (Doukas et al 2007). A working group composed of participants from relevant national energy stakeholders, such as power producers, government managers, financing organizations, and researchers in Greece selected the criteria. Using a multi-criteria decision aid approach via linguistic variables, the working group examined the energy technologies within the context of the Greek Technology Foresight Programme (Doukas et al. 2014).

At a local level, in Urnasch, a municipality in Switzerland, a stakeholder-based MCA was carried out to assess future energy systems. The set of criteria and indicators was selected by a steering board (composed of four local actors: mayor, environmental department head, energy association head, and president of the local electricity supply company) and by an academic team. The final set of criteria and indicators employed in the MCA via the Analytic Hierarchy Process (AHP) method were selected by energy consumers, experts and academics, and energy industry actors (Trutnevyte et al. 2011).

In a pilot case study in Norway, the equivalent attribute technique (EAT) was used to assess future energy-supply infrastructure (Loken et al. 2009). The study made use of the results of a previous MCA wherein the multi-attribute utility theory (MAUT) was employed. In this case the researchers selected the criteria. Preference elicitation interviews were carried out among six individuals in the energy sector. The participants, in their 'imagined' roles as managers of an energy company, provided their priorities with regards to the expansion of the current energy system.

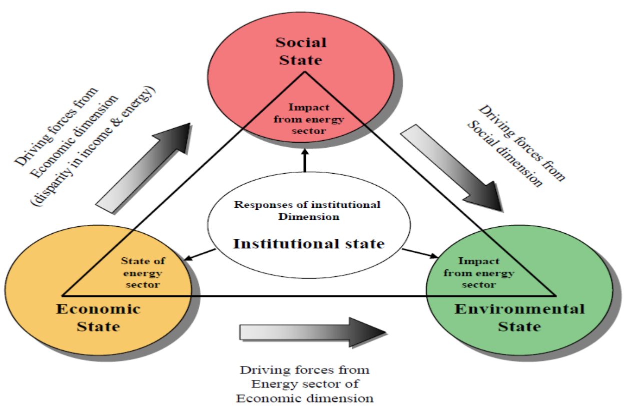
In most of the cases at the local/regional level (see table 1), the inclusion of stakeholders in the selection or validation of evaluation criteria and indicators was not evident. The selection of criteria and indicators for assessing current and future energy technology options was done by the researchers themselves. Furthermore, it is clear that assessing future energy technologies while integrating and mapping local (urban) stakeholders' perspectives and views at a wider scale (i.e. European level) is lacking. On one hand, a European-wide MCA study, such as in the case of NEEDS project, looked at the preferences of national stakeholders. On the other hand, there are various distinct local/regional MCA studies that cannot be used for a unified framework in mapping local stakeholders' preferences at the European level.

2.3.2 Sustainability and resilience criteria for energy options evaluation

The International Atomic Energy Agency (IAEA) for first time attempted to approach energy sector from a sustainability angle. IAEA initiated a complex and long process of selecting, developing and validating energy related indicators within the framework of Indicators for Sustainable Development (ISD) in 1999. This was conducted in collaboration with various UN member states and other international organizations, including the United Nations Department of Economic and Social Affairs (UNDESA), the International Energy Agency (IEA) under the umbrella of Agenda 21 and the United Nations Commission on Sustainable Development (UN CSD).

The original ISD framework considered the economic, social, environmental and institutional dimensions of sustainable development. According to this framework the four dimensions are interrelated (exhibit 1). By applying this concept on the energy sector the interrelationships among the various sustainability dimensions of the energy system were identified. The environmental state associated with the energy system is affected by driving forces originating from the economic and social dimensions. The social state of the energy system is, in turn, influenced by certain driving forces originating from the economic dimension. The institutional dimension can affect all the other three dimensions—social, economic and environmental—through corrective policies that influence the sustainability of the whole energy system.

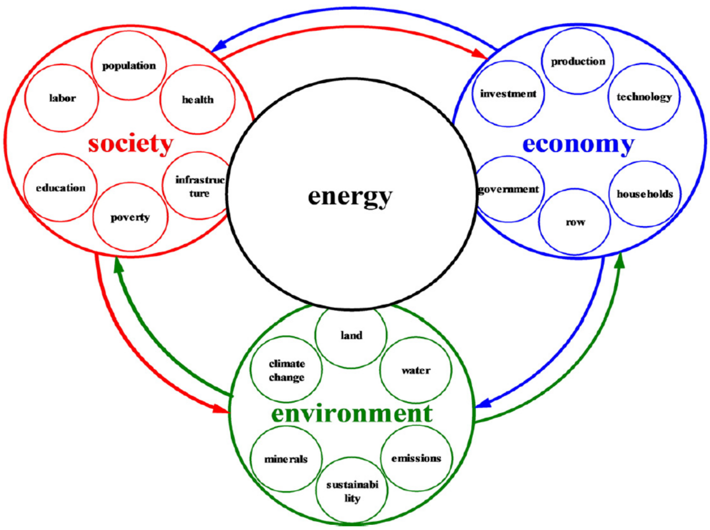
Figure 6: Interrelationships among sustainability dimensions of the energy sector



Source: IAEA/IEA (2001)

Millenium Institute in 2005 also developed a conceptual framework called Threshold 21 (T21) that integrates system dynamics and allows representation of feedbacks between different sustainability sectors and components (figure 7). T21 approach supports policy makers to recognize the value of interrelationships existing between energy, environmental, economic and societal systems.

Figure 7: Interrelationships between energy systems and sustainable development subsystems



Source: Millenium Institute (2005), Bassi (2009), Musango and Brent (2011)

The concept attempts to help to understand the short and long term impacts of energy issues in an integrated manner for modelling and planning sustainable policies in a complex policy environment at a national and country level.

Sustainability indicator frameworks

Meta-studies of urban sustainability indicators have identified hundreds of indicator frameworks that can be used to structure the selection and conceptualization of metrics (e.g. Walton et al., 2005). Maclaren (1996) summarizes this diversity by enumerating the main framework types including domain-based (e.g. social, economic, environmental sustainability), goal-based, and causal (e.g. driver pressure- state-impact-response OECD, 2003). Almost any of these methods could be applied to urban energy systems but the complexity and commonness of energy use suggests that a single approach is unlikely to be perfect and ideal.

IAEA in cooperation with UNDESA, IEA, the Statistical Office of the European Communities (Eurostat) and the European Environment Agency (EEA) developed a core set of energy indicators for sustainable development (EISD) (IAEA, 2005). The original set of 41 indicators was reduced to a final core set of 30 indicators. The original name "Indicators for sustainable energy development (ISED)" was then modified to "energy indicators for sustainable development (EISD)" to reflect the view held that "sustainable energy development" tends to refer only to renewable energy, rather than the broader spectrum of energy choices. This name change was considered necessary to avoid future misunderstandings in discussions relevant to energy and sustainable development. The 30 energy indicators for sustainable development presented were classified according to the three major dimensions of sustainability: economic (16 indicators), environmental (10 indicators) and social (4 indicators). The main objective of this indicators' framework was to assess the energy sustainability at the country level and provide a tool for comparison.

Afghan et al. (2000) developed a set of sustainability indicators for the assessment of energy systems. They classified the energy sustainability indicators in 4 different type of indicators such as resource (4), environment (4), social (3) and efficiency (3).

Shen et al. (2010) conducted an extensive literature review on the type of criteria and indicators that have been developed for the assessment of renewable energy sources by different studies. They classified the criteria and indicators according to the 3 main sustainability goals namely energy, environmental and economic. Social related aspects were not specifically addressed but indirectly integrated in economic and environmental categories. Table 3 shows all the assessment criteria for renewable energy sources that according to Shen et al., (2010) have been used in the literature.

Table 3: Criteria classification for renewable energy assessment according to Shen et al. 2010

Policy goal	Criteria	Description	Sources
Energy goal	Energy price stability	The price of final product generated from renewable energy sources is not easily fluctuated	Mamlook et al. (2001), Komor and Bazilian (2005), Liposcak et al. (2006), Begic and Afgan (2007), Bureau of Energy of Ministry of Economic Affairs (2007), Wang et al. (2009a, 2009b), Jovanović et al. (2009)
	Security for energy supply	The consistent availability of sufficient dependent on secure supplies of energy	Komor and Bazilian (2005), Burton and Hubacek (2007), Lund (2007), Cai et al. (2009a, 2009b)
	Low energy prices	The price of final product generated from renewable energy sources is acceptable	Komor and Bazilian (2005), Shaw and Peteves (2008)
	Stability for energy generation	The output generated by renewable energy sources is not easily fluctuated	Gross (2004), Taljan and Gubina (2009), Georgilakis and Katsigiannis (2009)
Environmental goal	Carbon emissions reduction	The extents to which renewable energy sources diminish the emission of CO_2	Diakoulaki and Karangelis (2007), Burton and Hubacek (2007), Chatzimouratidis and Pilavachi (2007), Chatzimouratidis and Pilavachi (2008a), Chatzimouratidis and Pilavachi (2008b), Wang et al. (2008), Wang et al. (2009a, 2009b), Jovanović et al. (2009), Løken et al. (2009), Beccali et al. (2003), Komor and Bazilian (2005)
	SO_x and NO_x emissions reductions	The extents to which renewable energy sources diminish the emission of SO_x and NO_x	Diakoulaki and Karangelis (2007), Begic and Afgan (2007), Chatzimouratidis and Pilavachi (2007), Chatzimouratidis and Pilavachi (2008a), Chatzimouratidis and Pilavachi (2008b), Jovanović et al. (2009), Komor and Bazilian (2005)
	Environmental sustainability	The development meets the needs of the present without compromising the ability of future generations to meet their own needs	World Commission of Environment and Development (1987), Komor and Bazilian (2005)
	Low land requirement	The power plants utilizing renewable energy sources will not occupy large land	Afgan and Carvalho (2002), Beccali et al. (2003), Wang et al. (2008), Chatzimouratidis and Pilavachi (2008a), Chatzimouratidis and Pilavachi (2008b), Wang et al. (2009a, 2009b)
Economic goal	Local economic development	The extents to which renewable energy source can stimulate the domestic economic development	Komor and Bazilian (2005), Williams et al. (2008), Sastresa et al. (2010)
	Increasing employment	The extents to which renewable energy source can create jobs	Haralambopoulos and Polatidis (2003), Beccali et al. (2003), Komor and Bazilian (2005), Erdoğmuş et al. (2006), Madlener et al. (2007), Doukas et al. (2007), Begic and Afgan (2007), Chatzimouratidis and Pilavachi (2008a), Chatzimouratidis and Pilavachi (2008b)
	Technical maturity	The extents to which application of renewable energy sources is technically mature	Beccali et al. (2003), Wang et al. (2008), Huang et al. (2008), Wang et al. (2009a, 2009b)
	Potential for commercialization	The potential of successful commercialization based on assessed renewable energy sources	Lee et al. (2007), Lee et al. (2009)
	Market size	The demand of final products (electricity, gas, fuel, etc.) generated by renewable energy sources	Lee et al. (2007), Lewis and Wiser (2007), Lund (2009)
	Reasonableness for investment cost	The investment cost of renewable energy system is acceptable	Mamlook et al. (2001), Afgan and Carvalho (2002), Liposcak et al. (2006), Diakoulaki and Karangelis (2007), Madlener et al. (2007), Begic and Afgan (2007), Doukas et al. (2007), Jovanović et al. (2009), Wang et al. (2009a, 2009b), Chatzimouratidis and Pilavachi (2009a)

Recently the Environment Protection Agency (EPA, 2011) developed a comprehensive framework of multiple benefit indicators of renewable energy and energy efficiency measures. This framework highlights the relationship between the benefits supporting decision makers to better evaluate the benefits of interest and avoid double counting. The study defines type of direct energy impacts and their associated benefits classifying them in 3 categories: 1) energy system benefits, 2) environmental and health benefits and 3) economic benefits. In addition the framework distinguishes primary and secondary benefits, direct effects and macroeconomic benefits and environmental (physical) benefits from human health (welfare) benefits.

While most of the indicator frameworks have been developed to assess the sustainability of energy at the national level, few studies have been conducted to establish sets of indicators at the local level. Del Rio and Buguillo (2008) developed an integrated framework of indicators for the assessment of the impact of renewable energy deployment on local sustainability, whereas

Kowalski et al. (2009) developed a comprehensive list of indicators to assess different sustainable energy scenarios at the local level. Some local related indicators that were identified by these studies are:

- impact on the productive diversification of the area
- impacts on employment
- (regional/local) social cohesion
- human development
- income distribution
- impact on tourism
- local R&D
- industry creation
- impact on municipal budget
- regional economic development,
- import independency and
- influence on habitats.

Another related study by Donkelaar and Amara (2010) concluded on the 20 most used assessment criteria for energy projects (Table 4). Most of the criteria identified are classified as environmental showing the importance of environmental/resources issues and implications of energy interventions.

Table 4: The 20 most used assessment criteria for energy related projects (Donkelaar and Amara, 2010)

No.	**Criterion**	**Category**	**Score**
1	Energy & water use and savings	Environment	8
2	Raw materials use and savings	Environment	6
3	Greenhouse gas emissions	Environment	11
4	Air pollution	Environment	12
5	(Ground and surface) water pollution	Environment	10
6	Depletion of fresh water resources	Environment	8

7	Soil degradation	Environment	5
8	Waste creation & disposal	Environment	8
9	Use and management of hazardous chemicals and waste	Environment	5
10	Impact on biodiversity (or flora and fauna)	Environment	12
11	Impact on landscapes or land use	Environment	8
12	Noise	Environment	8
13	Cost efficiency	Economic	7
14	Employment creation	Economic	9
15	Health issues (mortality and morbidity)	Social	8
16	Safety issues (e.g. accident rates)	Social	5
17	Influence on food security	Social	6
18	Local income generation	Social	5
19	Education component /capacity building / awareness raising	Social	5
20	Equal opportunities	Social	5

The aforementioned frameworks of indicators refer mainly to sustainability evaluation of energy technologies at the energy supply. As discussed above there are numerous studies that have attempted to evaluate energy technologies in different contexts by considering also environmental, social, economic and technological aspects of sustainability.
Various authors attempted to include technological aspects of energy systems in the sustainability assessment frameworks either from an energy system perspective (Lund, 2009, Shen et al. (2010) or from a technology market perspective (Lee et al. 2007, Lewis and Wiser 2007), expanding and improving the existing sustainability assessment frameworks. These energy system related criteria were the first attempts of incorporating implicitly system resilience aspects in the sustainability assessment frameworks of energy systems.

There are also some studies investigating the European energy security of supply (Chevalier, 2005, Constantini et al., 2007) and vulnerability of European energy system on fuel imports (Gupta, 2007, World Energy Council, 2008, Roupas et al., 2009, 2011, Doukas et al, 2011, Skouloudis et al, 2011). Considering the Fukoshima disaster aftermath in 2012, the increasing reliance on fuel imports (European Commission, 2014), the recent crisis in Ukraine with the risks involved for the EU security of energy supply, and the likely impacts of a changing climate to the European energy system (Dowling, P., 2013), the issue of resilience of future energy technologies is becoming a major priority for EU. Furthermore, Milman and Short (2008) argue that indicators measuring urban sustainability have narrow focus and solely describe the current state of the urban system. Existing sustainability indicators will not provide sufficient information nor will they offer information about the likelihood of system improvements over time. They argue that indicators incorporating a measure of system resilience provide a missing but credible information.

Although the concept of system resilience has been contextualized in different fields (Holling 1973, Tyler and Moench, 2012, Collier et al., 2013) there are very few studies that explicitly address system resilience in the energy sector. O'brien and Hope (2010) conducted a study on exploring how to incorporate resilience aspects into the energy system. According to them "the transition to low carbon pathways is best realized where resilience underpins processes of adjustment to counter vulnerabilities and exploit beneficial opportunities to maximise social well-being" (O'brien and Hope, 2010).

Molyneaux et.al (2012) performed a resilience analysis of electricity system using a measure of composite Resilience Index which calculates resilience of the national power system. According to Molyneaux et. al 2012, a robust power system is an essential component of a country´s functioning economic system including a network of financial transactions. Economic losses occur due to power fluctuations and blackouts. Key resilience attributes are redundancy, efficiency and diversity. A resilient system should be efficient, conserve resources and minimise the costs, strengthen diversity, reduce the risks associated with fuel supply, spare capacity or redundancy to allow unplanned surges in demand or the loss of electricity, and secure if it relies on foreign sources. The following criteria are selected for the composite Resilience Index Molyneaux et al. 2012 developed:1) Non-renewable fuel used in generation, 2) Generation efficiency, 3) Distribution efficiency, 4) carbon intensity, 5) Diversity of generation, 6) Redundant power for use in GDP, 7) Reliance on imports

Looking at the various studies on sustainability assessment of energy technologies along with the growing literature on resilience and systems thinking approach to energy systems, an evident outcome would be to integrate sustainability and resilience aspects in the assessment of energy systems in order to improve decision making, policies, measures and projects.

2.4 Weighting methods for the elicitation of stakeholders' preferences

Criteria weights elicitation techniques have been developed within the framework of MCA to integrate stakeholders' preferential information into the decision making process. During energy and climate policy evaluations, stakeholders and decision makers implicitly or explicitly express their perceived relative importance between criteria by assigning weighting factors to them. Stakeholders' objectives and policy priorities should be taken into account and even get incorporated into the decision making process in a structured, systematic and transparent way. This process can render decisions more defensible and acceptable.

There are various techniques within MCA methodologies to determine criteria weights. Based on the concept of compensation and trade-offs between criteria, methods can be also distinguished between compensatory and non-compensatory. Compensatory weighting techniques are used in Multi Attribute Utility (MAU) methods, while non-compensatory ones are used mainly in outranking methods. The former assume strong compensation (trade-offs) between criteria and are used as scaling factors, while the latter reject this assumption and are used as importance coefficients in the respective aggregation formula. For a more detailed description of weighting techniques see Grafakos et al. (2010a).

Non-compensatory weighting methods reflect in principle global values about the relative importance of criteria and do not pay particular attention to the impact range of the specific decision context. The most broadly used non - compensatory weighting methods are:

- Direct point allocation or fixed point scoring techniques (Hajkowicz et al. 2000, Poyhonen and Hamalainen, 2001)
- Ratio or direct importance weighting methods (procedures) (Fischer, 1995, Weber and Borcherding, 1993)
- Pair wise comparison techniques
- Resistance to change technique (Rogers and Bruen, 1998).

Compensatory weighting methods aim at showing the hidden dilemmas behind a number of mutually exclusive options evaluated across multiple criteria for making stakeholders become aware of the potential gains and losses implied by their choice in the specific decision context. Thus, it is meaningful to elicit them by taking into consideration the impact range in each single criterion (Keeney, 1992). In this sense, derived weights have no absolute meaning and do not reflect general values in life but only preferences and priorities in the face of considered alternatives. The most widely applied compensatory weighting methods are:

- Swing method (von Winterfeldt and Edwards 1986)
- Trade off method (Keeney and Raiffa, 1976)
- SMART (Edwards, 1977)
- MACBETH-Measuring Attractiveness by a Categorical Based Evaluation Technique (Bana e Costa and Vansnick, 1994)
- Conjoint (regression methods)

2.4.1 General classification of weighting methods

There are variant procedures to determine criteria (attributes) weights. They can be classified in main different groups of procedures according to their characteristics. They can be algebraic or statistical, decomposed or holistic, direct or indirect and compensatory or non - compensatory.

- *Algebraic* procedures often compute the n weights from a set of n – 1 judgments using a simple system of equations. *Statistical* procedures are using some regression analysis based on redundant set judgments.
- *Decomposed* procedures are based on the comparison of one or one pair of attributes at a time and *holistic* methods are based on the holistic evaluation of alternatives where the DM is taking into account not only the attributes, but the alternatives as well.

- *Direct* methods require the DM to compare the range of two attributes in terms of ratio judgments and *indirect* procedures ask the DM to express preference judgments to derive the weights.
- According to the concept of compensation and to the way that the weights are interpreted we are going to distinguish the methods on *compensatory* and *non – compensato***ry**. When the weights are considered as scaling factors then the method is compensatory. Trade - offs between the criteria are involved. Thus, in order to imply trade - offs between the criteria, the measurement scale (or the impact range or the performance of the criteria) should be taken into account by the DM.

2.4.2 Non-compensatory methods

- *Direct point allocation or fixed point scoring techniques* (Hajkowicz et. all 2000, Poyhonen and Hamalainen, 2001)

The decision maker (DM) is asked to distribute a fixed number of points among the criteria. Usually they are expressed as percentages where 100 points are allocated among the criteria. The attribute with the higher score is the most important one. This is a direct way of eliciting the relevant importance of the criteria having the ranking and the rating of them.

- *Ratio or direct importance weighting methods* (procedures) (Edwards, 1977, Fischer, 1995, Weber and Borcherding, 1993)

The direct importance (or ratio) methods involve two main stages. First the decision maker (DM) is required to rank the criteria and then he is asked to rate the criteria according to their relevant importance. For example the least important attribute can be assigned with a value of 10 and all the others can be rated as multiplies of 10. Alternatively the most important criterion can be assigned a value of 100 and all the others may be expressed in proportion to it. Then usually, the resulted weights are normalized to sum to one.

The simple multiattribute rating technique *SMART* (Edwards, 1997) is a typical representative and most common used technique of the direct importance weight methods. SMART is a whole process of rating alternatives through weighting attributes. Here we are referring to the weighting procedure of the technique. This is done in two steps: a) The DM is required to rank the importance of attributes from the worst attribute levels to the best levels, and b) he is asked to make ratio of importance estimates of each attribute to all others and then those judgments can be easily translated into normalized weights. Some weakness of SMART was corrected by the elaboration of SMARTS and SMARTER (Edwards and Barron 1994*)*.

- *Pair wise comparison techniques*

Pair wise comparisons involve the comparison of all criteria against each other in pairs. The number of the pair wise comparisons that should be executed in order to have all the criteria compared to each other is N = c (c- 1) / 2.

The *Analytic Hierarchy Process (AHP*) (Saaty, 1980, 1995) is the most popular technique of using pair wise comparisons. This method requires the DM to rate the importance of each criterion in pairs on a nine-point scale, varying from 1 (equally importance) to 9 (extremely more important). In other words the DM is asked "which criterion of the pair does he think that is more important and how much more important is it?". This process can be described briefly summarizing it into 5 steps: a) elicitation of DM judgments, b) representation of judgments in a matrix form, c) conversion to decimals, d) summation and e) normalization to obtain weights.

2.4.3 Compensatory methods

- *Swing methods* (von Winterfeldt and Edwards 1986)

This method requires the DM to choose from the criteria which one to move from the worst to the best level at a hypothetical alternative. The criterion with the most preferred 'swing' is the most important one and will be assigned with 100 points. Next the DM is asked to select a second attribute to be moved from its worst to its best level as the second most desirable improvement. The DM is required to assign less than 100 points to it in order to express its relevant importance to the first preferred criterion. This process is being continued with all the remaining criteria which all are expressed as percentages of the largest swing.

- *Trade off methods* (Keeney and Raiffa, 1976)

These methods have the most developed theoretical background comparing to others. In the trade off procedure two hypothetical alternatives are considering which they differ into two criteria. The first has the best performance on one criterion and the second has the best performance at the second criterion. The DM is required to choose one of the two alternatives.

The selection reveals his preference on the most important criterion. In order to elicit the value of weights the following process is being followed: The DM is asked to adjust one of the two attribute performances in order to reach the level of indifference between the two alternatives. This can be done either by worsening the chosen alternative at the good outcome or by improving the non-chosen alternative at the bad outcome. It is needed to have n-1 comparisons of pairs of the hypothetical alternatives in order to calculate the weights of n criteria. In order to have a complete pair wise comparison of the criteria we need to make n (n-1) / 2 comparisons. In this case there is a high probability for inconsistencies and thus consistency tests are necessary for the reformulation of some DMs' preferences.

- *"Resistance to change grid" based on Personal Construct Theory.*

This method was developed by Hinkle (1965) but was adopted from Rogers and Bruen (1998) to estimate the relative importance of environmental criteria. This weighting technique is developed to be included in *outranking MCA methods* and particularly in ELECTRE. It has elements from the "swing" methods but also from the pair wise comparison techniques. It can be considered as a mixture of "swing" and pair wise comparison procedure. However, the way of calculating the weights is different. Each criterion is assumed to have two different poles of performance. Those sides of the poles are the desirable side and the undesirable side. Assuming that all the criteria are at the desirable side, the DM is required to compare all the criteria between each other in pairs and to choose which one is willing to move from the desirable side to the undesirable side having the other unchanged. Then the total score of each criterion is obtained from the number of times that it was resistant to change. Thus a hierarchy of the criteria is determined. This technique can be used only on a limited number of decision makers where the drawbacks of the method associated with a large-scale survey cannot be applied (Rogers and Bruen, 1998).

- *MACBETH* (Measuring Attractiveness by a Categorical Based Evaluation Technique) (Bana e Costa and Vansnick, 1994). This technique considers the weights as scaling constants and the weight elicitation procedure is a part of the overall technique. This weight elicitation procedure is not assessing the weights directly according to their relevant importance but it takes into account the (impact) range of each attribute. The method integrates "swing", (pair wise) and trade – off elements providing also the necessary consistency tests for the coherency of the procedure. The weights correspond to the concept of trade off; requiring the DM to answer how much would be willing to give up from one swing of performance of one criterion to achieve an increase of swing of performance of another one. The question that can be answered assuming that all the criteria are at their worst impact levels, is to assess whether the gain with respect of performance of one criterion by moving from worst to best level is greater or less than the corresponding gains for each other criterion.

- *Conjoint (regression) methods*

This method, which is the typical example of a holistic and indirect procedure, requires the DMs to rank or rate the different alternatives according to their preferences and then the analyst using some regression statistical analysis can derive the single value functions and the weights for these functions. The regression procedure is the most common used conjoint method. The conjoint methods are deriving the relative importance of the criteria through an indirect and holistic way.

A necessary precondition to use the conjoint method is to have a large number of alternatives and criteria in order to apply the regression analysis. People have the tension to ignore or to misinterpret many attributes, still important ones, when ranking the multi objective alternatives, treating them in an inconsistent way. This is due to the fact that by using this method the DMs are not involved on the whole process of the elicitation of weights without being asked to reflect and reassess their initial preferences. Furthermore, this holistic non - interactive approach and the judgment of all attributes at once makes impossible the consideration of the attributes in a careful, consistent and insightful manner. Thus their preference statements cannot be considered as defensible and balanced (Hobbs and Meier, 2000).

It should be stated at this point that the work that has been done by Munda (1995) on developing the Novel Approach to Imprecise Assessment and Decision Environments (NAIADE), a method that considers criteria weights as importance coefficients, defines indifference and preference thresholds but also allows a certain degree of compensation in the criteria aggregation (for more information see Munda, 1995). In addition, after thoroughly discussing the concepts of compensability and incommensurability (technical and social), Munda (2005) further developed the framework of Social Multi-Criteria Evaluation (SMCE) where criteria weights are considered as importance coefficients, robustness analysis is incorporated and social compromises are explored (for more information see Munda 2005, Gamboa and Munda, 2007, Munda, 2009).

Within the climate policy decision making context, several weighting methods have been applied for the elicitation of stakeholders' and decision makers' preferences. Bell et al. (2001) organised a workshop with climate policy experts and policy makers where he systematically explored the applicability and the usefulness of different MCA methods in integrated assessment of climate policies. Participants were in favour of the possibility to revise their initial preferences on weights either by using one method that allowed revision or by combining different weighting techniques. The weighting methods examined at this study comprised of point allocation, swing, analytical hierarchy process, and trade off. The organizers of that workshop concluded that the use of multiple methods can enhance understanding of the policy problem and trade - offs between criteria.

2.4.4 Factors influencing the weighting procedures and potential biases

Having classified the main weights elicitation procedures and after providing a brief description of them we can refer to some structure factors that often influence the determination of attribute weights.

1) Attribute (impact) range

Weighing methods that do not address criteria impact range sensitivity might lead to biased weights (Hayashi, 2000, Hamalainen and Alaja, 2008). It has been reported (Weber and Borcherding, 1993, Fischer, 1995) that there is an attribute range effect on the weights; meaning that the weight of an attribute is elicited as a function of the attribute range. A DM should adjust the weights to attribute ranges in order to have stable preferences. Proper adjustment of the weights would have required lowering weights for small-perceived value ranges, and increasing them for large ones. If, instead, importance judgments were insensitive, reflecting a generalized social concern rather an appropriate re–scaling of attributes, the multi-attribute value models will be distorted (Stillwell et all, 1987). In other words, the weighting procedure should be in certain cases range sensitive. Furthermore, Fischer (1995) stressed that if a value function is normalised relative to the attribute range outcomes in the local context, then attribute weights should be range sensitive and adjusted to the range of attributes. But, when the value function is normalized relative to the global context, then attribute weights should be range insensitive, meaning, it should remain unaffected from changes of the range of attributes (Fischer, 1995).

In order to investigate the degree or the possibility of the attribute range sensitivity in a weighting procedure Fischer examined the Value Comparison Hypothesis. According to this, the greater a weight evaluation procedure involves cross attribute comparison of value the more sensitive the elicited weights will be to the range of attribute values in the local text (Fischer, 1995).

This hypothesis leads to a prediction about certain weighting methods. Particularly, the direct importance techniques that do not involve cross attribute comparisons are not attribute range sensitive. From the other hand the indirect methods like swing, trade off and conjoint procedures and are expected to be relatively range sensitive.

Actually, swing and trade off methods were found to be more range attribute sensitive procedures comparing to direct ratio method. For direct ratio methods the DMs did not adjust the weights when the range attribute was change supporting the Hypothesis (Fischer 1995). Additionally, according to relevant experiments of von Nitzsch and Weber (1993) the regression weighting procedures indicate a significant degree of range sensitivity in contrast of direct importance techniques. More specifically, the DMs at the direct ratio methods, determine the importance of an attribute independently of the range of attribute. Even if the attribute range is specified to the DM, the range sensitivity is quite small. In the contrary, at the conjoint analysis and regression methods the DMs are considering the attribute ranges at their preference judgments. This is mainly due to the fact that the decision maker is required to compare alternatives and alternatives are defined normally based on the full range of attributes. According to their experimental comparison between direct ratio method and regression approach, the regression approach proved to be much more range sensitive (von Nitzsch and Weber, 1993).

Von Nitzch and Weber (1993) conclude that for prescriptive decision-making, there are some points relevant to attribute range sensitivity that seem to be important according to their results based on experiments about range sensitivity. Weighting methods that do not incorporate attribute ranges when weight judgments are elicited might lead to biased weights. “Even if the range of attributes is mentioned, decision makers often do not adjust their importance judgments properly. Therefore methods based on importance judgment like simple ranking, rating, or ratio methods and multicriteria methods, which require importance judgments (like AHP), should only be used with great care" (Von Nitzch and Weber, 1993, p. 942).

Another experiment from Borcherding et al (1991) comparing ratio, swing and trade off methods, showed that the DMs using the ratio method did not consider the attribute range of the costs (a criterion with large range). When they used the swing method and they were asked explicitly to consider the range of the attribute they did take into account the range but not at a very larger extent and as a result the criterion costs did not rated much higher with this method either. In the trade - off method the DMs weight the costs a bit more and thus this approach was more range sensitive than the other two. However, this attribute could have been weighted even more. This didn't happen due to the complexities and difficulties of the trade - off method (Borcherding et al, 1991).

2) Evaluation scale

Few of the weighting methods (e.g. AHP and MACBETH) are using evaluation scale to express the importance judgments of DMs. The selection of the numerical evaluation scale, which is assigned to verbal expressions at the AHP and MACBETH, is an important factor which influences the weights. The 1 – 9 numerical scale overestimates the ratios assigns to the verbal expressions (Poyhonen, et al., 1997). The balanced scale according to their study led to more accurate results and more consistent statements. The decision makers focus on the verbal statements to express their preferences while the numerical scale fails to capture the numerical counterparts of the verbal expressions. Thus, the balanced scale is preferred comparing to the original 1 – 9 numerical scale in order to have more accurate and consistent weights (Poyhonen, Hamalainen and Salo 1997, (Poyhonen and Hamalainen, 2001).

3) Splitting criteria (criteria – sub criteria) and hierarchy effects (hierarchical structure)

It has been reported that when an attribute is split into sub attributes there is an effect on the weighting outcome and a difference between the weight of the attribute and the sum of the sub attributes where they were supposed to be equal. Experimental evidence in multi-criteria weighting techniques shows that when a criterion is split into sub criteria there is an effect (splitting or hierarchical bias) on the weighting outcome and a difference between the weight of the criterion and the sum of the sub criteria where they were supposed to be equal (Weber and Borcherding, 1993, Poyhonen et al., 2001, Hamalainen and Alaja, 2008). For ratio and swing methods the sum of weights of the sub attributes is considerably greater than the weight of the overall attribute (Weber and Borcherding, 1993).

Additionally, according to a relevant experiment that Weber et. all (1988) carried out, the degree of the split of an attribute to sub attributes enhances the attribute weights. This splitting effect is independent of the attributes that were split, independent of the DMs but somehow dependent on the method of weighting. Holistic procedures seem to perform better and to be less splitting biased since they focus subjects on the alternatives rather only on the attributes. In these terms, conjoint and regression methods perform somewhat better than the decomposed procedures (Weber et. all 1988).

Furthermore, a similar issue of the splitting effect is the structure of the *hierarchy effect*. An important question that arises is whether the attribute is higher at the hierarchy level influences the weight that will be elicited. An experiment using the ratio method showed that the higher an attribute is at the hierarchy tree the greater the weight it gets (Weber and Borcherding, 1993).

4) Spread of weights (or max weight ratio)

The spread of weights is measured by the maximum weight ratio. Pohyonen and Hamalainen (2001) clearly showed that the spread of weights is strongly dependent on the number of attributes. The inclusion of more criteria in the procedure results to the increase of spread of weights or alternatively produces wider difference between maximum and minimum weights of the criteria. They carried out a comparison of different weighting techniques and they showed that Direct, Swing and Tradeoff procedures yield similar max ratios while SMART and AHP produce larger spread of weights. The same finding was reached from (Weber et. all 1988) on their experiment where they claimed that ratios of weights of the least to most important attribute appropriately increased as the number of attributes increased.

5) Reference point

There is an influence at the interpretation of criteria weights from the reference situation that the decision maker is and from the plausible impact range that he is considering. Weber and Borcherding (1993) stress another important matter that plays a vital role and has an influence on the weighting elicitation procedure.

6) (In)consistency

There is the risk for stakeholder's inconsistencies which are expressed as differences between the stakeholder's judgments and the derived weighting factors. One approach to overcome this difficulty is using rank order information about criteria (Hayashi, 2000). The DM perceives inconsistencies as mistakes not purposely. They are expressed as discrepancies and differences between the DM judgments and the weighting results. However, they enable the DM to learn more about the elicitation procedure and the different aspects of the decision problem. Usually, they are reconciled by requiring the DM to make a final judgment, reducing the inconsistency. Weber and Borcherding (1993) concluded that there is no evidence to be sure if the (or how) the degree of inconsistency is correlated to the validity of the weighting elicitation outcome. Poyhonen and Hamalainen (2001) comparing and testing different weight attribute elicitation procedures reached to the conclusion that the inconsistency between the statements is dependent on the number of attributes and on the numbers used in the evaluation (e.g. the evaluation scale at the AHP). Particularly, for the AHP it has been demonstrated from Poyhonen, Hamalainen and Salo (1997), Poyhonen and Hamalainen (2001) that new balanced scales (instead of the original 1 - 9 point scale used from Saaty) are decreasing the inconsistency of the statements and increase the accuracy of the results as the selection of the evaluation scale influences the AHP weights (Poyhonen, Hamalainen and Salo, 1997). In order to have the ability to demonstrate several consistency checks the number of DMs should be relatively small (Lahdelma, et all 2000).

Borcherding et. al (1991) demonstrated that there is a difference concerning the consistency between different weighting methods and that this is related to the number of attributes that had to be compared. This is rational and could have been predicted as more attributes requires more comparisons for the DMs and simply presents more opportunities to be inconsistent. The results of their comparison showed that ratio method fared best closely followed by the swing method and trade off method had the worst performance (most inconsistent) by far. The inconsistency showed at the ratio and swing methods are mainly due to the large number of comparisons. The trade - off method is mainly due to the complexity of the method and the task itself (Borcherding et. all 1991).

MCA has been also applied for the elicitation of stakeholders' views and trade - offs for the assessment of different energy scenarios and more particularly for assessing the role of carbon dioxide capture and storage. The direct point allocation weighting method was used to facilitate respondents to weight the importance of evaluation criteria (Shackley and McLachlan, 2006). Direct point allocation has been incorporated to a MCA decision support tool developed for the regulation of emissions from international civic aviation sector (Solomon and Hughey, 2007). A pair–wise approach based on Analytic Hierarchy Process (Saaty, 1980) has been applied to elicit stakeholders and experts' views for the assessment of climate change impacts on agricultural land use (Abildrup et al., 2006).

In most of the above applications practitioners and researchers have not addressed the potential biases and difficulties of weighting methods adequately. Ignoring the risks attributed to these biases regarding their application might undermine the results of a study (Poyhonen and Hamalainen, 2000).

Several authors have emphasised the need of minimisation of the cognitive burden to the respondents by providing them guiding and technical support during the entire process of eliciting their preferences (Bell et al. 2001, Bell et al. 2003, Borges and Villavicencio 2004). Nowadays the use of software that combine different methods widely increases, practitioners and analysts do not need to use the methods in puristic disconnected manner and they are able to refine the methods to be more suitable for a particular decision making situation. Poyhonen et al. (2001) clearly stated that "the strict boundaries between different methods are already passed history". In order to foster the users to respond further to the policy problem, reconsider their initial preferences, think harder their value systems, and deliberate their preferential judgments towards the evaluation criteria, it is deemed necessary to use parallel multiple techniques (Hobbs and Meier, 2000, Bell et al. 2001).

Revision of the process and possibility for reformulation of stakeholders' preferences enhances the sense of control and understanding of the MCA methodology by the stakeholders. In addition, combined use of different methods and provision of technical support during the entire process, result into minimisation of potential biases, enhance appropriate use of the MCA methods and facilitate confident expression of stakeholders' preferences. A holistic approach (e.g. initial ranking) should be complemented by a decomposed weighting technique to facilitate the stakeholders to express their weighting preferences in a more insightful way (Hobbs and Meier, 2000). Bell et al. (2003) tested how MCA techniques can assist users to incorporate their background knowledge, to improve understanding of trade - offs, and to perceive importance of value judgements by ranking hypothetical GHGs mitigation policies. In particular, the users mostly recommended the reconciliation of weighting factors from multiple methods for actual decision making.

Based on the above analysis and to the best of my knowledge, decision making for evaluation of energy and climate option appears to lack of an integrated multi criteria weighting method that combines abilities of different techniques' to derive stakeholders' preferential information and perspectives in a structured, transparent, interactive manner and moreover to address the main potential biases of the weighting methods. The above analysis highlights the need to develop an integrated multi criteria weighting methodology that consists of ranking and weighting parts by integrating their capabilities to derive verbally, numerically, and graphically stakeholders' preferences.

Considering this background the author developed an integrated weighting methodology that consists of gradual sequential weighting steps in order to elicit stakeholders' preferences verbally, numerically and graphically. The integrated weighting methodology was tested in the field of energy and climate policy options in order to be further refined and applied for the assessment of energy technological options. While the next chapter describes the different elements and steps of the overall methodology including the development of the weighting approach, the testing application of the weighting methodology including its steps, the actual application, the results, conclusions and lessons learned was published in a peer reviewed book chapter that can be found in Annex 1.

Chapter 3: Integrated MCDA assessment methodology

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3.1 Evaluation context and definition of alternative actions

This first step is to identify the decision context and issue(s) under consideration, to agree on the focus and the scope of the analysis, to recognise external constraints and to explicitly identify the type of recommendation that is needed.

After the identification of the problem's nature and decision context, decision analysts and/or stakeholders should strive to formally define the detected possible decision actions and develop alternatives that will be assessed.

Alternative actions are usually thought as 'given', in the sense that they are a priori and strictly defined. However, alternatives may result from the systematic exploration of the objectives pursued in the considered decision context. Especially in problems of strategic nature, the main challenge is to detect interesting alternatives –not obvious or apparent at first sight- on the basis of the main concerns expressed during problem identification and decision context definition.

Energy technologies under investigation

The energy technologies under investigation were selected by reviewing the most prominent current and future energy technologies that can reduce carbon emissions. Advanced fossil fuel based energy technologies were also selected in order to provide an overall and complete comparative assessment framework. The selected technologies, which are considered as average and representative reference technologies in Europe, reflect the state-of-the-art on electricity production. Tables 5 and 6 show the selected energy technologies and their characteristics.

Table 5: Energy technologies under investigation and their characteristics

Low-Carbon Energy Technologies		Descriptions
1	**Integrated Gasification Combined Cycle (IGCC) coal**	Future reference technology for 2030 is an IGCC power plant. IGCC technology is an emerging advanced power generation system having the potential to generate electricity from coal with high efficiency and lower air pollution (NO x, SO_2, CO and PM10) than other current coal-based technologies.
2	**IGCC coal with Carbon Capture and Storage (CCS)**	IGCC technology lends itself very well to CCS due to the higher pressure of the gas stream and the possibility to achieve the highly concentrated formation of CO_2 prior to combustion. For this to be possible then after having been cleaned of particulates the syngas enters a shift reaction unit in which the methane is reacted with steam to produce hydrogen and CO_2. The preferred technique for CO_2 separation in applications at higher pressure (i.e. IGCC) is currently physical absorption using solvents commonly used in commercial processes. Once captured, the CO_2 can then be treated in the same way as for the other technologies incorporating CCS. The resulting power plant net efficiency for this technology scenario is 48.5%. CO_2 transport and storage is modelled in the same way as for Pulverized Coal power plants.
3	**Gas Turbine Combined Cycle (GTCC)**	GTCC power plant involves the direct combustion of natural gas in a gas turbine generator. The waste heat generated by this process is then used to create steam for use in a steam generator, in a similar manor to that of IGCC technologies. In this combined cycle power plant around two-thirds of the overall plant capacity is provided by the gas turbine. Reference technology for large natural gas power plants is a 500 MW Combined Cycle (CC) unit. The analysis focuses on a base load power plant. Technology development until 2030 is taken into account with higher power plant efficiencies.
4	**GTCC with CCS**	The electricity generation aspect of this technology is exactly the same as the GTCC without CCS. The flue gas from the GTCC then enters the same CO_2 separation, stripping, drying, transportation and sequestration process to that used for coal and lignite CO_2 capture.
5	**Nuclear European Pressure Water Reactor (EPR)**	This 'Generation III' design of nuclear reactor uses either uranium oxide enriched to 4.9% fissile material (uranium-235) or a mix of uranium-235 and mixed uranium plutonium oxide (MOX), with pressurized water as the moderator and cooling agent. The heat from the reaction is used to produce steam to drive a steam turbine generator. It features not only superior reliability and safety over its current 'Generation II' counterparts but also higher efficiency. This results in less high-level radioactive waste per unit of electricity generated that requires either reprocessing or long term storage in geological repositories.
6	**Wind onshore**	The exploitation of wind energy has increased exponentially during the last decades, and there is still large unexploited wind energy potential in many parts of the world – both onshore and offshore. However, the success story of onshore wind energy has led to a shortage of land sites in many parts of Europe, particular in north-western Europe. Vestas' V80 2 MW turbine serves as current reference technology for onshore wind power in Germany The capacity factor for a generic optimal site near to the coast of the North Sea is assumed to be 0.29. Future wind turbines in 2030 with higher capacities are assumed to be located at the same or similar sites.
7	**Wind offshore**	The shortage of land sites for onshore wind energy has spurred the interest in exploiting offshore wind energy. Offshore wind farms consisting of multiple wind turbines all connected to a single transformer station are more financially viable than individual turbines. Offshore sites also enjoy the advantage of having significantly more stable and higher wind speeds than onshore sites and which leads to a longer turbine life. Future wind turbines in 2030 with higher capacities than the current ones are assumed to be located at the Danish part of the North Sea (HornsRev) or similar sites. The whole park is assumed to consist of eighty Vestas V80 turbines with monopile steel foundations.
8	**Solar Photovoltaics (PVs) - crystalline silicon**	The PV installation is small and integrated onto a new or existing building. At 420 kW, this is suited to the roof of a public or commercial building and is too large for most domestic residences. Photovoltaic (PV) reference technology for crystalline silicon is the laminated, integrated slanted-roof multicrystalline-Si module in, which is adapted to the electricity production of 850 kWh kWp. Not only efficiency increase for the PV-cells as such, but also reduced energy demand in the production steps of the PV chains are taken into account for the modeling of the future 2030 reference PV units.
9	**Hydropower**	The hydro plant Illanz/Panix (Switzerland) is used as the reference reservoir site. Lifetime of the dam is assumed to be 150 years.
10	**Biogas CHP**	Biogas (SNG) from forest wood gasification is assumed to fuel CHP units. Basis for the production of SNG via wood gasification is the assessment of a 50 MW demonstration plant. A commercialized methanation unit with double capacity and increased efficiency, as well as improved CHP unit SNG combustion, reflect the expected technology development until 2030.

Table 6: Reference energy technologies under investigation for 2030 in Europe

	Coal	Natural Gas	Nuclear	Hydro power	Wind power	Wind power	Photovoltaic	Biogas
Technology	Integrated Gasification Combined Cycle (IGCC)	Combined Cycle (CC)	European pressure water reactor (EPR), Generation III	Storage dam	Onshore wind (park, 50 turbines, 50 x 4,5)	Offshore wind (park, 50 turbines 80 x 20)	Multi crystal line- Si panel, roof-top	Combined heat & power (CHP)
Capacity el. (MWel)	450	500	1500	53			0.02	0.2
Capacity th. (CHP)								0.15
Reference Location	Germany, Rostock	Italy, Naples	France, Cattenom	Switzerland, Ilanz/Panix	Germany, North	Denmark	Switzerland	Switzerland, Baden
Operating time (full load hours per year)	7000	8000	8000	2476	2700	4000	850	7500
Efficiency electric (%)	51.5	61	33.8	89			20	41.7
Lifetime	30	25	60	150	20	20	30	15

source: Roth et al. 2009

3.2 Selection of evaluation criteria

Criteria selection and validation process

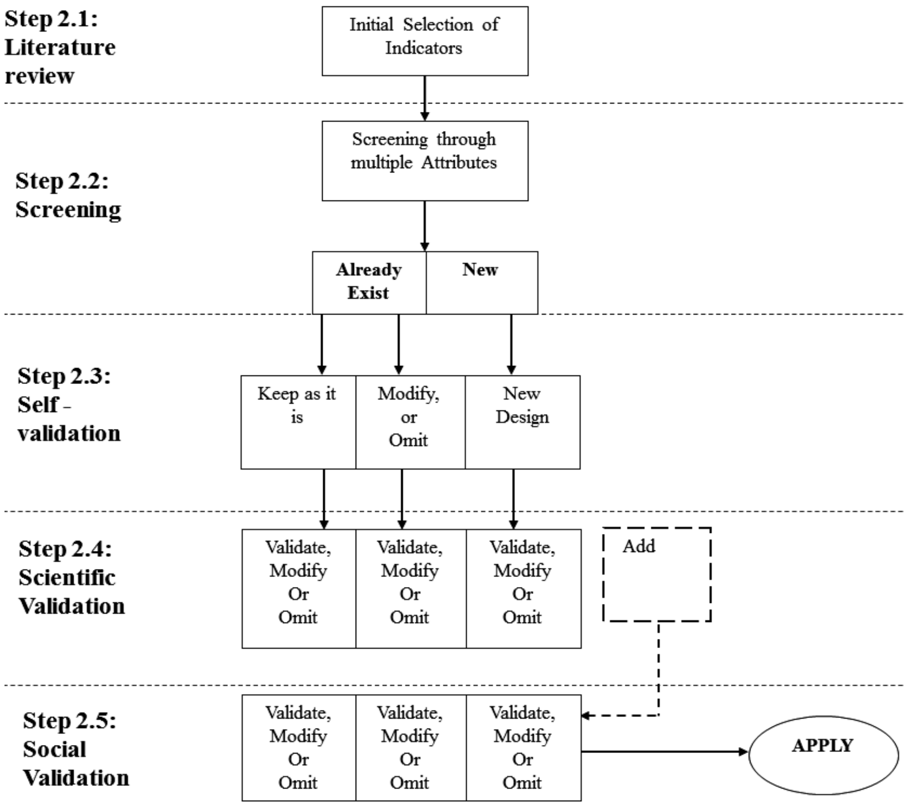
In the current study, an extensive literature review on evaluation criteria and indicators that have been utilized in previous studies, was conducted. The commonly used criteria and indicators were adopted, and a few more were added in the selection. The combination ultimately resulted in a new criteria and indicators framework for the evaluation of future low-carbon energy technologies in Europe. In that sense, the set of criteria and indicators needed validation from and refinement by the actual users and stakeholders.

The study modified the "3S" indicators' validation methodology developed by Cloquell – Ballester, et al. (2006) and applied it to the current research context by undertaking the following five steps for selecting and validating indicators:

- Extensive literature review
- Screening of indicators
- Self-validation and refinement (based on rigorous internal peer review),
- Scientific validation and refinement (based on experts review), and
- Social validation and refinement (based on a survey of local stakeholders)

Figure 8 illustrates diagrammatically the 5 steps of the selection and validation of indicators (envisioning) stage of the overall integrated MCDA sustainability assessment framework that was depicted in figure 1.

Figure 8: The selection and validation process of indicators



3.2.1 Extensive literature review

The initial selection of evaluation criteria and indicators was based on an extensive literature review of studies in the field of low-carbon energy planning and integrated sustainability assessment of energy options. The literature review included both indicator based approaches of sustainability assessment of energy technologies and non- indicator based frameworks addressing sustainability and resilience aspects of energy systems.

3.2.2 Screening of indicators

The use of indicators to measure progress and track trends towards specific policy objectives (Cobb and Rixford, 1998) has been extended widely to numerous sustainability assessment frameworks in the last two decades. Sustainability indicators are simple measures, most often quantitative, that represent a state or a trend towards achievement of economic, social and/or environmental development objective in a defined region or sector (Hezri and Dovers, 2006).

Indicators have been designed and used to serve multiple purposes and is instrumental in the sustainability policy and decision making cycle. Indicators can be used to determine baseline conditions (state) and current performance, predict future trends, but also to function as monitoring and warning systems. Indicators can also be used for making comparisons (across time and space or with targets), in performance review, and for improving scientific and policy understandings (Gallopin, 1996, Cool and Stankey, 2004, Hezri and Dovers, 2006).

The selection and validation of evaluation criteria and indicators is an important part of any environmental assessment and decision making process, including energy and climate change mitigation evaluations (Cloquell – Ballester et al., 2006; Bockstaller and Girardin, 2003). Based on literature that delves on measuring energy sustainability, it has been emphasized that there is no particular indicator framework that is suitable to all applications (Keirstead, 2007). Hence, it is necessary to take into account the intended goals for the use of the criteria. Moreover, criteria have to be chosen selectively in order to maximize their effectiveness and relevance (Kierstead 2007). However, when researchers and analysts apply a multiple criteria or multiple indicator assessment framework, they often neglect this very essential stage of the decision making process. Criteria and indicators are usually applied intuitively by the analysts (Hak et al. 2012). According to Bockstaller and Giraldin (2003), many indicator developers do not consider the validation of indicators, probably because they assume that long term acceptance of indicators by users suffice to indicate their credibility. Experts often attempt to deduce stakeholders' preferences instead of including them directly in the decision making process. According to Kowalski, et al. (2009), most applications on energy issues focus on technical aspects. Also, these generally do not involve stakeholders in the decision making process in a systematic and participatory way.

During the selection process, the evaluation criteria and indicators were screened. In particular each indicator was filtered through specific attributes as those have been described by Belton and Stewart (2002), Keeney and Gregory (2005), and Grafakos et al. (2010a):

- **Operational:** Being able to specify how well each mitigation option meets the objectives expressed by the evaluation criteria.

- **Value relevant:** Linking the concept of each criterion to the final objectives it is meant to represent. In other terms, it presupposes that an objective is comprehensively described by underlying criteria.
- **Decomposed:** Possibility to break down an objective into specific means.
- **Reliable:** A malfunctioning criterion should not render the whole set of criteria unworkable.
- **Measurable:** Degree of measurement of the performance of alternatives against specified criteria.
- **Non-redundant:** Limiting the number of criteria addressing the same objective, meaning avoidance of duplication of information in criteria.
- **Minimum in size:** The number of criteria employed should be only the absolutely necessary to provide representation of policy objectives.
- **Complete:** The set of criteria should be complete in order to capture all the key aspects of the objectives.
- **Understandable:** The selected criteria should be simple to comprehend not only by experts in the relevant field but by non - specialists as well.
- **Preferential independent:** Preferences associated with the performances of each option should be independent of each other from one criterion to the next.
- **Comprehensive:** The criteria in the selection should cover and/or relate to the different objectives, and that implicit value judgments are suitable to the decision problem.
- **Direct:** The set of criteria selected should directly be linked to the objectives, and that there are no controversial implications between tradeoffs.
- **Unambiguous:** Each of the criterion should be precise in its definition (i.e. how it describes or measures the elements involved).

In addition to these general conditions, we introduced a few more attributes that specifically apply to integrated sustainability assessment of low-carbon energy technologies in Europe at the local level:

- **Geographical coverage and local context:** The criteria should be applicable in Europe at the local level.
- **Data availability:** There should be available data or, in its absence, data collection methods.

3.2.3 Self-validation and refinement

After an extensive literature review and screening of the initial long list of indicators against the aforementioned attributes, the authors initiated the internal validation process. Researchers working on the study reviewed 40 preliminary indicators that passed the first screening. Afterwards, the researchers conducted several meetings that led to the refinement and selection of a set of 33 indicators. These indicators were classified under five criteria categories: environmental, social, economic, energy, and technology (market). Both sustainability and resilience criteria were embedded in the criteria categories.

3.2.4 Scientific validation and refinement

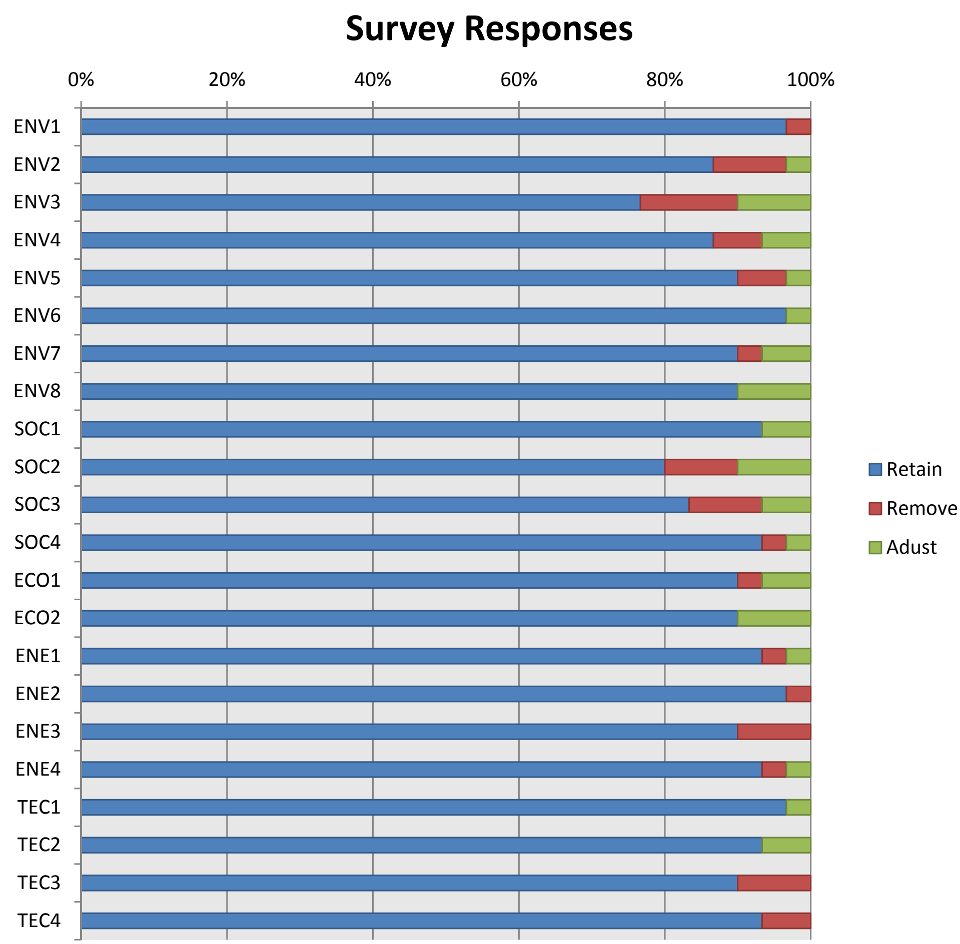
The set of 33 indicators were then reviewed by ten (10) European experts in the field of energy planning and energy technology assessment for further refinement and feedback. The experts participated in this process through email and phone communication and by completing a questionnaire. The experts expressed their views on whether they agree or disagree with the selection of indicators and if they could suggest any adjustments. Furthermore, experts had the option to suggest additional indicators to be included in the preliminary set. The experts could also add their comments and recommendations for further improvement of the indicators. The research team asked for clarifications in cases where it was deemed necessary, incorporated experts' comments and feedback, and made adjustments to the set of indicators accordingly. After the experts' validation and further internal discussions, the set of indicators came down to 22 classified in five different categories including both sustainability and resilience related indicators.

3.2.5 Social (stakeholers') Validation

Experts' validation process was followed by incorporating European stakeholders' views in the final set of criteria and indicators and therefore conducting a social validation procedure. The study was supported by the Local Governments for Sustainability, European Secretariat (ICLEI Europe) and the Intelligent Energy Europe (IEE) project, Covenant CapaCITY and many stakeholders who participated in the validation process were part of this network.

In the end, the number of criteria for evaluating low-carbon energy technologies was reduced to 22. Furthermore the set of indicators was further refined and their explanation was improved. The results of the social (stakeholders') validation established the wide acceptance of the indicator set with the range of local energy stakeholders who participated in the process (annex 2). Figure 9 summarises the all the responses of the validation stakeholders survey.

Figure 9. Validation survey responses



3.2.5 Categories of Criteria and indicators

Environmental category

Shen, et al (2010) highlighted the significance of carbon emissions reduction, environmental sustainability, SO_x and NO_x emissions reductions, and low land requirements. It has been established though numerous studies that CO_2 emissions of energy system is an important criterion in assessing energy technologies. In addition to the impact related aspect of CO2 emissions regarding their contribution to climate change, this criterion entails also a risk aspect regarding the potential of further expansion of carbon pricing. It is therefore important to be able to account for the vulnerability of energy technologies to increases of the energy prices due to the potential of carbon pricing (Molyneaux et al., 2012).

Reduction of local air pollutants, such as SO_x and NO_x emissions has been recommended by many studies as an evaluation criterion of energy technologies (Diakoulaki and Karangelis, 2007). Environmental sustainability, within the context of electricity, refers to the shift from fossil fuels to, justifiably, renewable energy. However, the evaluation of the impacts brought by the use of renewable energy should be according to noise pollution, landscape impact, microclimatic changes, and unpleasant odors (Beccali et al, 2003 in Shen, et al (2010). In SF Energy Invest (2010) as well as for the European Commission (2003), specific criteria were included under the environmental dimension. These include waste creation and disposal, including hazardous waste, noise and land use. Low land requirement has also been cited by different studies (e.g. Afgan and Carvalho, 2002; Beccali, et al. 2003, Andrews et al., 2011) as an important criterion. This is due to the fact that demand for land can cause economic losses which are comparative to the site value (Shen, et al., 2010). The issue of climate resilience hasn't been addressed yet by any sustainability framework of evaluation criteria of energy technologies, however it has been highlighted as a major issue by some recent studies (Christensen et al. 2011; Ebinger and Vergara 2011; Dowling 2013).

Social category

Considering the weaknesses on the category of **social indicators**, the NEEDS Project aimed to target this issue through participative procedures (Burgherr and Hirschberg, 2008; Paul Scherrer Institut, 2009; Gallego et al., 2010). NEEDS and Gallego et al., (2010) involved the establishment of a set of criteria and indicators for use in evaluation of future electricity generating technologies with clear balance between environmental, social and economic dimensions. Mortality and morbidity, accident fatalities and aesthetic/functional impact have been highlighted as the most prominent social criteria. Furthermore the level of public opposition to future plans of installation of energy technologies has been also identified as an important social issue that should be seriously taken into account during the evaluation process (Gallego et al., 2010).

Economic category

Regarding the **economic category**, the following criteria for evaluation were identified by Shen, et al. (2010) and Komor and Bazilian, (2005): local economic development, increasing employment, technical maturity, potential for commercialization, market size, and reasonableness for investment cost. Investment cost, which involves all costs related to purchase of equipment, engineering services, and technological installations, among others is another important consideration. Investment cost is a commonly used economic criterion that has been presented in many studies (e.g. Mamlook et al., 2001). Many studies also support the inclusion of job creation in the evaluation of energy projects (e.g. Haralambopoulos and Polatidis, 2003, Ragwitz et al., 2005). The creation of employment opportunities is a key priority globally but also in the European context since high unemployment rates have become a key concern in many European countries and cities particularly after the financial crisis of 2009. Employment creation in few cases is included in the social dimension instead of economic by the European Commission (2003). In some cases there is a distinction between long and short term employment, whereas Del Rio and Buguillo (2008) and Kowalski et al., (2009) specify to employment generation and creation of jobs at the local level.

Energy category

In the assessment of Shen et al (2010), and as supported by other studies, **energy criteria,** focusing on the resilience aspect of the energy systems (Molyneaux et al., 2012), such as energy price stability, security for energy supply, low energy prices, stability for energy generation and peak load response (Streimiekene, 2010) should be used in the evaluation of energy technologies. As the electricity sector is vulnerable to price fluctuations due to significant factors, such as production, policy matters, natural disasters, and unstable geopolitics, energy price stability should be taken into account. Security of energy supply, another important criterion, could be increased by taking advantage of local renewable energy sources (O'brien and Hope, 2010). As electric power from renewable energy can be intermittent, it is important to ensure electricity production. As such, it is also necessary to consider the stability of energy generation. Various studies (e.g. Komor and Bazilian 2005;

Shaw and Peteves, 2008; Shen, 2010) have also emphasized the importance of low energy prices as it is important to maintain the standard of living of citizens.

Technological - market category

Technological maturity is also a salient consideration for evaluation as more mature technologies are expected to have high success rates (Huang et al., 2008 in Shen, et al (2010). However, there are also technologies that are deployed in pilot sites and hence, are not subject to large-scale utilization. In some countries, policy measures enable the commercialization of these renewable energy technologies. Hence, the potential for commercialization has been considered in the assessment. Studies (e.g. Lee et al, 2007) have underlined the significant role of potential market size in industrial competitiveness. The market size – whether domestic or international – needs evaluation; a larger market size would naturally attract investments which would facilitate industrial development.

Based on the aforementioned discussion we developed an integrated framework of sustainability and resilience indicators for the assessment of low carbon energy technologies. Table 7 shows the list of evaluation criteria their corresponding descriptions along with their sources.

Table 7 (part 1). Final validated set of criteria and indicators

Criteria categories	Indicators	Description	Sources
Environmental	**ENV1: CO2eq emissions**	The indicator reflects the potential impacts of global climate change caused by emissions of GHGs for the production of 1 kwh.	Afghan et al. (2000), Lee et al. (2007), Diakoulaki and Karangelis (2007), Streimikiene et al. (2007), Burton and Hubacek (2007), Chatzimouratidis and Pilavachi (2007), Chatzimouratidis and Pilavachi (2008), Wang et al. (2008), Wang et al. (2009), Evans et al. (2009), Jovanovic et al. (2009), Loken et al., (2009), Beccali (2003), Komor and Bazilian (2005), Shen et al. (2010), Huang and Lo (2011), Cristobal (2011)
	ENV2: Climate resilience	The degree of resilience of the energy technology to the future climatic changes and extreme weather events.	IPCC (2007), Christiensen et al. (2011), Ebinger and Vergara (2011), Dowling (2013)
	ENV3: Noise pollution	Part of population feeling highly affected by the noise caused due to the function of the energy facility. This indicator is case sensitive and could have been measured as a factor of the noise generation by the energy technology estimated in dB multiplied by the number of people affected by the noise. However since we are investigating different energy technologies and systems at a European scale we cannot measure precisely this indicator and therefore we will use an ordinal relevant scale to measure the perceived noise.	Evans et al. (2009), Gallego and Mack (2010)
	ENV5: (Radioactive) waste	Amount of (radioactive) waste generated by the plant divided by energy produced	NEEDS, Afghan et al. (2000), Streimikiene et al (2007), Begic and Afgan (2007)
	ENV6: Waste disposal (infrastructure)	Waste generation during the life cycle of the fuel and technology or availability of waste disposal infrastructure	Afghan et al. (2000), Streimikiene et al (2007), Gallego and Mack (2010),
	ENV7: Ecosystem damages	This criterion quantifies the impacts to flora and fauna due to acidification and eutrophication caused by pollution from the production of 1 kWh electricity by the energy system and technology.	EC (2005), Evans et al. (2009)
	ENV8: Land use requirement	The land required by each power plant and technology to be installed	Afghan and Carvalho (2002), Beccali et al. (2003), Streimikiene et al (2007), Wang et al. (2008), Chatzimouratidis and Pilavachi (2008), Wang et al. (2009), Evans et al. (2009), Shen et al. (2010), Huang and Lo (2011)
	ENV9: Fuel use	Amount of fuel use per kWh of final electricity consumption	Afghan et al. (2000)
Social	**SOC1: Level of public resistance/opposition**	Energy system induced conflicts that may endanger the cohesion of society (e.g. nuclear, wind, CCS). Opposition might occur due to the perceptions of people regarding the catastrophic potential or other environmental impacts (aesthetic, odor, noise) of the energy technology/system. This indicator also integrates the aspect of participatory requirement for the application of the technology. The higher the public opposition, the higher the participatory requirement is.	Tsoutsos et al. (2009), Gallego and Mack (2010)
	SOC2: Aesthetic/functional impact	Part of population that perceives a functional or aesthetic impairment of the landscape area caused by the energy system. The aesthetic impairment is judged subjectively and therefore this criterion fits in the social category than the environmental one. In addition this is also a very location specific indicator and therefore an average metric will be determined measured in relative ordinal scale.	Evans et al. (2009), Gallego and Mack (2010)
	SOC3: Mortality and Morbidity	Mortality and Morbidity due to air pollution caused by normal operation of the technology. This indicator is considered as an impact and composite indicator since it integrates all human health impacts caused from air pollutant emissions as NOx, SO2 and PM.	Streimikiene et al (2007), Gallego and Mack (2010), Afghan et al. (2000), Komor and Bazilian (2005), Diakoulaki and Karangelis (2007), Begic and Afghan (2007),Chatzimouratidis and Pilavachi (2009), Chatzimouratidis and Pilavachi (2008), Jovanovic et al. (2009), Shen et al. (2010), Huang and Lo (2011)
	SOC4: Accident fatalities	Lost of lifes of workers and public during installation and operation. Surrogate for risk aversion. This criterion partly integrates the catastrophic potential of the energy system/technology.	Streimikiene et al (2007), Chatzimouratidis and Pilavachi (2008),Gallego and Mack (2009), Afghan et al. (2000), Komor and Bazilian (2005), Diakoulaki and Karangelis (2007), Begic and Afghan (2007),Chatzimouratidis and Pilavachi (2009), Chatzimouratidis and Pilavachi (2008), Jovanovic et al. (2009), Shen et al. (2010), Huang and Lo (2011)

Table 7 (part 2). Final validated set of criteria and indicators

Economic	**ECO1: Levelised costs (incl. capital, o&m, fuel costs)**	Levelised costs of energy (LCOE): investment costs, operational & maintenance costs, capacity factor, efficiency, material use.	Afghan et al. (2000), Mamlook (2001), Afghan and Carvalho (2002), Liposcak et al. (2006), Diakoulaki and Karangelis (2007), Lee et al. (2007), Madlener et al. (2007), Begic and Afgan (2007), Doukas et al. (2007), Wang et al. (2009), Jovanevic et al., (2009), Chatzimouratidis and Pilavachi (2009), Tsoutsos et al. (2009), Shen et al. (2010), Cristobal (2011), Huang and Lo (2011)
	ECO2: (Local) Employment	The extent to which the application of the technology can create jobs at the investment, operation and maintenance stage. Furtheremore the criterion of employment reflects partly the extent of the impact that the technology has to the local economic development by providing jobs and generating income.	Haralambopoulos and Polatidis (2003), Beccali et al. (2003),Komor and Bazilian (2005), Erdogmus et al. (2006), Madlener et al. (2007), Streimikiene et al (2007), Doukas et al. (2007), Begic and Afghan (2007), Chatzimouratidis and Pilavachi (2007), Chatzimouratidis and Pilavachi (2008), Tsoutsos et al. (2009), Shen et al. (2010) - Afghan et al. (2000), Williams et al. (2008), Sastresa et al. (2008) (related to local economic development
Energy	**ENE1: Energy cost stability/sensitivity to fuel price fluctuation**	The sensitivity of technology costs of electricity generation to energy and fuels prices fluctuations. The fraction of fuel cost to the overall electricity generation cost.	Mamlook et al. (2001), Komor and Bazilian (2005), Liposcak et al. (2006), Begic and Afghan (2007), Streimikiene et al (2007), Kruyt et al. (2009), Wang et al. (2009), Jovanovic et al. (2009), Shen et al. (2010), Komor and Bazilian (2005), Burton and Hubacek (2007), Lund (2007), Cai et al. (2009), Kruyt et al. (2009), Shen et al. (2010)
	ENE2: Stability of energy generation	Stability of output of electric power generated depending on the technology used. This reflects whether the energy supply is being interrupted. The presence of these interruptions impacts the electricity network stability. This criterion reflects whether the energy supply faces any interruptions due to the type of energy technology. This criterion reflects whether the energy supply faces any interruptions due to the type of energy technology.	Gross (2004), EC (2005), Taljan and Gubina (2009), Georgilakis and Katsigiannis (2009), Tsoutsos et al. (2009), Shen et al. (2010)
	ENE3: Peak load response	Technology specific ability to respond swiftly to large variation of demand in time / % representing the possibility to satisfy the required load.	Streimikiene et al. (2007), European Comission (2005)
	ENE4: Market concentration on supply	The market concentration on the supply of primary sources of energy that could lead to disruption due to economic or political reasons.	Gallego and Mack (2010), Kruyt et al. (2009)
Technological/ Market	**TEC1: Technological maturity**	The extent to which the technology is technically mature. The criterion refers to the level of technology's technological development and furthermore the spread of the technology at the market.	Beccali et al. (2003), Wang et al. (2008), Huang et al. (2008), Wang et al. (2009), Tsoutsos et al. (2009), Shen et al. (2010)
	TEC2: Market size (Domestic)	Demand for final products (of energy technologies) and potential market size domestically. The potential market size plays an important role to establish industrial competitiveness and stimulate economic growth.	Lee et al. (2007), Lewis and Wiser (2007), Lee et al. (2009), Lund (2009), Shen et al. (2010)
	TEC3: Market size (Potential export)	Demand for final products (of energy technologies) and potential market size internationally.	Lee et al. (2007), Lewis and Wiser (2007), Lund (2009), Shen et al. (2010)
	TEC4: Innovative ability	Flexibility and potential of the technology to integrate technological innovations.	Gallego and Mack (2010)

3.3 Assessment of alternative options' impacts

The performance that each alternative achieves towards all evaluation criteria should be measured (in cardinal or ordinal scale). The aim of this step is to obtain the impact of each alternative against the evaluation criteria. Normally models are calculating the impacts of each alternative option. In cases that models are not existent or available, it is important to gather information that indicate the possible or likely impacts of alternative options. Information then should be based on analysis of existing data or data obtained by field work or experts' judgments (Keeney 1982). Chapter 5 presents and discusses the results of the assessment of low carbon energy technologies against the selected evaluation criteria.

3.4 Preferences elicitation

Regarding the preferences elicitation process, Fischoff (2005) suggests that when eliciting respondents' preferences, the following conditions should be considered: (a) Multiple methods are needed to explore method invariance, (b) Constructive elicitation particularly when respondents have no familiarity with the problem at hand and therefore not fixed and well - articulated values (c) Enhanced communication is needed when respondents lack full understanding of the issues that they are evaluating. According to Riabacke et al. (2012), elicitation of preferences should be an iterative process, where the elicited values may have to be adjusted due to deviations from theoretical expectations or to an increased understanding of the problem and the context by the respondent.

The constructive preference elicitation methodology that has been developed to derive values for criteria weights is a combination of pair wise comparisons and ratio importance weighting methods, accompanied by a ranking technique for introducing the users to the notion of preferences towards the evaluation criteria. It further strengthens constructive elements and steps to reduce the cognitive burden to the stakeholders, while at the same time utilizing an iterative process.

Criteria sorting according to their level of importance: The respondents were asked to rate and distribute the evaluation criteria according to their level of importance in three groups: low, moderate, and high. The reason of introducing this step was to break down the large number of criteria in three (3) groups in order to reduce the cognitive burden of respondents on looking in all criteria simultaneously (Miller, 1956, Fischoff, 2005).

3.4.1 Ranking of criteria

The methodology integrates two different ways of ranking criteria and requires respondents to resolve conflicts and significant discrepancies between the two rankings. The first is a direct ranking and the second is an indirect one obtained from the weighting method (pair wise comparisons or swing). This first ranking is an introductory step as it is mainly used to familiarize the stakeholders in a simple way to the concept of ranking and comparing the criteria in a holistic approach. The introduction of the initial holistic ranking technique is being used also to provide the base for a ranking consistency test.

Initial Ranking: The second step introduces a simple initial ranking step, with low cognitive burden, in order to also familiarize the stakeholders to the notion of criteria importance. For each level (group) of importance, the respondents carried out direct ranking by assigning numbers (1 as the most important criterion, 2 as the second most important criterion, and so forth till the least important criterion). The criteria were presented to the respondents by highlighting the worst and best performance of each criterion and the impact range (the difference between worst and best performance). Then the criteria rankings of the three (3) groups of different levels of criteria importance were consolidated in one overall criteria ranking.

3.4.2 Pair wise comparisons of criteria

A pair wise criteria approach is applied to complement the ranking technique in order to derive respondents' weighting judgments regarding the criteria in a decomposed and systematic manner. Since the number of criteria is high (14), the pair wise comparisons that have been performed are n-1 in an abbreviated pair wise comparison format. The abbreviated format does not include all possible pair wise comparisons n (n-1)/2. Pairs are sequentially assigned (as a-b, b-c, c-d, etc.), where the initial criterion a is the first ranked criterion by the respondent, criterion b is the second ranked criterion, c is the third ranked criterion and sequentially the order of pairs of criteria is according to the initial criteria ranking. This approach, on one hand, assures randomness on the way that each subsequent pair is assigned between different respondents and thus minimizing problems with path dependency (Saaty, 1987), and on the other hand, maximizes the ranking consistency of stakeholders' preferences.

The respondent is required first to express his/her preferences of relative importance between every pair of criteria verbally and then to assign ratios on a 10 points scale between 0–1. The first criterion is assigned with relative score 1, to be used as the basis reference score for the calculation of the relative scores of the criteria determined by the sequential pair wise comparisons.

Then the obtained relative scores of criteria are translated into normalized relative importance factors (weights) Wi by the following formula:

$$Wi = \frac{RSi}{\sum_{n-1} RS} \quad (1)$$

where RSi is the Relative Score of criterion i compared to criterion j and Σ (RS) is the sum of Relative Scores of all criteria (n) after completing the whole set of abbreviated pair wise comparisons (n – 1). The survey tool enabled the generation of criteria weights as well as final ranking based on the results of the pair-wise comparisons. Survey respondents were able to observe the relative scores and weighting factors as well as the graphical representation of the criteria weights for reference.

3.4.3 Swing weighting method

Through the Swing method the worst performance in all criteria (worst score of the examined alternative technologies) was first presented to respondents. In addition, the best performance in all criteria (best score of the examined alternative technologies) was also presented to the respondents. The preference elicitation procedure consists in asking respondents to carefully look at the potential gains from moving from worst to best performance and then to decide which of the criteria they want to first shift to best performance. Assuming that this first swing is valued with 100 units on a hypothetical value scale, the stakeholders are asked to assign a value (<100) to the second criterion they want to move to its best performance, then to the third and so forth until the last criterion is moved to its best performance. Then the values obtained from this swing weighting process are normalized in criteria weights (percentages).

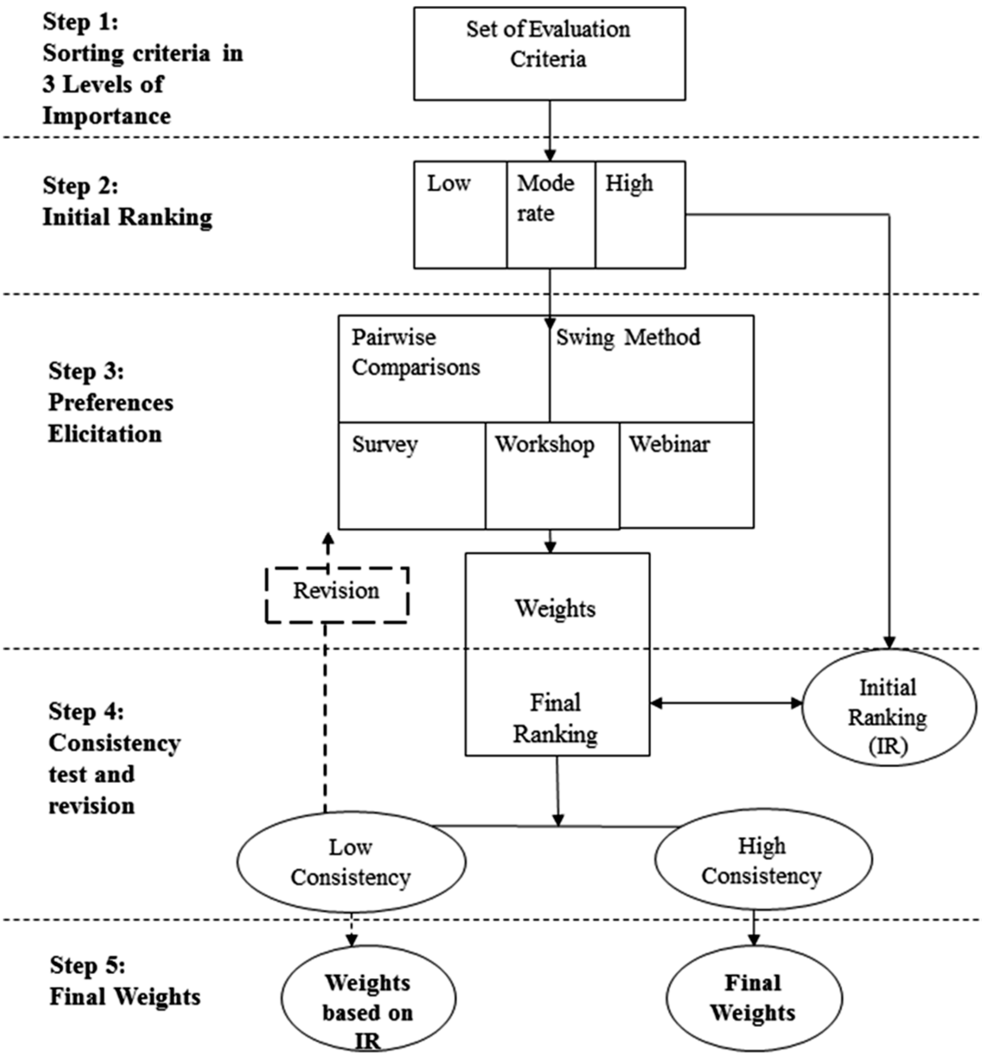


Figure 10. Schematic representation of the hybrid, constructive weighting methodology

3.5 Consistency check

A complete ranking of criteria is based on the actual choices and assuming transitive preferences. Keeney (1982) clearly states that one of the basic axioms of decision analysis is the transitivity of preferences. Although there is some criticism concerning the transitivity of preferences (Tversky, 1969), the assumption of transitivity is based on the findings of Peterson and Brown (1998) that people are transitive in their preferences revealed through a psychometric method of pair wise comparison method. In this case consistency within pair wise comparison method should be assumed as long as stakeholders are highly informed and careful, the degree of relevance between the items of the criteria set is the lowest possible, and the value contrast between choices is significant enough (Peterson and Brown, 1998, Strager and Rosenberger, 2006).

In addition, a ranking consistency index was introduced, based on Spearman's rank order correlation coefficient, to explore the degree of consistency between the initial ranking and the ranking based on pair wise comparisons. The Spearman Rank Order Correlation Coefficient (SROCC) was developed by Spearman, often denoted by the Greek letter "ρ", to use as a measure of correlation to handle data at ordinal scale, such as ranks. The SROCC is a non parametric measure of correlation that assesses how well an arbitrary monotonic function could describe the relationship between two variables, without making any assumptions about the frequency distribution of the variables.

The formula of the Spearman rank order correlation coefficient (ρ) is:

$$\rho = \frac{6*(\sum D^2)}{N(N^2-1)} \quad (2)$$

Where 6 is a constant and it is always used in the formula. D refers to the difference between a criterion's ranks on the two methods (simple ranking and pair wise) and N is the number of criteria. The value of the consistency threshold was set at 0.7. Low consistency was equivalent to or less than 0.5. Moderate consistency ranged from 0.5 and 0.7, while high consistency equaled to or exceeded 0.7.The survey respondents were asked to revise their preferences should the consistency index is below the threshold value. If the consistency index equaled to or exceeded the threshold value, the weighting process was completed (step 5). Otherwise, the respondents had to revise the initial ranking or the pair-wise comparisons in order to achieve high consistency. In conditions where low consistencies were observed, as well as preferences for initial ranking over the pair-wise comparisons, the procedure was simplified to reduce cognitive burden and time required and therefore the elicitation of weights was determined taking into account only the initial ranking. As Riabacke et al. (2012) suggests during preferences' elicitation "one must also keep in mind that practical techniques for elicitation are to a great extent a matter of balancing the obtained quality of elicitation with the time available and cognitive effort demand on the users for extracting all the required information".

3.6 Weights elicitation and Aggregation of preferences

The weights of the respondents who have achieved high consistencies as well as those who have preferred pair-wise comparisons were retained and considered as final weights. In cases where respondents achieved low and moderate consistency, and they expressed preference of the initial ranking, the ranking outcome of the pairwise comparisons was not considered. The large number of pairwise comparisons sometimes it is expected to pose high cognitive burden on the respondents. In cases of time pressure, lack of knowledge, imprecise data, respondent's limited processing capacity then rank ordering can be used to approximate the criteria weights (Barron and Barret, 1996; Roszkowska, 2013). Therefore weights were adjusted based on respondents' initial ranking. Ranking methods can be used if only ordinal information of respondents' preferences is available. In our case initial ranking that has been preferred by the respondent can be used to obtain numerical weights from the rank order using the *rank sum method* (Stillwell et al., 1981). The normalized weight wj of criterion j is calculated by

$$wj\ (RS) = \frac{n - rj + 1}{\sum_{k=1}^{n} n - rk + 1} \qquad (2)$$

Where rj is the rank of the j-th criterion and n is the number of criteria.

The study utilized the linear weighted summation method expressed in the aggregation additive rule to determine the overall value of each alternative energy technology. The selection of aggregation procedure is consistent with the weighting method used which utilizes the criteria weights as scaling factors (Belton and Stewart, 2002 and Cinelli et al., 2014).

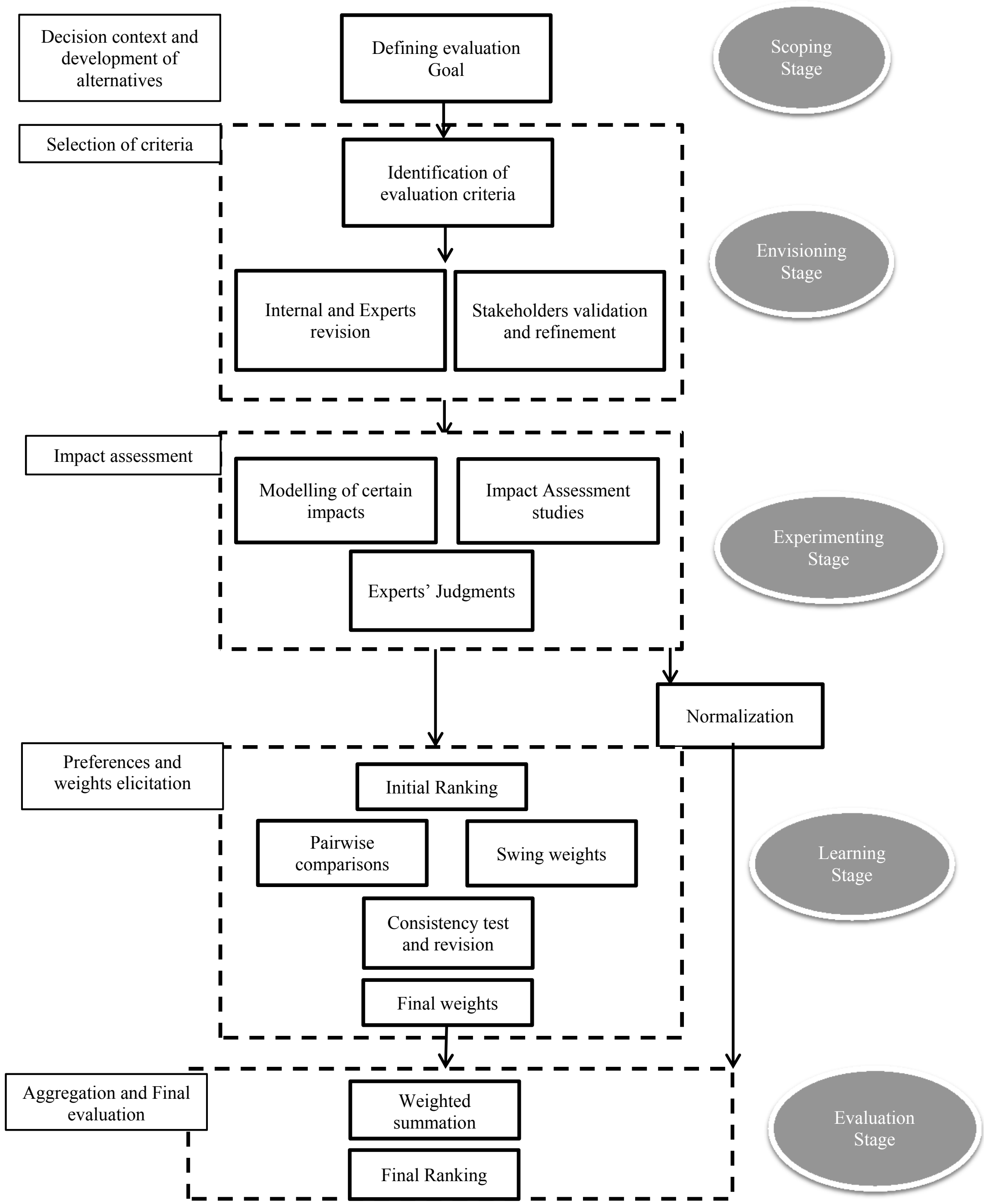
Based on the aggregation additive rule,

$$V(p) = \sum_j w_j * v_j(p) \quad (3)$$

the value of the overall effect of each decision alternative action, v_j, to each criterion is multiplied with its respective criterion weight, w_j, whereas the summation of these products determines the overall value of each alternative decision action V(p).

A computer-aided excel tool (chapter 4) was used to enable the local stakeholders to provide their preferences for the evaluation criteria and indicators. The study utilizes the linear weighted summation method expressed in the aggregation additive rule to determine the overall value of each alternative decision action (Grafakos et al. 2010a). The respondents were able to review the final scores of low-carbon energy technologies, including the contribution of each criterion through the excel-based tool. Moreover, the final weighted scores could be checked through graphic representations that were automatically generated. The overall integrated assessment framework is illustrated in figure 10 whereas the development of the Excel based weighting tool and its distinct steps are presented at Annex 3.

Figure 11: The overall integrated MCDA sustainability assessment framework



Chapter 4: Impact assessment of Low carbon energy technologies

(this chapter has been published in: Grafakos, S., and Flamos, A., 2015, Assessing low-carbon energy technologies against sustainability and resilience criteria: results of a European experts survey, *International Journal of Sustainable Energy*, doi: 10.1080/14786451.2015.1047371)

Multiple sources and studies (e.g. Roth et al., 2009, PSI, 2010) were used to quantify all selected energy technologies against 12 out of the 22 indicators, particularly the economic and some environmental indicators. These indicators were quantified in different measurement units.
The measurement of performance of the examined energy technologies against the evaluation criteria and indicators was based on different sources and methods. Both primary and secondary data collection methods were used. Data for the projected levelised costs of the energy generation technologies under investigation were collected from IEA (2010). Data on employment generation were obtained by studies on future energy technologies such as Ragwitz et al. (2009) and Wei et al. (2010). Data on CO_2 emissions, noise pollution, radioactive waste, waste disposal, ecosystems damages, fuel use, mortality and morbidity, accident fatalities, and energy cost sensitivity to fuel prices were obtained from the NEEDS project (Roth, et al., 2009, and Shenler et al., 2009) and Paul Scherrer Institute PSI (2010). The average reference technologies of this study were identical with some of the technologies evaluated in NEEDS project under common criteria. Data on land use requirement of different energy technologies were found in McDonald et al. (2009) and Andrews et al. (2011), whereas Streimiekene (2010) provided data for the performance scores of the energy technologies against the peak load response criterion. An experts' judgment survey of 40 European experts was conducted to obtain the expected impact values of the low-carbon energy technologies under investigation. The impact assessment matrix in Annex 4 illustrates the performance of energy technologies against the selected evaluation criteria.

Against this background the study integrates sustainability and resilience criteria in the assessment of energy technologies in Europe. The chapter presents the results of the experts' judgment impact assessment survey that was conducted in Europe. Furthermore, the current chapter is the second part of an overall assessment process of low carbon energy technologies that consists of the following parts: a) development of an integrated assessment framework of low carbon energy technologies (Grafakos et al., 2016), b) development of a weighting methodology for stakeholders preferences elicitation (Grafakos et al. 2010a; 2010b), c) impact assessment survey of low carbon energy technologies against selected sustainability and resilience criteria (current chapter) and d) incorporation of local stakeholders' preferences in the overall integrated evaluation of low carbon energy technologies (Grafakos et al., 2015a – next chapter).

The **structure of the chapter** is as follows: Section 1 discusses in brief main literature findings regarding assessments of the sustainability and resilience of energy technologies. Section 2 describes the methods and techniques that were applied for the assessment of the different energy technologies against the selected criteria. The results of the experts' judgment survey are presented in section 3. Section 4 discusses the results and their implications regarding energy and climate policy along with possible future research directions. Section 5 draws some conclusions derived from the study.

Many evaluations of energy technologies have been conducted at different levels. Energy technologies have been assessed at the local (e.g. Trutnevyte, et al., 2011, Begic and Afgan, 2007), national (e.g. Diakoulaki and Karangelis, 2007, Doukas et al., 2007), regional (Beccali, et al., 2003, Mourmouris and Potolias, 2013) and international (e.g. Makowski, et al, 2009, Schenler et al., 2009, Gallego - Carrera and Mack, 2010) levels. Most of these studies addressed mainly sustainability aspects of energy systems and were found short on considering explicitly energy systems' resilience perspectives. For a more detailed review on assessment of energy technologies against multiple criteria can be found in Pohekar et al. (2004), Kowalski et al. (2009) Braune et al. (2009) and Grafakos et al. (2010a).

Molyneaux et al. (2012) performed a **resilience analysis of electricity system** using a measure of composite Resilience Index which calculates resilience of the national power system. Key resilience attributes that were identified are redundancy, efficiency and diversity.

In a similar fashion, Gaudreau and Gibson (2010), conducted a **sustainability-resilience criteria** assessment of a small-scale biodiesel project. The project incorporated energy, transportation, waste management, security, public health and community aspects. They developed a project appraisal methodology that combined eight generic sustainability and nine resilience criteria. Expert judgments for evaluation of energy technologies were carried out by Gallego – Carrera and Mack (2010) and Sliogeriene, et al. (2013). In Gallego – Carrera and Mack (2010), energy experts evaluated the energy technologies against social evaluation criteria. Experts' judgment, as a whole, provided a strong technical foundation in the assessment process. According to Gallego – Carrera and Mack (2010) the technologies that were highly evaluated by the experts against selected social indicators were Photovoltaics, Gas turbine combined cycle and Cogeneration fuel cells. Coal and nuclear power systems were critically assessed by the experts whereas hydropower had diverse assessments against different criteria.

4.1 Experts' impact assessment process

4.1.1 Impact assessment

Multiple sources and studies (e.g. Roth et al., 2009, PSI, 2010) were used to quantify all selected energy technologies against 12 out of the 22 indicators, particularly the economic and some environmental indicators (table 8). These indicators were quantified in different measurement units. The remaining 10 indicators, that were not quantified by any studies for the prospective technologies in 2030, were included in the experts' impact assessment survey and were classified in two sub categories. a) Five (5) out of ten (10) remaining indicators had been qualitatively assessed by using the Likert measurement scale 1 to 5 by Gallego - Carrero and Mack (2010). These indicators were noise pollution, public resistance, aesthetic impacts, market concentration on supply and innovative ability. Even though these indicators had been quantified in the past, it was judged necessary to further validate and/or adjust them according to a more updated and recent survey. b) The remaining 5 indicators that were quantified for first time qualitatively by the current study were climate resilience, stability of energy generation, technological maturity, domestic market and potential for exports. The experts' impact assessment survey was conducted electronically by directly contacting the experts through their email and sharing the link of the online survey. The online survey was based on the free online survey tool of www.surveyexpression.com which provides a user friendly interface and data analysis tools. Annex 5 illustrates in details the online survey tool with all its steps and questions posed to the experts.

Table 8: The overall Sustainability and Resilience criteria framework

	Economic	Environmental	Social	Energy	Technological
Sustainability	Levelised costs (incl. capital, O&M, fuel costs)	CO_2eq emissions	**Aesthetic impact**		**Market size (Domestic)**
	Employment (short and long term)	**Noise Pollution**	Mortality and Morbidity		**Market size (Potential exports)**
		(Radioactive) waste	Accident fatalities		
		Waste disposal (infrastructure)	**Level of public resistance/**		
		Damage to ecosystems			
		Land use requirement			
Resilience	Energy cost stability/sensitivity to fuel price fluctuation	Fuel use		**Stability of energy generation**	**Technological maturity**
		Climate resilience		Peak load response	**Innovative ability**
				Market concentration on supply	

Note: The criteria with **bold** fonts are the ones included in the experts' impact assessment survey.

4.1.2 Experts' impact assessment survey

The identification and selection of experts was initially based on the extensive literature review of studies on the assessment of energy systems and technologies in Europe. Authors of these studies were contacted and invited to participate in the experts' survey. Then experts from related EC RTD projects such as NEEDS, CASES and EXTERNE series of projects were identified and contacted as well. Furthermore the snowball effect approach was also applied in a way that initially contacted experts were asked to identify and suggest additional experts that could participate in the survey. In overall 100 experts from Europe were contacted and invited to participate in the online survey. Out of the 100 experts that were invited, finally 40 individual energy experts across Europe participated in the online survey. One out of the 40 energy experts submitted an incomplete questionnaire and therefore was not considered at the final assessment. Majority (66%) of the experts came from Western Europe (The Netherlands, Germany, Switzerland, and Austria). Twenty percent (22%) represented Southern Europe (Greece and Spain), and 8% came from Northern Europe (United Kingdom) while one respondent was non-European (USA).

These experts characterized themselves as scientists (27%), engineers (20%), economists (15%), researchers (10%), academics (10%), consultants (5%), experts/specialists (5%), and a risk analyst (3%). Scientists were from the social, environmental, and energy fields. Respondents who characterized themselves as consultants and experts/specialists were from the energy, financial, economic, and environmental fields. Academics were University professors and lecturers.

The questionnaire provided background information on the 10 reference energy technologies under investigation: Integrated gasification combined cycle (IGCC), IGCC with Carbon Capture and Storage (CCS), gas turbine combined cycle (GTCC), GTCC with CCS, Nuclear European Pressure Reactor (EPR), hydropower, solar PV, wind onshore, wind offshore and biogas CHP.

Table 8 illustrates the criteria, with bold letters, that were included in the survey. The likely impacts of the energy technologies on five out of the ten criteria had been evaluated in previous studies (Roth et al. 2009 and Gallego - Carrera and Mack, 2010). Therefore the current survey attempted also to validate or adjust, whenever necessary, the results of the previous studies. The respondents were asked to judge/score in a Likert scale from 1 to 5 the level of impact that the different reference technologies would have against the selected criteria in the year 2030 in Europe. The aim was to minimise scores on negative criteria such as *noise pollution, public resistance, aesthetic impact, discontinuity of energy output,* and *market concentration of supply.* Therefore for these criteria the higher their level of impact on scale 1 to 5, the worse their performance was. For the positive criteria we aimed to maximise, such as *climate resilience, technological maturity, innovative ability, market size potential (internal* and *external*), the higher the level of impact in the scale from 1 to 5, the better their performance was.

4.2 Assessment survey results

Tables 9 and 10 present the overall results of the experts' impact assessment survey depicting the average and median performance values respectively.

Table 9: Average performance values of selected indicators

	Sustainability criteria					Resilience criteria				
Energy Technologies	Noise Pollution*	Public Resistance*	Aesthetic Impact*	Market Size (Domestic EU)	Market Size (Potential export)	Climate Resilience	Stability of Energy Generation	Market concentration on supply*	Technological maturity	Innovative ability*
IGCC - Coal	3,0	3,4	3,4	2,8	3,0	2,8	1,8	3,23	3,8	2,4
IGCC w/ CCS	2,7	3,6	3,4	2,7	2,6	3,0	1,9	3,18	2,7	3,3
GTCC - Gas	2,2	2,9	2,8	3,7	3,5	3,0	1,9	3,11	4,4	2,8
GTCC w/ CCS	2,3	3,5	3,1	2,9	2,8	3,1	1,9	3,16	2,9	3,3
Nuclear EPR	2,0	4,6	3,4	2,2	2,8	2,9	2,1	3,47	3,4	2,7
Hydro	1,7	3,2	3,5	3,2	3,1	3,5	2,4	3,04	4,8	2,1
Wind On	2,7	3,2	3,6	4,1	3,8	3,5	3,8	2,62	4,4	3,4
Wind Off	1,5	2,3	2,6	4,1	4,0	3,4	3,5	2,85	3,9	3,8
Solar PV	1,3	1,8	2,3	4,1	3,8	3,7	3,8	2,68	4,2	4,3
Biogas CHP	2,0	2,2	2,0	3,7	3,4	3,3	2,5	2,88	4,0	3,4

Note: Dark and light color cells indicate worst and best performances respectively

*: indicates criteria that have incorporated the validated values from previous study

Table 10: Median performance values of selected indicators

	Sustainability criteria					Resilience criteria				
Energy Technologies	Noise Pollution*	Public Resistance*	Aesthetic Impact*	Market Size (Domestic EU)	Market Size (Potential export)	Climate Resilience	Stability of Energy Generation	Market concentration on supply*	Technological maturity	Innovative ability*
IGCC - Coal	3,1	3,3	3,4	3,0	3,0	3,0	1,5	3,3	4,0	2,3
IGCC w/ CCS	2,6	3,3	3,4	3,0	3,0	3,0	2,0	3,2	3,0	3,5
GTCC - Gas	2,1	3,1	2,7	4,0	4,0	3,0	1,5	3,2	4,0	2,9
GTCC w/ CCS	2,3	3,4	3,1	3,0	3,0	3,0	2,0	3,2	3,0	3,5
Nuclear EPR	2,0	4,5	3,4	2,0	3,0	3,0	2,0	3,4	4,0	2,7
Hydro	1,6	3,4	3,5	3,0	3,0	3,5	2,0	3,3	5,0	2,1
Wind On	2,7	3,3	3,5	4,0	4,0	3,0	4,0	2,9	4,0	3,4
Wind Off	1,4	2,6	2,5	4,0	4,0	4,0	3,0	2,9	4,0	3,7
Solar PV	1,2	2,0	2,3	4,0	4,0	4,0	4,0	2,9	4,0	4,4
Biogas CHP	1,9	2,0	1,7	4,0	4,0	3,0	2,0	3,2	4,0	3,3

Note: Dark and light color cells indicate worst and best performances respectively

*: indicates criteria that have incorporated the validated values from previous study

4.2.1 Sustainability criteria

Noise pollution

The respondents were asked to evaluate the extent that residents will be disturbed by noise caused during the energy generation or the transport of materials to and from the plant. In overall, the technologies with the worst performance were IGCC-coal, Wind onshore and IGCC with CCS. The technologies with the best performance on noise pollution criteria were Solar PV and wind offshore.

Level of Public Resistance

Based on past experiences of public opposition and resistance against the energy technology in question, the respondents were asked to evaluate the level of public opposition of constructing the energy system. Nuclear EPR was evaluated as the technology that is likely to have the highest level of public resistance followed by IGCC with CCS. On the other hand solar PV and biomass evaluated with the lowest level of public resistance.

Aesthetic and Functional Impairment

Often the operation of energy systems creates obstructions to the landscape due to cables, industrial plants, mines, turbines, etc.) and causes aesthetic and functional impairment. The energy technology that was evaluated with the highest level of aesthetic and functional impairment was wind onshore followed by Hydro, Nuclear and IGCC with CCS. According to the experts judgments biomass had the best average performance followed by solar PV.

Market Size (Domestic EU)

Furthermore the respondents were asked to evaluate the extent of the domestic (EU) demand of the energy technology under question in 2030. Solar PV and wind offshore were evaluated with the highest scores. On the other hand Nuclear EPR was evaluated with the lowest score, followed by IGCC - CCS.

Market Size (Potential for Exports Outside of EU)

Finally the respondents were asked to evaluate the extent of the international demand (outside of European Union) of the energy technology under question in 2030. According to the experts wind offshore, wind onshore and solar PV have the highest potential for exports outside of EU. IGCC with CCS and GTCC with CCS will have the lowest potential for exports outside of EU.

4.2.2 Resilience criteria

Climate resilience

Climate resilience is described as "the degree of resilience of the energy technology to the future climatic changes and extreme weather events." The experts were asked to evaluate the level of resilience that the energy technologies will have in 2030 against climate change and climate variability impacts, such as extreme heat and cold, extreme wind, stress on water resources, floods, coastal erosion, and sea level rise. The technologies with the highest average performance, assessed against climate resilience, were Solar PV, Wind onshore, Hydropower and wind offshore. Nuclear EPR and IGCC were scored with the lowest average performance.

Discontinuity of energy output (Stability of Energy Generation)

The respondents were asked to evaluate the level of fluctuation/discontinuity of the energy output of the energy technology under question in 2030. According to experts judgments, the technologies with the lowest level of fluctuation of energy output were the fossil fuel based technologies IGCC-coal, IGCC with CCS and GTCC-gas, GTCC with CCS. The technologies with the highest level of fluctuation of energy output were Wind onshore and Solar PV. According to both average and mean values the greatest difference on the assessment of technologies was observed at this criterion.

Market Concentration on Supply

Regarding the market concentration on supply criterion, the experts were asked to evaluate the potential of disruption of electricity supply due to the fact that there are few suppliers in the energy technology in question in 2030. Nuclear EPR was evaluated with the worst performance on market concentration on supply followed by IGCC – coal. Wind on shore and solar PV were evaluated with the best performances.

Technological Maturity

It is necessary to evaluate the technological maturity of energy technologies which will determine the rate of their success of their development. Hydropower, GTCC-gas and wind-onshore were the technologies with the highest potential of technological maturity. CCS coal and gas technologies were evaluated with the lowest performance.

Innovative Ability

The ability to integrate new technological innovations and progress is essential to the long term survival of energy technologies. The technologies with the highest average performance according to the experts were Solar PV and Wind offshore whereas the technologies with the lowest average performance were Hydropower and IGCC – coal.

4.3 Discussion on experts' impact assessment survey

Based on the evaluation results we can draw some general remarks regarding the selected technologies evaluated by an integrated framework of sustainability and resilience criteria. Our experts survey to a large extent confirmed the results of previous related studies (Gallego - Carrera and Mack, 2010) on the 5 commonly examined criteria (see figure 12).

Furthermore, we can clearly observe that the experts favored solar PV as it performed best of all the technologies in 5 (climate resilience, noise pollution, public resistance, innovative ability and domestic market size) out of the 10 criteria. Wind offshore was also well evaluated by the experts achieving best scores of all technologies on Domestic market size and Potential for exports and receiving very positive scores on other criteria such as climate resilience, noise pollution, aesthetic impact, market concentration of supply and innovative ability.

On the contrary Nuclear power was not favored as it performed worst, according to the experts judgments, in 3 criteria (public resistance, market concentration of supply and domestic market size). IGCC with CCS was evaluated also relatively low, having the worst performance of all technologies at the criteria of technological maturity and Potential export and performing relatively poor against the other criteria. Similarly IGCC was evaluated critically in most of the criteria performing worst on climate resilience and noise pollution while performing best on stability of energy generation.

Hydropower had diverse evaluations ranging from best score in technological maturity to lowest score in innovative ability and average scores in most of the other criteria. Wind onshore received also diverse evaluations achieving best score at the market concentration of supply criterion and worst scores at the aesthetic impact and stability of energy generation. The evaluations to the other criteria were mostly positive.

Biomass received the best score at the aesthetic impact criterion, whereas at the other criteria it was evaluated from moderate to positive level. Natural gas technologies were also moderately to positively evaluated by the experts in most of the criteria.

It is interesting to note that both fossil fuel based technologies with CCS received worse scores for public resistance (higher level), and technological maturity (lower level) and better scores for innovative ability (higher level) and climate resilience (higher level), than their counterparts without CCS.

As was noted in 3.2 section, the experts' sample was constructed based on the snowball sampling technique. The final formation of the sample therefore didn't allow for analysis of experts' judgements from different European regions. For instance the experts' sample didn't include any experts from Central and Eastern Europe. A future research direction that we are planning to explore is the analysis of the likely performances of the selected energy technologies based on experts' judgements from different European regions according to a more balanced and stratified experts' sample.

Convergence of experts' judgments

In overall, most of the experts approved the evaluations of the 5 out of 10 indicators based on the previous study (Gallego - Carrera and Mack, 2010). However there were many experts that provided different judgments particularly on the evaluation of technologies against the public resistance indicator. Figure 12 illustrates the share of agreements and partial differentiations of values from previous evaluations (Gallego - Carrera and Mack, 2010) by the current group of experts for the 5 out of 10 selected criteria.

Figure 12: Level of agreement of expert judgments with previous studies for selected criteria

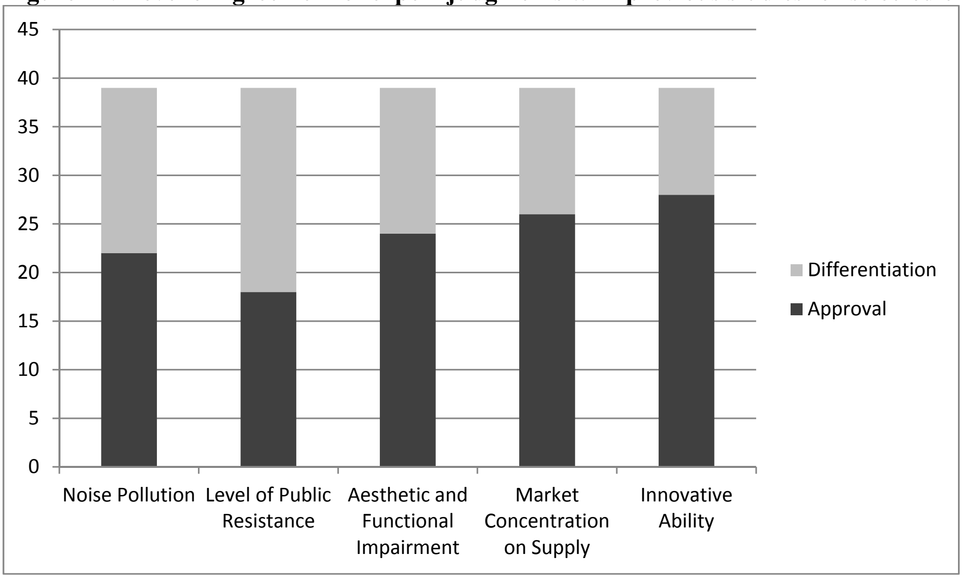


Table 11: Convergence of experts based on standard deviation of experts evaluations

	Noise Pollution*	Public Resistance*	Aesthetic Impact*	Market Size (Domestic EU)	Market Size (Potential export)	Climate Resilience	Stability of Energy Generation	Market concentration on supply*	Technological maturity	Innovative ability*
IGCC - Coal	0,53	0,77	0,48	0,97	1,20	1,13	1,04	0,55	0,86	0,37
IGCC w/ CCS	0,57	0,62	0,45	1,02	1,18	0,96	1,07	0,45	1,06	0,68
GTCC - Gas	0,56	0,53	0,39	1,00	1,11	1,19	1,13	0,60	0,63	0,45
GTCC w/ CCS	0,47	0,65	0,33	1,01	1,09	1,15	1,12	0,49	1,03	0,59
Nuclear EPR	0,57	0,24	0,56	0,91	1,08	1,23	1,23	0,36	0,87	0,57
Hydro	0,51	0,61	0,44	1,04	1,19	1,18	0,91	0,53	0,44	0,46
Wind On	0,48	0,60	0,36	0,95	1,01	1,11	0,84	0,53	0,49	0,35
Wind Off	0,55	0,60	0,57	0,71	0,94	1,20	0,91	0,41	0,65	0,35
Solar PV	0,55	0,54	0,56	0,85	1,10	1,12	0,98	0,65	0,70	0,38
Biogas CHP	0,25	0,59	0,55	0,86	1,32	1,11	0,99	0,66	0,66	0,43

Note: Lower values indicate greater degree of convergence

*: indicates criteria that have incorporated the validated values from previous study

The standard deviation was used as a simple measure of the level of convergence between experts' score values (table 11). A large standard deviation indicates that the score values are spread far from the mean and a small standard deviation indicates that they are clustered closely around the mean. In order to identify the degree of convergence of experts' evaluations we classified the criteria in two broad categories: a) criteria that the energy technologies were evaluated for first time by experts and b) the criteria that the energy technologies have been evaluated from previous studies and presented to this group of experts for validation. Regarding the second category, as was mentioned above, the experts confirmed to a large extent the previous evaluations which resulted in higher degrees of convergence. Interestingly, the highest and the lowest degree of convergence was observed on the scores of technologies against the criterion of public resistance. The majority of experts agreed that the technology with the highest likelihood to face public resistance is Nuclear EPR whereas the highest disagreement was on the level of public resistance of IGCC-Coal. Some experts assumed that probably the pressing climate risks will create public resistance against coal based technologies whereas other experts didn't share this view.

Experts shown very high degree of convergence on evaluating wind onshore as the technology with the highest instability of energy generation (discontinuity of energy output). Similarly the vast majority of experts agreed that the Nuclear EPR would have the highest potential for market concentration of supply, whereas high divergence between experts' evaluations was observed on the scores of Solar PV and Biomass against the same criterion.

Furthermore, most of the experts agreed on the evaluation of hydropower as the technology with the highest level of technological maturity, whereas they had the highest divergence on the evaluation of IGCC with CCS which was scored as the technology with the lowest technological maturity by 2030. Similarly, experts had the highest divergence on their evaluation regarding the score of IGCC with CCS against the criterion of Innovative ability. These results definitely imply that further research is needed on the deployment, technological maturity and innovation potential of CCS technologies. Most of the experts agreed that Solar PV has the highest level of innovative ability in 2030. Regarding the market size both domestically and externally, the vast majority of experts agreed that wind offshore has the highest market potential, whereas the highest level of disagreements were observed on the potential of export of biomass and domestic market potential of hydro.

Regarding the *climate resilience* criterion, the experts agreed on the level of resilience of IGCC with CCS and had major disagreement on the level of resilience of Nuclear EPR. In overall the highest divergence was observed on the technologies evaluations against the climate resilience and market size potential for export criteria. These results exhibit high degree of uncertainty which further indicates fruitful ground for future research on the likely climate impacts on energy systems and the potential of these energy technologies under investigation to be deployed and exported globally.

4.4 Concluding remarks of the chapter

The main innovative features of this study were the evaluation of low carbon energy technologies against a selected set of criteria combining sustainability and resilience aspects, along with the application of a large European expert survey for the evaluation of low carbon energy technologies.

This chapter presented and discussed the assessment results of the experts' assessment survey. The selection of criteria was based on a 3 steps approach which included extensive literature review, experts judgments and stakeholders validation (Grafakos et al., 2016). An experts' impact assessment survey was conducted for the assessment of the technologies against 10 criteria that were not yet quantified in the literature. In overall, the experts evaluated solar PV with the highest score in comparison to all the other technologies in 5 (climate resilience, noise pollution, public resistance, innovative ability and domestic market size) out of the 10 criteria. On the other hand, Nuclear power was relatively low evaluated as it performed worst, according to the experts' judgments, in 3 criteria (public resistance, market concentration of supply and domestic market size). It should be noted that the results and conclusions reflect the performance of technologies against a selected sub-set of the overall criteria set, with 4 out of 10 criteria focusing on technological aspects, while excluding economic criteria from the evaluation. The reason is that the other 12 criteria have been quantified by other studies. The authors intend to include all 22 criteria at an overall energy technologies' evaluation at the next stage of the research.

The analysis of convergence of experts' evaluations revealed that further research is needed to explore the technological maturity and future deployment of CCS technologies since there is still large uncertainty and disagreement on how they will be deployed in the future. Furthermore it became clearly evident that Nuclear EPR has the highest likelihood to face public resistance. In addition, still experts agree that Wind onshore will have relatively low energy generation stability which points out on further research on how to increase its stability through smart energy grids or other technological means.

Chapter 5: Eliciting local stakeholders' preferences for the evaluation of low carbon energy technologies in Europe

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Aim of this chapter is to incorporate stakeholders' preferences on evaluation criteria based on European local (urban) stakeholders' survey and to evaluate future low-carbon energy technologies in Europe from a local stakeholders' perspective. Furthermore the study aims to apply a systematic methodology for the refinement and validation of evaluation criteria and indicators for the integrated sustainability assessment of low-carbon energy technologies. The researchers carried out a three-step validation process, and an integrated weighting methodology based on different Multiple Criteria Decision Analysis (MCDA) techniques. Moreover, the inclusion and participation of energy experts and stakeholders in the stages of criteria validation, refinement and elicitation of weighting preferences, allowed for a robust participatory evaluation of low-carbon energy technologies in Europe.

5.1 Introduction

Important policy and investment decisions should be made regarding the current and future energy technologies that would be deployed in the coming years and decades (IEA 2014). At the local level, cities and municipalities have come up with their own energy initiatives. The Covenant of Mayors, a network of local and regional authorities committed to the implementation of sustainable energy policies, has been established and more than 4,000 signatories have pledged their commitments and outlined their specific actions through their Sustainable Energy Action Plans (Covenant of Mayors 2013).

Centralized supply systems are the conventional way of delivering electricity services. Large-scale power plants fuelled by coal, natural gas, or nuclear technology, are constructed to provide high voltages into the electricity grid (IEA 2009). With the advancement of renewable energy technologies, discussions on whether cities can become more independent from distant energy sources or whether they could produce their own energy have arisen (Grubler and Fisk 2012 in Steinberg and Lindfield 2012).

Development planning and decision making in the energy sector necessitates for the participation of relevant stakeholders, from electricity producers and energy associations to environmental groups and local communities. Urban energy stakeholders include those who have legitimate responsibilities for energy projects (e.g. government authorities – national, regional, and local), those who support and oppose these initiatives (e.g. non-governmental organizations (NGOs), consumer associations, homeowner groups) as well as those who depend on it (e.g. energy users and customers).

Each stakeholder group, however, has its own objectives, priorities, and preferences. For example, local authorities purchase energy services to meet the needs of their constituents, while energy producers are responsible for energy generation. Meanwhile, the local population is directly or indirectly impacted by these energy-related decisions. Nevertheless, the multiple, often conflicting views of stakeholders have to be taken into account in order to reach a consensus as well as to ensure transparency in the decision making process.

Structuring and analyzing a multi-actor and multi-objective complexity is therefore crucial. One method for addressing such problems is Multiple Criteria Decision Analysis (MCDA). MCDA has been widely used for sustainable energy planning, as a useful tool in facilitating decision making among different stakeholder groups, in expanding the range of possible outcomes, and in assessing the performance of technologies against a set of evaluation criteria (Pohekar and Ramachandran 2003; Kowalski et al. 2008; Braune et al. 2009).

However, a universal ranking of energy technologies that has been attempted already (Chatzimouratidis and Pilavachi 2008; Evans et al. 2010) would not be applicable in all cases and geographical contexts. Based on literature that delves on measuring urban energy sustainability, it has been noted that there is no particular indicator framework that is suitable to all applications (Keirstead 2007). Hence, it is necessary to take into account the intended goals for the use of the indicators. Moreover, indicators have to be chosen selectively in order to maximize their effectiveness and relevance (Kierstead 2007).

The selection and validation of evaluation criteria and indicators is an important part of any environmental assessment and decision making process, including energy and climate change mitigation planning (Cloquell – Ballester et al. 2006; Bockstaller and Girardin 2003). Cloquell –

Ballester et al. (2006) developed the “3S” methodology for validating indicators in the field of environmental studies. However, when researchers and analysts apply a multiple criteria or multiple indicator assessment framework, they often neglect this very essential stage of the decision making process. Criteria and indicators are usually applied intuitively (Hak et al. 2012).

In many multiple criteria analysis (MCA) applications, the entire inclusion of stakeholders is not considered. Often experts attempt to deduce stakeholders’ preferences instead of including them directly in the decision making process. According to Kowalski et al. (2009), most applications on energy issues focus on technical aspects, without involving stakeholders in the decision making process in a systematic and participatory way. Nevertheless, like in other research areas, a trend towards increased inclusion of stakeholders can be observed in energy research as well. The current study applies the “3S” validation methodology in the context of low-carbon energy planning for the selection and refinement of sustainability indicators.

Furthermore, involving different stakeholders in the energy planning and decision making process increases legitimacy, facilitates learning, and allows for the inclusion of multiple perspectives (Braune et al. 2009; Van der Gaast 2009). Stakeholders feel responsible and obligated to participate in project-related activities (Omann in Braune et al. 2009). The inclusion of their varied interests in the planning and decision making process facilitates long-term commitment and cooperation in implementing energy alternatives (Tsoutsos et al. 2008 in Tsoutsos et al. 2009).

Including stakeholders at the initial stage of the decision making (e.g. selection of evaluation criteria) is imperative for a participatory process. With issues on public acceptance, stakeholder participation is crucial to guarantee success as well as stability of energy supply systems (Braune et al. 2009). The step of criteria weighting wherein stakeholders express subjective judgments is another step that could foster direct participation of stakeholders and inclusion of their preferences into the decision-making process (Borges and Villavicencio 2004; Grafakos et al. 2010a). However the design and implementation of such interaction with stakeholders is considered a major challenge and should be carried out carefully (Makowski et al. 2009).

This section applies the integrated weighting methodology that was presented in previous section to incorporate stakeholders’ preferences in energy and climate change policy context. The current chapter presents an application of the criteria weighting methodology for the sustainability assessment of future low-carbon energy technologies in Europe at the local level. The methodology allows for the provision of factors of relative importance of criteria, depending on stakeholders' preferences. Stakeholders' preferences are incorporated in the analysis in both stages of selection/validation and weighting of evaluation criteria. Furthermore a computerized interaction is designed in eliciting the preferences of stakeholders. This provides stakeholders with support in analyzing their desired objectives in relation to the outcomes of the elicitation process.

The weighting preferences of local stakeholders were used as a basis for conducting the MCDA sustainability assessment of reference future low-carbon technologies in electricity production in Europe. This research looks into the preferences of local (urban) stakeholders at the European level which, to the best of our knowledge, has not been previously studied. Findings of this study may advance the promotion of a local stakeholder-driven process in low-carbon energy evaluation and planning both in validation and weighting of indicators in Europe.

This research provides insights on how local stakeholders in Europe value the selected evaluation criteria and low-carbon energy technologies under investigation. It highlights discrepancies on local stakeholders' preferences that could indicate areas of potential conflict during local energy planning and implementation of low-carbon energy technologies. As such, results of this study may be significant in local stakeholders' preference mapping in Europe as well as in potential conflict identification.

Based on this framework, this section aims at: a) applying a systematic methodology for the refinement and validation of criteria and indicators for the evaluation of low-carbon energy technologies; b) determining the factors of relative importance of the evaluation criteria and indicators based on European local (urban) stakeholders' preferences; and c) evaluating selected future low-carbon energy technologies in Europe from a local stakeholders' perspective.

The section is structured as follows: Sub-section 2 presents a literature review of studies on MCDA applications in local energy decision making context. Sub-section 3 describes the main methodological components and data collection methods of the current research. Sub-section 4 reports about the results on the a) refinement and validation of criteria/indicators; b) application of the weighting methodology for eliciting local stakeholders' preferences; and c) final ranking of low-carbon energy technologies based on stakeholders' preferences. The final sub-section discusses the main implications of the research findings, future research directions, and concluding remarks.

5.2 Results and empirical analysis

5.2.1 Initial ranking

Based on frequency count and percentages, the criteria that were considered of high importance by the weighting survey respondents were as follows: CO_2eq emissions, ecosystem damages, mortality and morbidity, accident fatalities, employment generation, levelised costs, resilience to climate change, and radioactive waste (figure 13). Table 12 below shows the results of the initial ranking, including the average ranking positions, of the different criteria.

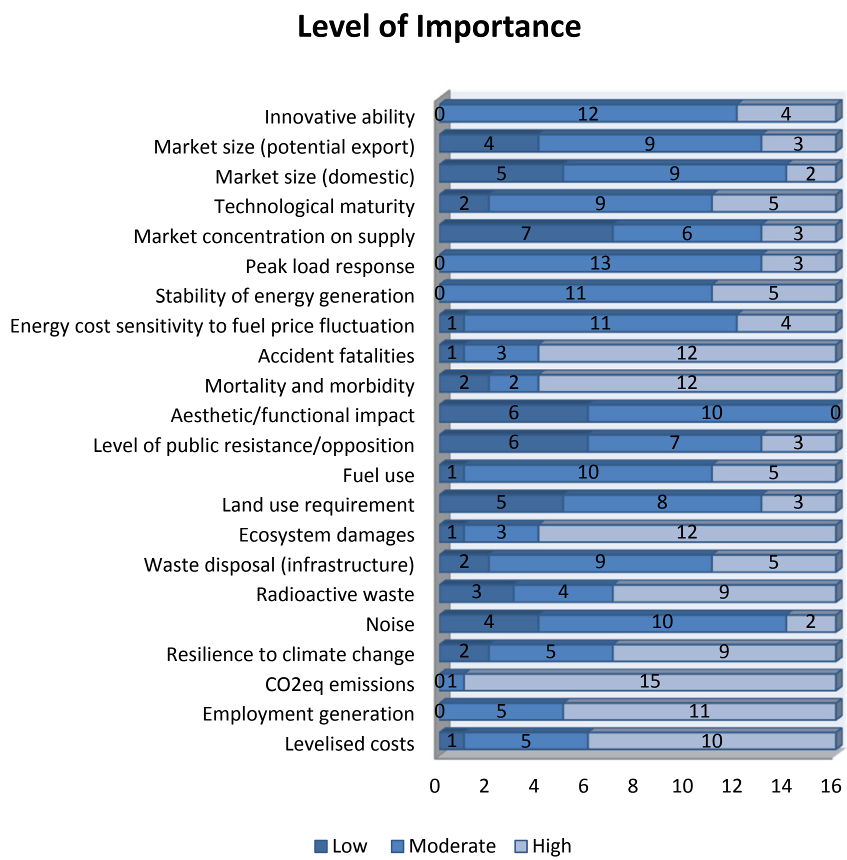

Figure 13.Level of importance of the evaluation criteria and indicators.

Table 12.The initial ranking and the corresponding average ranking positions of the evaluation criteria based on respondents' preferences

Initial Ranking	Criteria	Average Ranking Position
1	CO_2eq emissions	3.50
2	Levelised costs	5.06
3	Ecosystem damages	5.94
4	Accident fatalities	6.75
5	Mortality and morbidity	7.19
6	Employment generation	7.38
7	Radioactive waste	9.38
8	Fuel use	9.63
9	Resilience to climate change	9.75
10	Energy cost sensitivity to fuel price fluctuation	10.50
11	Stability of energy generation	10.88
12	Waste disposal (infrastructure)	11.06
13	Innovative ability	11.13
14	Technological maturity	12.19
15	Peak load response	12.69
16	Noise	14.25
17	Land use requirement	14.50
18	Market size (potential export)	14.69
19	Level of public resistance/opposition	15.13
20	Market concentration on supply	15.38
21	Market size (domestic)	15.81
22	Aesthetic/functional impact	17.63

The initial ranking shows that CO_2eq emissions is the most preferred criterion with an average ranking position of 3.5 (table 12). This is followed by levelised costs, ecosystem damages, accident fatalities, mortality and morbidity, employment generation, radioactive waste, fuel use, resilience to climate change, and energy cost sensitivity to fuel price fluctuation. Rounding off the list are stability of energy generation, innovative ability, waste disposal (infrastructure), technological maturity, peak load response, noise, land use requirement, market size (potential export), level of public resistance/opposition, market concentration on supply, market size (domestic), and lastly, aesthetic/functional impact.

5.2.2 Pair-wise comparisons results

The initial ranking provided the basis for the consistency check. As such, the results of the initial ranking were compared with the results (final ranking) of the series of pair-wise comparisons. Table 13 below presents the consistency levels that respondents achieved.

Table 13: Respondents Consistency levels

	Values	Number of Respondents
Low	>0,5	9
Moderate	0,5 - 0,7	4
High	0,7>	7

As there were some respondents who achieved low and moderate consistency, where few of them were in favor of the initial ranking, the ranking outcome of the pairwise comparisons was not considered reliable. The large number of pairwise comparisons in these cases probably posed high cognitive burden on the respondents who proved inconsistent and therefore led to unreliable outcomes. Therefore, in cases where low or moderate consistency was observed, in combination with respondent's preference on initial ranking, the outcomes of pairwise comparisons from these respondents were not considered and instead weights were adjusted based on respondents' initial ranking. The constructive process that was integrated in the weighting method, on one hand tested the consistency of stakeholders' preferences and on the other hand "forced" the stakeholders to rethink, revise their initial preferences and better think about the issue of criteria importance.

Based on the results of the approach wherein weights of selected responses were adjusted, CO_2eq emissions topped the list with an average weighting score of 0.083. Levelised costs, ecosystem damages, mortality and morbidity and resilience to climate change were on the list of top five preferred criteria. Figure 14 illustrates the final criteria weights and ranking based on stakeholders preferences. These results though should be further tested at a larger sample where trends and patterns of local stakeholders preferences can be revealed.

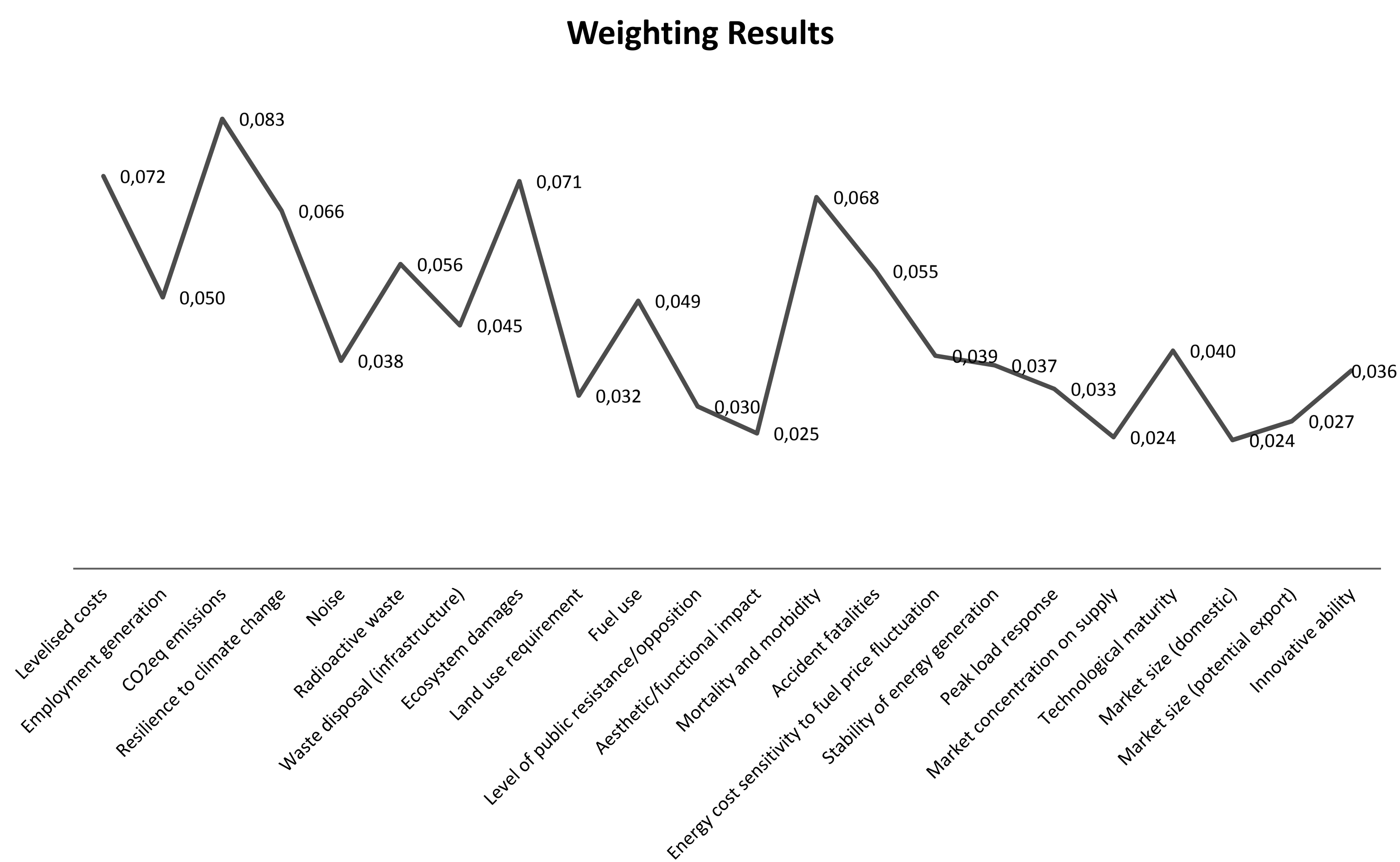

Figure 14. Weighting results based on pair-wise comparisons and adjusted weights

5.3 Stakeholder groups

For the purpose of analyzing the preference of local stakeholder groups, the respondents were grouped into three broad categories, namely public authorities (n=5), energy industry actors (n=5), and technical professionals (n=5). There was one respondent from an NGO. The results of the final ranking were considered in analyzing the 3 local stakeholder groups' preferences. Public authorities were composed of respondents who came from the government sector – both national and local levels. Energy industry actors were represented by respondents from the following stakeholder groups: electricity and energy associations, electricity producers, and energy agencies. Lastly, technical professionals were respondents who belonged to the following stakeholder groups: consultants – advisors and academic – research.

5.3.1 Stakeholder groups preferences

From the distribution of weighting scores in figure 15 all three groups of local stakeholders expressed high preferences for CO_2eq emissions, levelised costs, ecosystem damages, and resilience to climate change. CO_2eq emissions was the most preferred criterion by both energy industry actors and technical professionals, while this ranked 5th among public authorities.

It could be observed that public authorities gave more importance on ecosystem damages which ranked 2nd in the list. Moreover, public authorities expressed high preferences for social criteria. Mortality and morbidity was considered as the number one criterion, while accident fatalities ranked 3rd.

Energy industry experts also showed high preference for mortality and morbidity. However, this criterion was not given much importance by technical professionals. Accident fatalities, however, was ranked 8th among technical professionals and 12th among energy industry actors. Meanwhile, technical professionals had expressed high preferences for fuel use which ranked 2nd among this stakeholder group. It could also be observed that compared to public authorities and energy industry experts, technical professionals expressed more preference for certain energy and technological criteria.

Technological maturity and market size - both domestic and potential export, for example, received more weights from technical professionals compared to what the other stakeholder groups have provided. It could also be observed that public authorities, compared to the weights provided by energy industry experts and technical professionals, provided relatively low weights to certain energy and technological criteria, such as market size - domestic and potential export, stability of energy generation, and peak load response.

Also, energy public professionals and technical professionals provided the same weights to radioactive waste while energy industry experts gave a relatively lower weight to this criterion. Technical professionals also provided relatively lower weights to social criteria, such as mortality and morbidity and accident fatalities, compared to the other two stakeholder groups. Interestingly, energy and industry actors gave relatively higher weights to level of public resistance/opposition and aesthetic/functional impact compared to the other groups. Figure 15 shows the convergence and divergence of preferences among the three different local stakeholder groups.

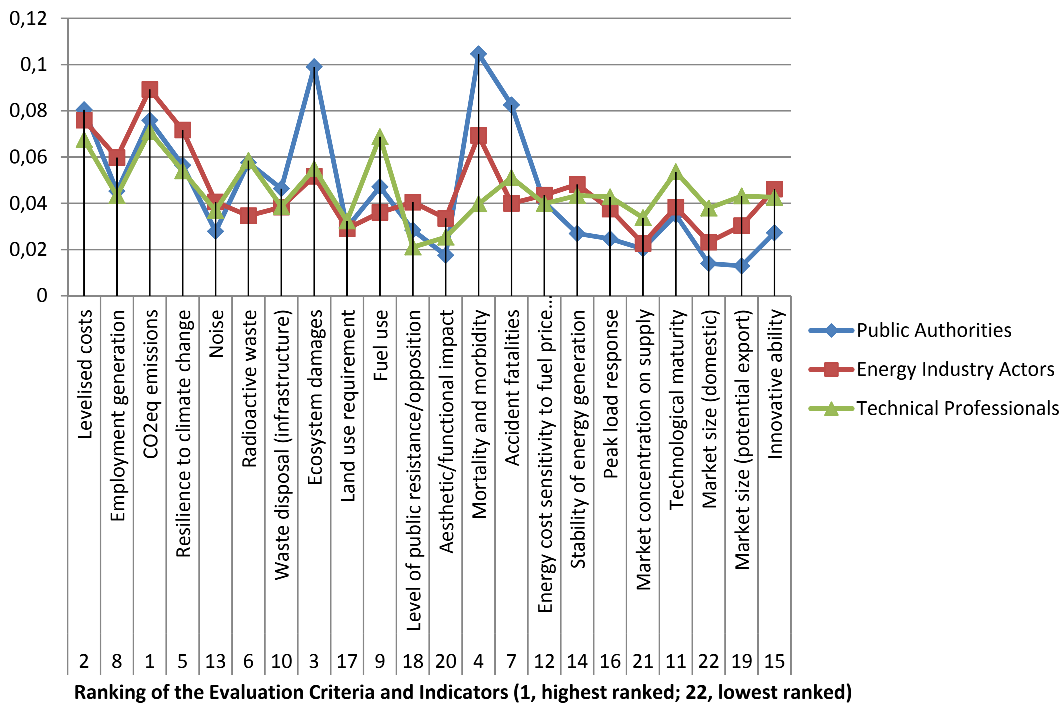

Figure 15. Distribution of weights for all criteria among the three stakeholder groups

5.3.2 Clustering Priorities

Although the above analysis of weights and stakeholders priorities is insightful, this data can be analysed further to see the level of homogeneity of stakeholder groups and if there are any identifiable "priority bundles" or groupings of criteria that respondents tend to prioritize more. It can further be examined to see if certain "types" of stakeholders tend to weight more certain criteria categories. Cluster analysis was conducted on the survey data with these objectives in mind. Hierarchical agglomerative clustering methods were employed. First, each individual stakeholder was considered as an individual cluster, and then close pairs of clusters were merged using Ward's method for clustering and the squared Euclidean distance to measure the distance between different observations. The resulting dendrogram suggests a three-cluster solution (Table 14). Stakeholders (respondents) in each cluster have weighted similar groups of criteria and utilise similar priorities when evaluating low carbon energy options (table 15). According to cluster weights and their average values, three "priority clusters" were created:

1) *Energy market priorities:* Stakeholders (respondents) in this cluster proved to have higher priorities (weights) on energy and technological criteria.
2) *Environmental priorities*: Stakeholders (respondents) in this cluster have higher priorities (weights) on most of environmental criteria.
3) *Socio-economic priorities*: Stakeholders (respondents) in this cluster have higher priorities (weights) on most of social and economic criteria

Table 14: Cluster analysis results

Criteria Categories	Criteria	Cluster 1: Energy Market Priorities			Cluster 2: Environmental Priorities			Cluster 3: Socio-economic Priorities		
		Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum
Economic	Levelised costs	0,09	0,07	0,00	0,09	0,06	0,03	0,16	0,09	0,06
	Employment generation	0,07	0,04	0,01	0,08	0,06	0,04	0,08	0,05	0,02
Environmental	CO2eq emissions	0,13	0,07	0,00	0,16	0,10	0,05	0,09	0,06	0,03
	Resilience to climate change	0,13	0,06	0,00	0,14	0,09	0,02	0,08	0,04	0,00
	Noise	0,08	0,05	0,01	0,08	0,04	0,01	0,04	0,02	0,00
	Radioactive waste	0,06	0,03	0,00	0,14	0,08	0,02	0,06	0,04	0,02
	Waste disposal (infrastructure)	0,04	0,03	0,00	0,10	0,06	0,03	0,07	0,03	0,01
	Ecosystem damages	0,06	0,03	0,00	0,15	0,09	0,05	0,14	0,08	0,05
	Land use requirement	0,06	0,03	0,01	0,07	0,04	0,02	0,03	0,02	0,01
	Fuel use	0,18	0,08	0,02	0,06	0,04	0,02	0,07	0,03	0,01
Social	Level of public resistance	0,04	0,03	0,02	0,05	0,03	0,01	0,07	0,04	0,01
	Aesthetic/ functional impact	0,06	0,03	0,02	0,04	0,02	0,00	0,04	0,02	0,00
	Mortality and morbidity	0,09	0,04	0,02	0,11	0,06	0,02	0,20	0,11	0,00
	Accident fatalities	0,08	0,05	0,02	0,10	0,06	0,01	0,10	0,06	0,03
Energy	Energy cost sensitivity to fuel price fluctuation	0,07	0,05	0,02	0,06	0,03	0,01	0,06	0,04	0,02
	Stability of energy generation	0,08	0,05	0,03	0,04	0,02	0,01	0,08	0,04	0,01
	Peak load response	0,11	0,05	0,02	0,04	0,02	0,00	0,05	0,03	0,01
	Market concentration on supply	0,10	0,04	0,02	0,02	0,01	0,00	0,05	0,03	0,01
Technological	Technological maturity	0,16	0,06	0,02	0,09	0,03	0,00	0,06	0,04	0,02
	Market size (domestic)	0,08	0,04	0,01	0,03	0,01	0,00	0,06	0,02	0,01
	Market size (potential export)	0,12	0,04	0,01	0,03	0,01	0,00	0,07	0,03	0,01
	Innovative ability	0,11	0,05	0,01	0,05	0,02	0,00	0,07	0,05	0,02

Regarding the homogeneity of stakeholder groups the following observations can be drawn from the cluster analysis (see also table 14). The highest homogeneity was observed in Public Authorities group, where 4 out of 5 respondents belong in cluster 2 that gives more emphasis on environmental priorities. Technical experts proved to be relatively homogenous where 3 out of 5 respondents belong in cluster 1 that gives more emphasis on energy market priorities and the other 2 respondents belong in cluster 2 that emphasizes more environmental priorities. Energy industry actors group also proved to be relatively homogenous, as 3 out of 5 respondents belong in cluster 3 that emphasizes socio-economic priorities whereas the other 2 belong in cluster 1 that gives emphasis on energy market priorities.

Table 15: Type of stakeholders in each cluster (Priorities)

	Technical Experts	Energy Industry Actors	Public Authorities	NGOs	Total
Energy Market Priorities	3	2	0	0	5
Environmental Priorities	2	0	4	1	7
Socio-economic Priotities	0	3	1	0	4
Total	5	5	5	1	16

5.4 Evaluation of low-carbon energy technologies

The evaluation of low-carbon energy technologies was conducted, applying the weighted summation method, based on the criteria weights derived from local stakeholders' preferences and the technologies' impacts measured by different methods as explained in section 3.3. It was found that the highest ranked low-carbon energy technology is wind off-shore (0.79), followed by solar PVs (0.78), hydropower (0.74), wind on-shore (0.73), GTCC (0.58), GTCC with CCS (0.57), EPR (0.57), biomass (0.56), IGCC with CCS (0.53) and IGCC (0.45). Figure 16 shows the final scores of each low-carbon energy technology, illustrating the contribution of each evaluation criterion to the final score. As can be observed from figure 16, technologies with high scores at the most important criteria, weighted by the stakeholders, in principle achieve higher overall final scores.

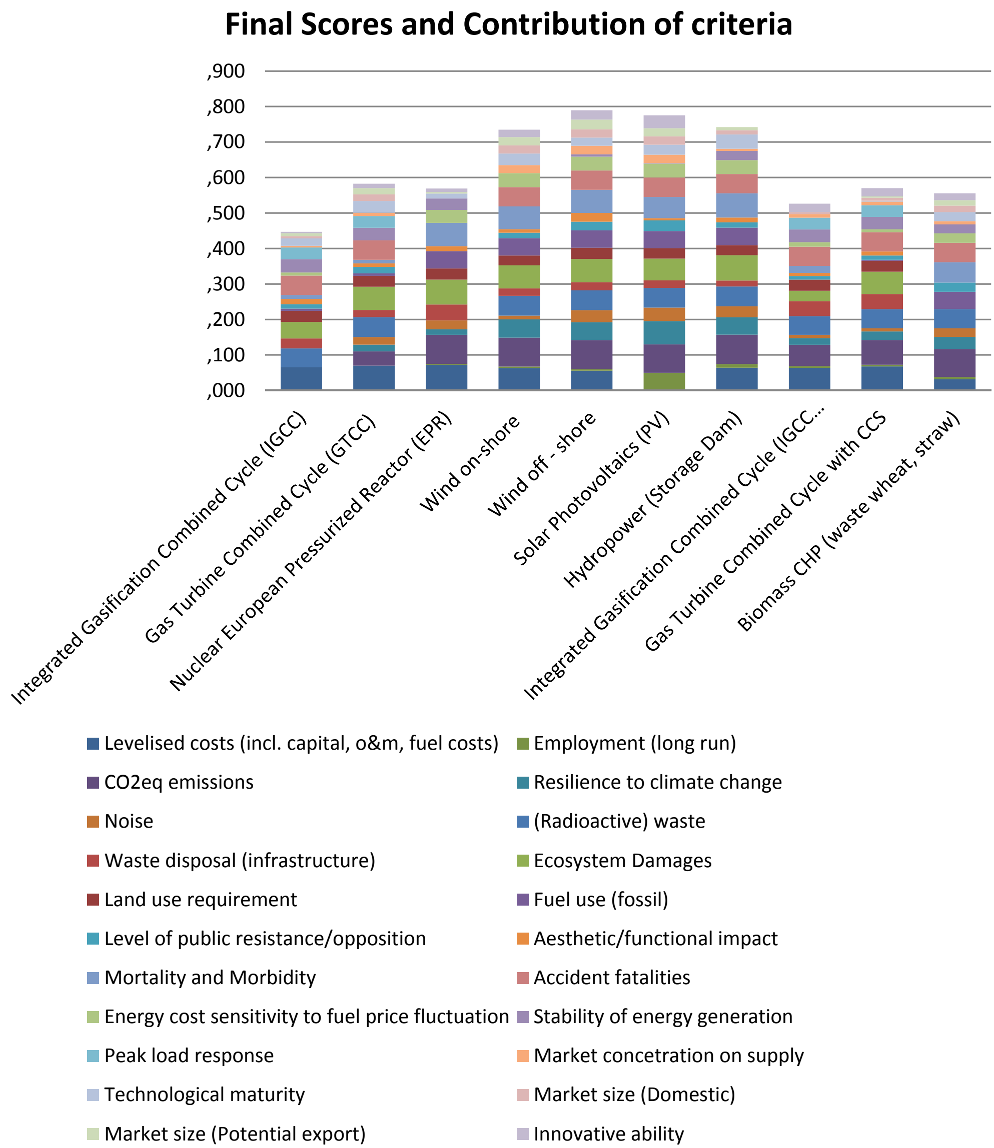

Figure 16. The final scores of the low-carbon energy technologies and the contribution of all criteria based on local stakeholders' perspectives.

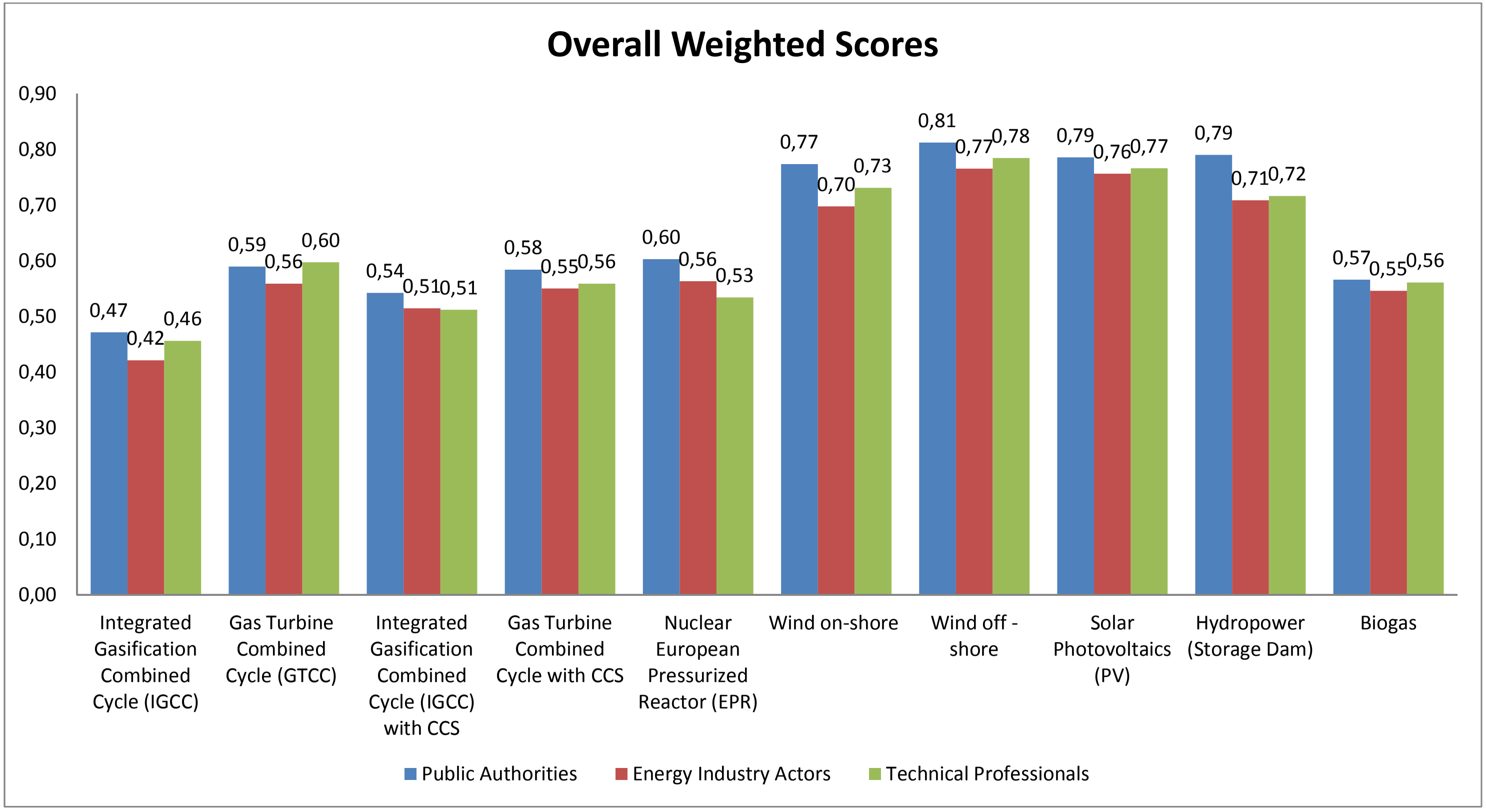

Figure 17.The overall weighted scores of low-carbon energy technologies per stakeholder group.

It could be observed (figure 17) that among the three stakeholder groups, wind off-shore is the highest ranked low-carbon energy technology. Solar PV is the 2nd ranked technology for energy industry actors and technical professionals, while public authorities favored hydropower. Solar PV is the 3rd ranked technology among public authorities, while energy industry actors favored hydropower. Meanwhile, wind on-shore is the 3rd ranked technology among technical professionals, while public authorities and energy industry actors ranked it 4th. It could be observed from the rankings among the three local stakeholder groups that renewable energy technologies outrank other technologies, such as fossil-fuel based ones (e.g. IGCC and GTCC) and nuclear technology (EPR).

However, if the assessment will consider the levelised costs alone (see figure 18), this will result to a different ranking (IEA, 2010). EPR, which has the lowest levelised costs, will be the top ranked low-carbon energy technology with 69 USD/MWh whereas biomass CHP (245 USD/MWh) and solar PVs (382 USD/MWh) would ranked last as the most expensive technologies.

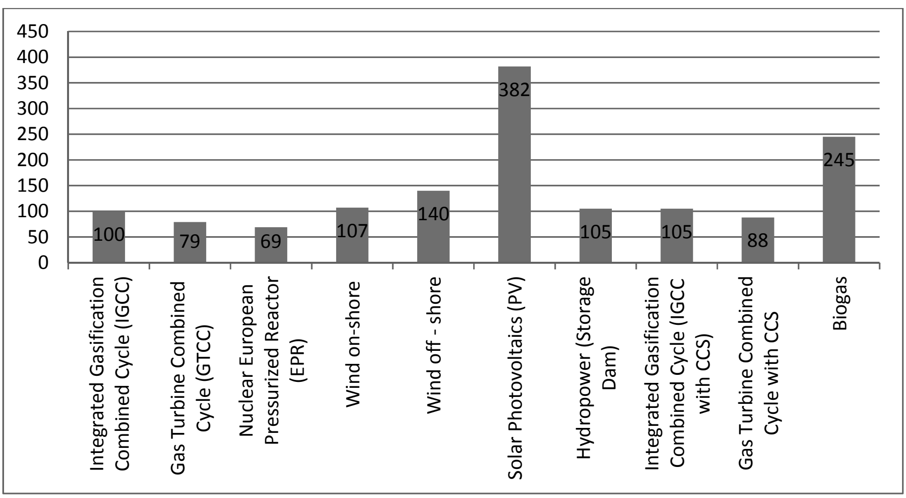

Figure 18. Levelised costs of low-carbon energy technologies (IEA, 2010)

5.5 Discussion

Validation of criteria

One of the main innovative aspects and contributions of the study is the integration of sustainability and resilience indicators in an overall assessment framework for low carbon energy technologies which, to the best of our knowledge, is lacking in the literature. There are numerous studies looking at the sustainability aspects of energy technologies and few that have been conducted the last years focusing explicitly on resilience aspects (O'Brien and Hope, 2010, Molyneaux et al., 2012). It is deemed necessary to develop approaches and frameworks that consider both sustainable development sub-systems and technology development in order to enhance sustainable technology development (Musango and Brent, 2011). Different low carbon energy technologies, particularly in the electricity sector, are versatile with multiple interrelationships with environmental, social and economic dimensions of sustainability, while at the same time are vulnerable to external shocks and disturbances such as energy prices fluctuation, concentration of energy supply, future climate change threats and other natural disasters, reliance on non - renewable resources (O'Brien and Hope, 2010, Molyneaux et al., 2012, McLellan et al., 2012). This integrated assessment framework of indicators is the first attempt to bring together sustainability and resilience aspects providing an analytical tool to policy makers on identifying the potential sustainability impacts and vulnerabilities of different energy technologies.

The developed integrated assessment framework of indicators has been applied on the evaluation of selected current and future low carbon energy technologies in Europe at the local level by incorporating stakeholders' preferences in the assessment process in order to enhance legitimacy, participation and learning. The framework applied with the support of the Covenant CapaCITY, a project co-funded by the Intelligent Energy Europe programme, and led by the Local Governments for Sustainability ICLEI. The majority of respondents approved the integrated framework of criteria and indicators and its application for evaluating low carbon energy technologies (Grafakos et al., 2015a).

The developed integrated MCA framework which combines both sustainability and resilience aspects of energy technologies, strengthens local decision making by a) providing information both on sustainability impacts of energy technologies such as environmental and socio-economic impacts but also on resilience and vulnerability aspects of the technologies, b) providing a validated and robust framework that can capture potential impacts, risks and disturbances of the energy systems, c) allowing stakeholders' active participation, while at the same time d) facilitating a flexible and adaptive decision making process that can be easily adjusted to different local circumstances.

During this study and the extensive literature review that was conducted, it was found that often some resilience aspects of energy systems have been considered implicitly in sustainability assessment frameworks (e.g. energy security of supply, fuel price fluctuation) (see also table 3). However other types of resilience issues (e.g. potential climate change impacts) were completely neglected. Furthermore, interestingly it was found that specific aspects could be seen either from a sustainability or resilience perspective. For instance the indicator of "GHG emissions" could be considered as an environmental impact through the contribution to GHG emissions and climate change problem but also as a resilience aspect, reflecting the financial risks of carbon intensive technologies, in case of a price is tagged on carbon either through carbon tax or a higher price of carbon emission allowance (Molyneaux et al., 2012). In that case, both perspectives should be considered explicitly by giving emphasis and possibly additional weight to these criteria.

Moreover, this framework can be adjusted and used either by local or national policy makers for the integrated assessment of specific energy technologies. The application of the assessment framework aims to enhance guidance and evidence based support of local and national decision makers when planning and developing energy technologies and policies towards a low carbon and resilient development pathways. By this chapter I hope to further trigger discussion on the importance of explicitly integrating sustainability and resilience aspects and indicators in the assessment of low carbon energy options, technologies and policies.

Another novel aspect of the study is the modification of the "3S" validation process in the context of low carbon energy planning and assessment. The modified "3S" validation process along with the involvement of a wide range of experts and stakeholders made possible the development of a refined set of evaluation criteria and indicators.

Although there were few suggestions for the adjustment or removal of criteria, the validation process proved important as it revealed several misinterpretations of criteria descriptions that were addressed at this stage prior to weighting. The descriptions of the criteria were improved and better reflected stakeholders' suggestions and minimized possible misinterpretations of criteria during the weighting phase that might have affected the weighting results and final ranking of technologies. In addition, we could also observe that the misinterpretations were mainly expressed from few individual respondents and none from specific type of stakeholders that could have suggested removal of specific criteria. Furthermore, the validation process allowed stakeholders to express their suggestions for removal or adjustment of certain criteria. This indicated which criteria could be potentially weighted with a low level of relative importance during the weighting process.

Looking both at the results of the stakeholders' validation survey and criteria weights, specifically the correlation between the percentage of removal and the ranking/weighting of criteria, aesthetic/functional impact seemed to be the less preferred – and least important – criterion. Based on the two aforementioned attributes, aesthetic/function impact was suggested for removal by 10% of the respondents (as well as for adjustment by another 10%) and has ranked 20th in the final ranking. It also ranked last (22nd) in the initial ranking of respondents. In other words, the criterion of aesthetic/functional impact was suggested for removal and also received a very low weight and ranking evaluation (Grafakos et al., 2015a).

Most of the times researchers either develop indicators intuitively or consider only experts' judgments during selection of indicators, neglecting stakeholders' perspectives (Cloquell – Ballester et al., 2006; Hak et al., 2012). The proposed approach integrates stakeholders' views in the very initial stage of the assessment process, namely during the selection and validation of indicators. This could effectively reduce the risk of conflict between energy project designers and relevant stakeholders (Cloquell – Ballester et al., 2006).

The scrutiny of the validation process and inclusion of stakeholders a) enhanced the relevance of criteria and indicators, b) contributed to improved and clearly described set of criteria and indicators, c) improved the robustness of the assessment framework by increasing the acceptance of selected criteria, and d) provided a first indication of the potentially least important criteria. As Cloquell – Ballester et al. (2006) argue, these validation stages are complementary so that the indicators' credibility and usability increases as we complete and move from one validation stage to the next. Furthermore, the proposed framework suggests an application of a participatory Multiple Criteria Assessment framework for energy technologies aiming at the active participation of different stakeholders during its actual application, that would lead to a an adaptive decision making process.

Criteria weighting

As the initial ranking provided the basis for the consistency check, the results of the pair-wise comparisons were checked in order to assure their consistency and reliability. By applying different ranking and weighting techniques, an opportunity for a consistency check was established to enhance the reliability of stakeholders' preferences. Most of the times and as has been pointed out by Bell et al. (2003) this is commonly neglected. By using different methods we were able to detect inconsistencies by comparing the different ranking results. As Bell et al. (2003) concluded such inconsistencies are an opportunity to reflect on results from different framings of the issue at hand. By using a single method such kind of opportunity is lost (Bell et al. 2003).

It is important to note that 31% of the respondents achieved low consistencies between their initial and final rankings. As it has stated also by Borcherding et al. (1991), Grafakos et al. (2010a) and Riabacke et al. (2012) the study conveyed that the difference in consistency between weighting methods could be related to the large number of criteria for comparison, particularly common in the case of pairwise comparisons. This research study involved 22 pairs of criteria for comparison which resulted on high cognitive burden to the respondents. Hence, with the large number of pairs for comparison, inconsistencies inevitably arose. This was expected as during prescriptive decision analysis processes, according to Riabacke et al. (2012), perceptions change and evolve, and the representation of these perceptions are not static. The respondents were then asked to modify their preferences should their weighting scores did not reach the consistency threshold value. However, having to repeat the pair-wise comparisons could have been a challenge for some of the respondents since this would have required additional time.

Furthermore it could be observed that due to the cognitive demands as well as time constraints, the respondents were more comfortable with providing the ranking order directly to a list of criteria than selecting the extent to which a criterion is relatively more important for each pair-wise comparison. As Riabacke et al. (2012) suggests for the elicitation of weights, ranking methods using surrogate weights in the interpretational proved to be less cognitively demanding.

In Grafakos, et al. (2010a), a sample of individual stakeholders and experts in the climate and energy policy field has expressed satisfaction as well as approval for combining ranking and pairwise comparisons as approaches in weighting energy and climate criteria. The study showed that the initial ranking facilitated a gradual approach to the evaluation problem. The pair-wise comparisons, on the other hand, enabled a more accurate expression of the respondents' preferences. The number of the criteria (14) in that study was significantly less than the number of criteria (22) that were selected to be assessed in this study.

Cognitive limit is one of the challenges in stakeholders' preference elicitation. In a decision problem which involves a small set of alternatives and criteria, most people can make their selection intuitively. However, with a large set of alternatives and criteria, relying on intuition and/or experience seems inadequate and thus needs further support. The conclusions are in accordance with Makowski et al. (2009) about the additional challenge of the mix of qualitative and quantitative indicators as well as of preferences that are often times irregular, non-sequential, and with threshold values. The computerized interaction was considered important in helping stakeholders to construct their preferences. This provided stakeholders with support in analyzing their desired objectives in relation to the outcomes of the elicitation process. As Riabacke et al., (2012) stated, practical techniques for elicitation are to a great extent a matter of balancing the quality of elicitation results with the time available and cognitive burden on the respondents for eliciting all the required information.

5.2 Stakeholders' preferences on evaluation criteria

Local stakeholders, in general, expressed high preferences for CO_2eq emissions, levelised costs, ecosystem damages, employment generation, resilience to climate change, fuel use, and waste disposal which show implied responsibility towards local benefits and negative externalities. Mortality and morbidity, accident fatalities as well as radioactive waste also achieved high preferences from the respondents which show how local stakeholders value the welfare of the public, including workers, during project installation and operation. The potential impacts of energy technologies on human health and safety are considered a priority. Understandably, human health and safety are primary considerations.

Local stakeholders and society in general, are still concerned about radioactive waste because of its potential to cause – whether likely or unlikely –catastrophic accidents or be used in terrorist attacks. In the aftermath of the Fukushima nuclear disaster in Japan in 2011, radioactive waste and nuclear safety remain controversial topics. Aesthetic/functional impact did not achieve high preference among the local stakeholders. Although debate is inevitable regarding the aesthetics of current infrastructure of specific renewable energy technologies (e.g. wind and solar), mechanisms are available for the deployment of these technologies in unobtrusive ways (Kaldellis et al. 2013b).

Public authorities prioritize public health protection and safety – and in general, certain social criteria - as proven by their high preferences for mortality and morbidity and accident fatalities. Public authorities also give significant priority to ecosystem damages, CO_2eq emissions as well as levelised costs which reflect their concern for local environmental protection as well as economic outlays.

In spite of sharing similar preferences with public authorities and energy industry experts, technical professionals have a unique high preference for fuel use. This research study also concludes that technical professionals, when compared to the weights provided by other stakeholder groups, have higher preferences for certain energy and technological criteria. On the other hand, public authorities provide least priority to certain energy and technological criteria, while technical professionals have provided least preferences for certain social criteria. However the sample of the stakeholders group does not allow for generalization of the results and indicates the need of applying this methodology in a larger sample of different local stakeholder groups along Europe.

Ranking of low-carbon energy technologies

This research concludes that wind off-shore, solar PV, hydropower, windon-shore, and GTCC are the low-carbon energy technologies that rank highest while considering the preferences of local stakeholders. On the other hand, IGCC with CCS and IGCC were the least significant low-carbon energy technologies among all three stakeholder groups.

The results of the NEEDS project (Schenler et al. 2009) also showed high preferences for renewables, such as solar, wind, and biomass technologies. Centralized gas options (e.g. combined cycle and combined heat and power CHP) as well as nuclear technologies were the mid-performing group of technologies, while coal and lignite technologies were considered the worst performers. In Turkey, Topcu and Ulengin (2004), in their ranking of alternative energy sources, wind power proved to be the most preferred option. Wind was also the highest ranked alternative, followed by biomass and PV, in an MCA by Mourmouris and Potolias (2013) in Greece.

However, considering levelised costs alone, EPR exhibited the lowest costs, followed by fossil fuel-based technologies (GTCC, GTCC with CCS, IGCC, and IGCC with CCS). Renewable energy technologies, such as hydropower, wind, and solar, have higher levelised costs. However, the results of the study also show how certain technologies (e.g. renewables) that rank relatively low in a cost-based assessment are otherwise most preferred and highly ranked if multiple criteria and aspects are considered in the assessment. One can surmise that economic costs certainly play a role in decision making, regardless of stakeholders' propensity for choosing other sustainability criteria. As demonstrated in the results of the study, costs matter, but only up to a certain extent. Other sustainability criteria, such as social and environmental ones, should also drive the assessment process.

Implications for low carbon energy policy

As for low carbon energy policy, it can be concluded that based on the overall preferences of stakeholders, there should be focus on policies enabling the local deployment of renewable energy technologies that reflect the most preferred local priorities, such as CO_2 emissions reductions, levelised costs, ecosystem damages, and employment generation.

Moreover, key differences regarding local stakeholder preferences could be highlighted during local low carbon energy planning. Within the decision making context, relevant stakeholders and decision makers would have informed opinions about the value judgments of local stakeholders which need to be taken into account in the process of developing low carbon energy policies.

Also, knowledge about key issues of the problem at hand could be a topic for knowledge sharing, awareness raising and information dissemination, among other policies.

Conclusions of the chapter

The constructive weighting methodology applied in this study allows for a thorough process for eliciting weighting preferences. The methodology subjects survey respondents to be consistent in their preferences. Moreover, the use of different techniques enhances the reliability of the results as respondents had the opportunity to check and revise their preferences. MCA practitioners often apply a ‘one-size-fits-all’ approach even though different methods work better for some people and situations than for others (Bell et al. 2003). Particularly on the low consistencies between the preferences, this could be attributed to the large number of criteria involved and the cognitive burden it imposes to respondents. However, the demonstration of the constructive weighting methodology shows great potential for better decision making as well as for further enhancement in its application.

Overall, the research study was able to map, albeit in a limited manner, the preferences of local energy stakeholders. Through these elicited preferences, the low-carbon energy technologies that best meet the evaluation criteria prioritized by local energy stakeholders were assessed. This research study presents, on one hand, how local energy stakeholders prioritize certain economic, environmental, social, energy and technological criteria. On the other hand, this research shows which low-carbon technologies rank high taking into account local energy stakeholders priorities.

In this study, a constructive weighting methodology was applied to elicit European local stakeholders’ preferences on evaluation criteria of future low-carbon energy technologies. However, this research study merited a small number of respondents. As such, there is a need for further application of this weighting methodology to a large number of local stakeholders at the European level. This research study mapped three broad categories, namely public authorities, energy industry actors, and technical professionals. It would be substantive to map the preferences of distinct local stakeholder groups that apply within a larger local energy context in Europe.

The constructive weighting methodology for this study can also be applied in a group decision context wherein local stakeholders and decision makers meet face-to-face e.g. workshops, consultation meetings. Furthermore, this weighting methodology could be carried out through an online process of interaction e.g. webinar. Furthermore, different weighting methods could be tested to observe and compare any differences and similarities in the results. Also, by applying different weighting methods, the researchers can also examine the level of consistency of stakeholder preferences and how this is affected by the type of weighting methodology and framing.

Lastly, in situations wherein decision makers have to engage on the development of low carbon energy strategies through this method, local stakeholders' preferences can be mapped out. This is crucial for the identification of potential conflicts and resolution of actual ones in order to reach consensus on the development of local low carbon energy strategies.

Chapter 6: Integrated MCDA assessment methodology application at the European Local Governments' context

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6.1 Introduction

The dominant policy paradigm for global climate change in the last decade has, to a large extent, adopted a top-down approach. State, regional, and local governments (LGs) develop and carry out climate change policies, programmes, and actions developed through dialogues at the international, supra-national, and national policy levels. There is considerable evidence, however, that many LGs are agenda setters, front runners, and pioneering innovators in terms of climate change initiatives (Reckien et al., 2014). In the long run, LGs, which can establish and implement climate change mitigation action plans in their own jurisdictions, will play substantial roles to reverse the rise of global greenhouse gas (GHG) emissions (Hoppe et al., 2014; Hernandez – Escobedo, et al., 2015).

The concentration of GHG emissions in the atmosphere should be limited to 450 ppm to remain within the safe threshold of global average temperature of no more than 2 degrees centigrade (IPCC, 2011). The global climate change policy architecture, which was built under this assumption, led to binding agreements wherein the main emitters commit to limit their GHG emissions by certain levels according to their historic responsibilities and capacities to mitigate.

The European Union (EU) climate change policy, with its sustainability targets, has been considered as the most ambitious among the main emitters so far. The so called "20-20-20" targets for 2020 aim to reduce GHG emissions, increase renewable energy production, and increase energy efficiency by 20% in 2020. The EU 2030 Strategy aims to achieve even more ambitious climate change mitigation targets, such as 40% GHG emissions reduction compared to 1990 levels (EC, 2015). As outlined in its roadmap to a low-carbon economy, the European Union aims to reduce GHG emissions by 80%–95% by the year 2050 compared with 1990 levels (EC, 2015).

Important policy and investment decisions should be made regarding the current and future energy technologies that will be deployed in the coming years and decades (IEA,2014). At the local level, cities and municipalities have come up with their own energy initiatives and low-

carbon strategies (Hoppe, et al., 2015).
The Covenant of Mayors (CoM), a network of local and regional authorities committed to the implementation of sustainable energy policies, has been established and more than 4000 signatories have pledged their commitments and outlined their specific actions through their Sustainable Energy Action Plans (Covenant of Mayors, 2013).

Centralized power supply is the conventional way of delivering electricity services. Large-scale power plants fueled by coal, natural gas, or nuclear technology are constructed to provide high voltages into the electricity grid (IEA, 2009). With the advancement of renewable energy technologies, discussions on whether cities can become more independent from distant energy sources or whether they could produce their own energy have arisen (O'brien et al., 2010) .

Low-carbon energy technologies, which range from solar photovoltaics to carbon capture and storage, vary in technological maturity, industry status, and market potential. Each one has its corresponding advantages and disadvantages as well as constraining and facilitating factors in development and implementation (Castellano et al., 2015). Also, a wide range of technologies are in the process of research, development, and demonstration.

Prior to implementation, there are several techno-economic approaches, which provide quantitative cost results, for assessing low-carbon energy technologies and policies (Gross et al., 2007; Blesl, et al., 2010; IEA, 2010; Oikonomou et al., 2011b). A number of studies and projects which investigate the externalities of energy, attempt to quantify emissions of electricity technologies, and monetize their respective external costs have emerged. In these undertakings, several methods were developed and systematic efforts were made to assess the environmental impacts of electricity production expressed in monetary units (EC, 2005; Hirschberg et al., 2007).

There is also an emerging load of studies focusing on the assessment of abatement potentials combined with estimated costs of certain electricity technologies (Ordorica-Garcia et al., 2007; Amann et al., 2011). Although techno-economic studies provide useful information on abatement costs of mitigation technologies, they do not consider other important factors relevant to policy implementation, such as socio-political and public acceptance issues, security of energy supply, stakeholders' preferences, and local communities' priorities. Despite the conduct of detailed research towards the evaluation and assessment of climate abatement technologies, there are still major gaps in reconciling and quantifying other local co-benefits or co-impacts (Urge-Vorsatz, 2014).

An important challenge for climate policy would be the alignment and coordination of climate policies and priorities at the local, national and international levels (Lefvevre, 2012). It is important to consider local communities' preferences and perceptions when designing climate and energy policies. The acceptance or rejection of these policies or actions, to a large extent, will depend on the consideration of local priorities and their contribution to local sustainability and resilience (Del Rio and Buirguillo, 2008). It has been found that there is a clear contradiction between the EU and national renewable electricity policies and the responses at the local level due to context-specific conditions and interests that pose barriers to the implementation of climate policies (Monni and Raes, 2008).

As energy policy and planning aims at achieving different sustainability objectives, it becomes necessary to integrate economic, environmental and social dimensions in the process (Grafakos et al., 2011; Doukas et al., 2014). Furthermore, many authors underline the importance of considering energy resilience aspects as a component of a sustainable energy future (Molynaux et al., 2012; Grafakos and Flamos, 2015). An ideal future energy system should be able to reduce the negative impacts on the environment and natural resources, create opportunities for economic and social development, enhance its capacity to absorb external disruptions (IEA, 2014), consider a long-term perspective (Neves et al., 2015), increase participation (Stagl, 2006), and contribute to greater sustainability.

In the above-mentioned framework, it is considered essential to be able to identify and assess LGs' priorities within a sustainable energy planning context. Therefore, it is necessary to involve the LGs and other relevant actors and to consider their preferences in the energy planning process (Burton and Hubacek, 2007). In this respect, the legitimacy of the process is significantly improved and better chances of actual implementation can be achieved (Keeney, 1992).

Various studies have demonstrated that the multi-attribute model, one of the main multiple criteria decision analysis practices, provides a normative and practical method in supporting people to understand and construct their preferences among alternatives (Willis et al. 2004; Willis et al., 2012). Differences in respondents' priorities could be explained by the relative importance (weight) they assign on each impact criterion. The current study developed and applied a methodology for eliciting criteria weights that reflect LGs' sustainability priorities regarding the deployment of future low-carbon energy technologies as has been initially explained in chapter 5.

Although different authors have emphasized the importance of considering LGs' views (Burton and Hubacek, 2007; Kowalski et al. 2009) no empirical evidence exists in the literature regarding any measurement of European LGs' priorities and preferences. In this context, the main objective of this chapter is to assess the European LGs' priorities that would provide important insights for energy policy with regard to climate change mitigation in the electricity sector. The results of this study would provide insights on LGs' priorities that should be considered during the development, planning and implementation of climate mitigation and energy policy. The study aims at addressing the following questions:

- Which are the main priorities of European LGs regarding low-carbon energy technologies assessment and planning?
- Which are the most important sustainability criteria (priorities) of European LGs according to population size and geographical region?
- What is the relationship between different LGs priorities but also between LGs priorities and their GDP *per capita*?

The chapter is structured as follows: Section 2 discusses the context of assessment that consists of the energy technologies under investigation and the selected evaluation criteria (priorities). Section 3 focuses on the methodological tools that were employed in the study to collect and analyse empirical data. Section 4 presents the results of the study regarding the LGs' priorities and energy options that meet these priorities. Furthermore, Section 4 presents how the priorities of LGs differ between various evaluation criteria categories. Section 5 discusses the results' implications for climate and energy policy and future research directions as well.

6.2 Defining the Assessment Problem

For this study, the ten (10) reference electricity generation technologies (as introduced in tables 5 and 6) under investigation for the year 2030 in Europe are as follows: integrated gasification combined cycle (IGCC) coal, IGCC coal with carbon capture and storage (CCS), gas turbine combined cycle (GTCC), GTCC with CCS, Nuclear European Pressure Water Reactor (EPR), wind onshore, wind offshore, solar photovoltaics (PVs), hydropower, and biogas combined heat and power (CHP). These energy technologies under investigation were selected from a review of current and future energy technologies that could reduce carbon emissions in Europe (Grafakos et al., 2015a).

The assessment of different reference electricity technologies that would be employed by the year 2030 in Europe requires the consideration of different aspects, impacts, costs and benefits that the implementation of technologies would cause to multiple actors. These impacts could range from global, such as GHG emissions, to local, such as health impacts due to air pollution.

Multiple actors and stakeholders that might be affected by the decision of certain energy technologies should be involved in the decision making process and their preferences and priorities should be considered and incorporated for the evaluation of energy technologies. This type of complex, multi-factor, multi-agent assessment problem is congruous with a multiple criteria decision analysis process.

Multiple Criteria Analysis (MCA), particularly using multi-attribute models, has been widely applied in environmental, energy, and risk decision making. However, even though it is recognized as a valid and sound decision making analysis approach (Scrieuciu et al., 2014), its application in the field of climate change policy assessment remains relatively limited albeit its increasing use (Kowalski et al., 2009). Recently, other authors provided a more detailed review of MCA applications in climate change policy (Grafakos, et al., 2010a; Scrieusiu et al., 2014).

Two main features of MCA makes this approach adequate for analyzing LGs' priorities regarding sustainability objectives of future energy systems. Firstly, MCA allows the simultaneous consideration of multiple criteria (attributes) that are relevant to a set of alternative options—or energy options in our case. The multiple criteria could span from broad sustainability objectives to local and national priorities related to energy planning. Secondly, MCA facilitates the active engagement of relevant stakeholders through the process of criteria selection and weighting. It is particularly the systematic and structured weighting process that allows the elicitation of respondents' priorities and preferences. Combined use of different methods and provision of technical support during the entire process result into minimization of potential biases, enhance appropriate use of the MCA methods, and facilitate confident expression of respondents' preferences (Belton and Stewart, 2002; Bell et al., 2003). It is this specific process of criteria weights elicitation of LGs that our study focuses on.

As explained in chapter 3 the application of the methodology was based on the five (5) stages for selecting and validating the evaluation criteria:

- Literature review
- Screening of initially selected indicators
- Self—validation (desk study and internal peer review)
- Scientific validation (survey of external experts' views)
- Stakeholders' validation (survey of local stakeholders' views)

Table 16. Final set of selected and validated evaluation criteria and indicators.

Criteria Categories	Indicators	Description
Economic	ECO1: Levelized costs (including capital, operations and maintenance, fuel costs)	Levelized costs of energy (LCOE): investment costs, operational and maintenance costs, capacity factor, efficiency, material use.
	ECO2: (Local) employment generation	The extent to which the application of the technology can create jobs at the investment, operation and maintenance stage. Furthermore, the criterion of employment reflects partly the extent of the impact that the technology has to the local economic development by providing jobs and generating income.
Environmental	ENV1: CO_2eq emissions	The indicator reflects the potential impacts of global climate change caused by emissions of GHGs for the production of 1 kwh.
	ENV2: Noise pollution	This indicator is case sensitive and could have been measured as a factor of the noise generation by the energy technology estimated in dB multiplied by the number of people affected by the noise. However, since we are investigating different energy technologies and systems at a European scale we cannot measure precisely this indicator and therefore we will use an ordinal relevant scale to measure the perceived noise.
	ENV3: (Radioactive) waste	Amount of (radioactive) waste generated by the plant divided by energy produced.
	ENV4: Waste disposal (infrastructure)	Waste generation during the life cycle of the fuel and technology or availability of waste disposal infrastructure.
	ENV5: Ecosystem damages	This criterion quantifies the impacts of flora and fauna due to acidification and eutrophication caused by pollution from the

Criteria Categories	Indicators	Description
		production of 1 kWh electricity by the energy system and technology.
	ENV6: Land use requirement	The land required by each power plant and technology to be installed.
	ENV7: Fuel use	Amount of fuel use per kWh of final electricity consumption.
Social	SOC1: Level of public resistance/opposition	Energy system induced conflicts that may endanger the cohesion of society (e.g., nuclear, wind, CCS). Opposition might occur due to the perceptions of people regarding the catastrophic potential or other environmental impacts (aesthetic, odor, noise) of the energy technology/system. This indicator also integrates the aspect of participatory requirement for the application of the technology. The higher the public opposition, the higher the participatory requirement is.
	SOC2: Aesthetic/functional impact	Part of population that perceives a functional or aesthetic impairment of the landscape area caused by the energy system. The aesthetic impairment is judged subjectively and therefore this criterion fits in the social category rather than the environmental one. In addition this is also a very location specific indicator and therefore an average metric will be determined measured in relative ordinal scale.

Table 16. *Cont.*

Criteria Categories	Indicators	Description
Social	SOC3: Mortality and morbidity	Mortality and morbidity due to air pollution caused by normal operation of the technology. This indicator is considered as an impact and composite indicator since it integrates all human health impacts caused from air pollution emissions as NOx, SO_2, and PM.
	SOC4: Accidents and fatalities	Loss of lives of workers and public during installation and operation. Surrogate for risk aversion. This criterion partly integrates the catastrophic potential of the energy system/technology.
Energy system resilience	ENE1: Energy cost stability/sensitivity to fuel	The sensitivity of technology costs of electricity generation to energy and fuels prices fluctuations. The fraction of fuel cost to

	price fluctuation	the overall electricity generation cost.
	ENE2: Stability of energy generation	Stability of output of electric power generated depending on the technology used. This reflects whether the energy supply is being interrupted. The presence of these interruptions impacts the electricity network stability. This criterion reflects whether the energy supply faces any interruptions due to the type of energy technology.
	ENE3: Peak load response	Technology specific ability to respond swiftly to large variation of demand in time/% representing the possibility to satisfy the required load.
	ENE4: Market concentration on supply	The market concentration on the supply of primary sources of energy that could lead to disruption due to economic or political reasons.
	ENE5: Resilience to climate change	The degree of resilience of the energy technology to the future climactic changes and extreme weather events.
Technological/ market	TEC1: Technological maturity	The extent to which the technology is technically mature. The criterion refers to the level of technology's technological development and furthermore the spread of the technology at the market.
	TEC2: Market size (domestic)	Demand for final products (of energy technologies) and potential market size domestically. The potential market size plays an important role to establish industrial competitiveness and stimulate economic growth.
	TEC3: Market size (potential export)	Demand for final products (of energy technologies) and potential market size internationally.
	TEC4: Innovative ability	Flexibility and potential of the technology to integrate technological innovations.

6.3 Methods

6. 3.1. Weighting Preferences Elicitation Approach

A hybrid constructive weighting methodology, which combined different ranking and weighting methods, was employed to elicit and analyze stakeholders' preferences. The different elements of the hybrid weighting methodology have been developed and explained in section 3.3 of the PhD thesis and relevant publications (Grafakos et al., 2010a; 2010b; 2015a) and illustrated in figure 10. The current hybrid methodology strengthens the flexibility of the preferences elicitation approach by applying the appropriate method according to the different context, while at the same time utilizes a systematic iterative process.

6.3.2. Data Collection Methods

A computer-aided excel tool was developed to enable and guide the LGs to provide their preferences for the evaluation criteria. The respondents were able to see automatically-generated graphs of the weighting results and were requested to indicate the level of their actual preferences' representation by the results. Different data collection methods were utilized to obtain empirical data from LGs:

- *Survey*: LGs that were participating in the Covenant CapaCITY project were included in the list of potential participants. In addition, through an extensive review of SEAP-related databases, such as the CoM of the European Commission and the Carbonn of ICLEI, major European cities were identified and their LGs contacted either by email or phone. LG representatives were offered the option to fill in the excel tool with guidance and support from the research team. Twenty (20) LGs responded out of 100 that were contacted (20% response rate) and one of these was a representative of a LGs' association.
- *Face to face workshop*: A face to face workshop was conducted within the framework of the Covenant CapaCITY project, wherein LG representatives from different cities were invited to participate. In total, 18 participants filled out the excel tool under close guidance by the research analysts. Seven (7) out of the 18 participants were LG representatives.

- *Webinar*: Furthermore, as part of the Covenant CapaCITY project activities, a two-stage webinar was organized for European energy local stakeholders and LGs (see Annex 6) to participate in the survey and to discuss the results interactively. In total, twenty five (25) participants were involved in the interactive webinar, wherein five (5) were LG representatives.

The study was participated in by a total of 32 respondents. Thirty one (31) respondents were representatives of European LGs, while one (1) respondent was a representative of an LG association. The study was supported by the Intelligent Energy Europe (IEE) project, Covenant CapaCITY, and the ICLEI—Local Governments for Sustainability, European Secretariat (ICLEI Europe).

For the analysis, the European LGs were categorized according to their population size (large, medium-sized), geographical region (Western, Eastern, Northern, and Southern Europe), and GDP *per capita*. Secondary data on the GDP *per capita* and population size were obtained from the Eurostat (EU-28) and the World Bank (non EU countries). Due to the fact that data on GDP *per capita* was not available at the local level, we obtained and used data for the same indicator at the regional level.

6.4 Results

6.4.1. Overall Priorities

For the analysis of this study, we considered the 31 representatives of European LGs. The LGs which participated in the survey consisted of 16 large and 15 medium-sized cities. Furthermore, thirteen (13) LGs were from Western/North Europe (France, Austria, Finland, the Netherlands, Switzerland, United Kingdom, Belgium and Denmark), eleven (11) from South Europe (Italy, Spain, and Greece), and seven (7) from Eastern Europe (Romania, Poland, Turkey, Serbia, Georgia, Bosnia and Herzegovina, and Croatia) (Figure 2).

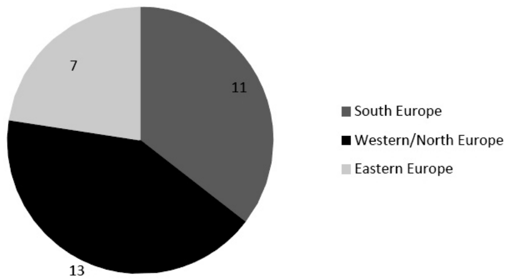


Figure 19. Geographical distribution of European LGs.

The overall list of LGs that participated in the survey along with their population size, geographical region, and level of GDP (in euros) *per capita* can be found at Annex 7. All the participating cities had developed SEAPs and submitted them either on the CoM of the European Commission or the Carbonn online Registry of ICLEI. We recognise the limitations of the relatively small sample size which does not allow representation of all European LGs and therefore any attempt for generalization of the results should be carefully considered.

According to the LGs' responses, the most important criterion, based on the average weights, is the criterion of "CO_2 emissions" (ENV1) (Figure 20). "CO_2 emissions" is followed by "mortality and morbidity" (SOC3), "ecosystem damages" (ENV5), "resilience to climate change" (ENE5), "employment generation" (EC2), "accident fatalities" (SOC4), "levelised costs" (EC1), and "radioactive waste" (ENV3) (see also Table 17 and Figure 20) . Figure 20 presents the boxplot of the average and median values of criteria weights along with the distribution of weights around the median value as was estimated using the R studio statistical software.

Table 17. Final average weights of criteria, final ranking and standard deviation.

Criteria	Average Weight	Rank	StDev
ENV1: CO_2eq emissions	0.073	1	0.032
SOC3:Mortality and morbidity	0.063	2	0.034
ENV5: Ecosystem damages	0.061	3	0.025
ENE5: Resilience to climate change	0.059	4	0.034

EC2: Employment generation	0.058	5	0.018
SOC4: Accident fatalities	0.054	6	0.023
EC1: Levelised costs	0.054	7	0.027
ENV3: Radioactive waste	0.049	8	0.034
SOC1:Level of public resistance/opposition	0.048	9	0.018
ENV4:Waste disposal (infrastructure)	0.047	10	0.015
ENV7: Fuel use	0.046	11	0.020
ENE1: Energy cost sensitivity to fuel price fluctuation	0.044	12	0.014
ENV6: Land use requirement	0.041	13	0.018
ENE3: Peak load response	0.038	14	0.015
ENE2:Stability of energy generation	0.036	15	0.012
TEC4: Innovative ability	0.036	16	0.015
TEC1: Technological maturity	0.035	17	0.013
TEC2: Market size (domestic)	0.035	18	0.014
ENV2: Noise	0.034	19	0.017
SOC2: Aesthetic/functional impact	0.032	20	0.017
ENE4: Market concentration on supply	0.031	21	0.013
TEC3: Market size (potential export)	0.028	22	0.013

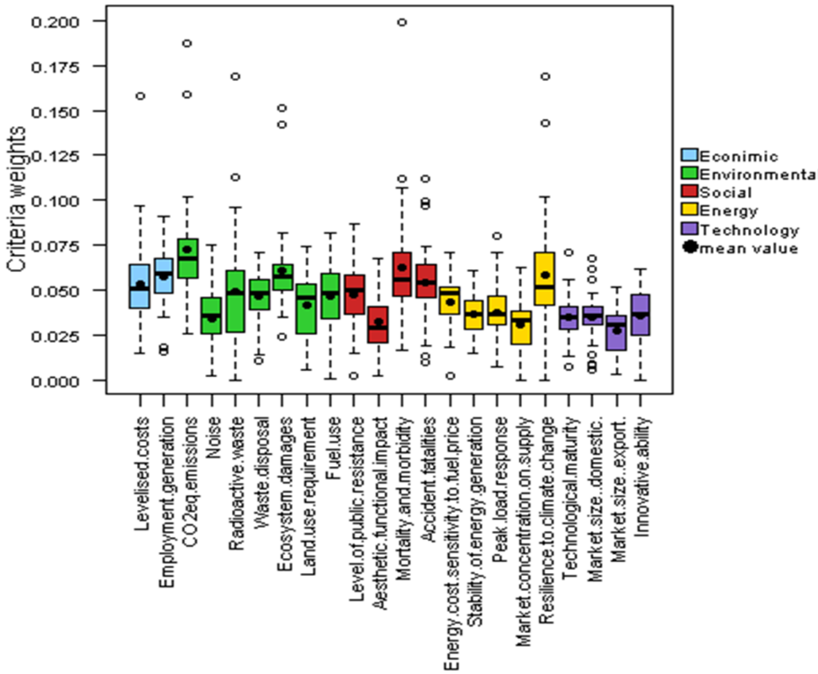


Figure 20. Boxplot with mean values of criteria weights and outliers.

Variability in the weights is measured by the interquartile range (IQR) which is illustrated by the boxplot. The IQR is equal to Q_3–Q_1, the difference between the 75th percentile (Q3) and the 25th percentile (Q1), the distance covering the middle 50% of the weighting values. The larger the IQR

(the boxplot), the higher the distribution of the weighting values is, which further means that there is high disagreement between the LGs on the weights assigned on the particular criterion. The median is shown by the line that cuts through the box. The average is shown by the black bullet in the box.

The boxplot also shows whether the elicited weights are symmetric (roughly the same on each side when cut down the middle) or skewed. A symmetric distribution of weights shows the median roughly in the middle of the box. A smaller section of the boxplot indicates the weights are more concentrated, whereas a wider section indicates that the weights in that section are more spread out.

We can observe that from the top one third of the highest weighted criteria, the criterion of "resilience to climate change" has the largest boxplot which means the highest distribution of weights and therefore the greatest divergence between the LGs' preferences. There are also two outliers or extreme values that pull the average weight of this criterion at a higher level. This observation is also confirmed by the high standard deviation that is estimated for this criterion (see Table 17).

Interestingly, the weighting values of the 3rd highest weighted criterion, "ecosystem damages" (ENV5), result to a relatively small boxplot indicating a concentration of weights around the median and high degree of agreement between the different LGs. A couple of outliers that have been observed for this criterion tend to increase the standard deviation (0.025).

The lowest standard deviation (0.018)—highest convergence—of the LGs weighting preferences, of the top one third highest weighted criteria, was observed for "employment generation" (EC2), whereas the highest standard deviation (0.034)—lowest convergence–was observed for "mortality and morbidity" (SOC3) and "resilience to climate change" (ENE5). We can observe outliers, extreme weighting values, in both criteria, which to a large extent resulted to the high standard deviation (Figure 20).

The top one-third most important criteria as weighted by the LGs included three (3) environmental, two (2) economic, two (2) social, and one (1) energy criteria. None of the criteria from the technological category were considered of high importance by the LG representatives.

6.4.2. Priorities of Different LG Groups

Comparing the criteria weighting results of LGs based on the size of the population, we can observe that large cities highly prioritize (more than 20%) "resilience to climate change" (ENE5) and "(radioactive) waste" (ENV3) (Figure 21). Four criteria were weighed at the top one third of the most important criteria in both population size groups of LGs. "CO_2 emissions" (ENV1) was weighted 1st by both large and medium population size LGs. "Employment generation" (EC2), "ecosystems damages" (ENV5), and "mortality and morbidity" (SOC3) were also weighted at the top one third of the most important criteria of both LG groups (Figure 21).

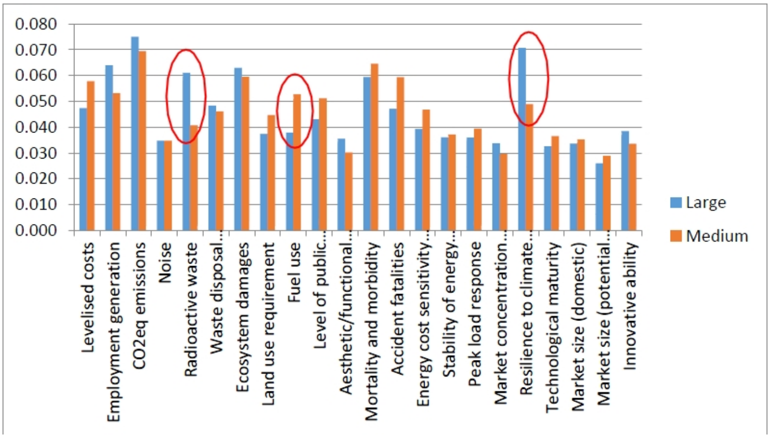


Figure 21. Average values of large and medium LGs' priorities.

Similarly the largest, more than 20%, differences between the criteria weights of different groups of LGs can be observed for "(radioactive) waste" (ENV3) and "resilience to climate change" (ENE5), that were weighted significantly higher by Southern and Eastern European LGs in comparison to Western/Northern European LGs. On the contrary, Western/Northern European LGs prioritized the criterion of "mortality and morbidity" (SOC3) significantly higher than the other European LGs (Figure 22).

Three criteria were weighed at the top one third of the most important criteria in all three groups of LGs. "CO_2 emissions" (ENV1) was weighted 1st by the groups of Eastern and Southern European LGs and 3rd by the group Western/Northern European LGs. "Levelised costs" (EC1) and "employment generation" (EC2) were also weighted at the top one third of the most important criteria of all LG geographical groups (Figure 22).

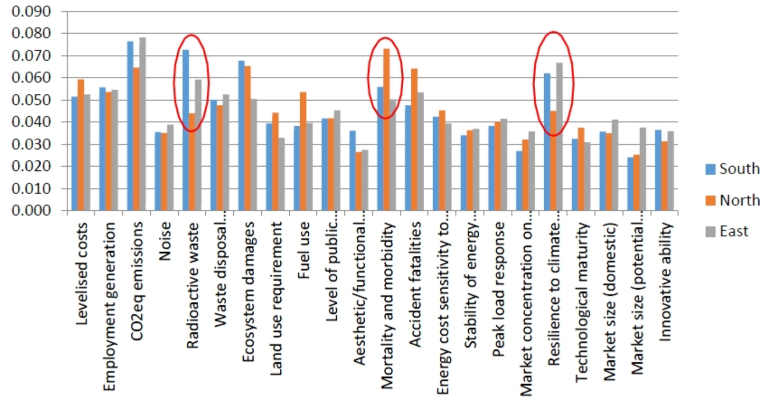


Figure 22. Average values of LGs' priorities from different geographical European regions.

6.4.3. Relationships of Criteria Weights

We conducted a Pearson correlation analysis for all possible pairs of criteria weights given by the

31 respondents to explore if there are any significant relationships between them. Here, we present the strongest positively correlated criteria weights with "r" higher than 0.7 which indicates very strong relationship. The weights of "CO_2eq emissions" (ENV1) were very strongly correlated (r = 0.8) with the weights of "resilience to climate change" (ENE5) (Figure 23).

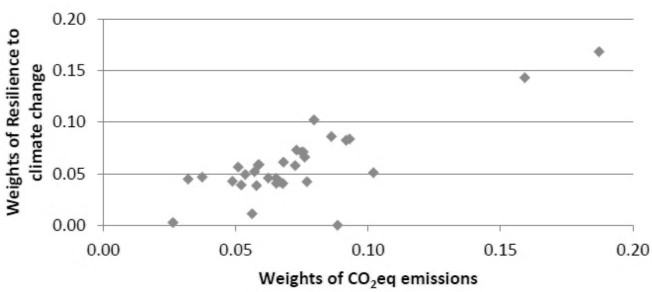


Figure 23. Relationship of weights of "CO_2eq emissions" and "resilience to climate change".

Furthermore, it was estimated that the weights of “mortality and morbidity” (SOC3) were strongly correlated (r = 0.73) with the weights of “accident fatalities” (SOC4) (Figure 24). Both criteria refer to different health-related issues caused by electricity generation operations. “Mortality and morbidity” (SOC3) refers to direct health impacts from air pollution due to burning of fossil fuels whereas,
“accident fatalities” (SOC4) refers to the risk of fatal accidents that could occur during the operation of certain energy systems.

It was also observed that there is strong negative correlation (r = −0.57) between “mortality and morbidity” (SOC3) and “innovative ability” (TEC4). This implies that when LGs highly prioritize health-related issues, they put less emphasis on technological innovation—and *vice versa*.

Figure 24. Relationship of weights of “morbidity and mortality” and “accident fatalities”.

Moreover, it was found that there is a moderate positive relationship (r > 0.3) between the variable of GDP *per capita* and the weights of the criteria “stability of energy generation” (ENE2) (r = 0.36), “innovative ability” (TEC4) (r = 0.35), “land use requirement” (ENV6) (r = 0.34), “technological maturity” (TEC1) (r = 0.32) and “energy cost sensitivity to fuel fluctuation” (ENE1) (r = 0.3) (Figures 25 and 26).

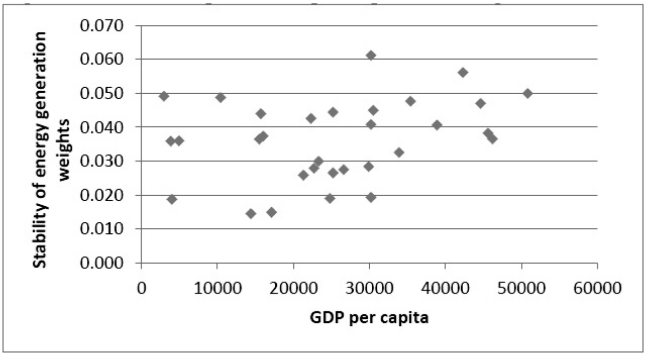


Figure 25. Relationship of GDP *per capita* and weights of "Stability of energy generation".

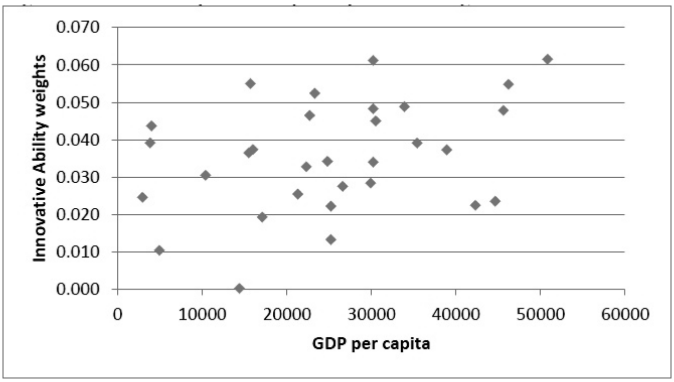


Figure 26. Relationship of GDP *per capita* and weights of "Innovative ability".

6.5 Discussion

According to the LGs' responses, the most important criterion, based on the average weights, is the criterion of "CO_2 emissions" (ENV1), followed by "mortality and morbidity" (SOC3), "ecosystem damages" (ENV5), "resilience to climate change" (ENE5), "employment generation" (EC2), "accident fatalities" (SOC4), "levelised costs" (EC1), and "radioactive waste" (ENV3).

"CO_2 emissions", as the most important criterion among LG representatives and across different geographical regions, clearly shows that the EU climate change mitigation policy objectives have reached the local level (Monni and Raes, 2008). Although this is considered more of an international and European-level priority issue, this can be attributed to the growing importance placed on climate change mitigation by European LGs and their conscious attempts to reduce emissions in their own localities as evidenced by their participation in the development and implementation of SEAPs (Covenant of Mayors, 2013).

Interestingly, the second ("mortality and morbidity") and third most important criteria ("ecosystems damages") are both related to air pollution from burning of fossil fuels. These criteria are also the two most common energy externalities highlighted in the literature (PSI, 2010; Diakoulaki and Grafakos, 2004), Roth et al., 2009). According to the results of this study, these issues were affirmed as highly important impacts from a European LGs' perspective. By combining these two highly weighted criteria, the issue of air pollution reduction is becoming the most important co-benefit of low-carbon electricity generation for LGs. This further indicates that climate change mitigation policies should seek how to maximize local air pollution reduction co-benefits as was also underlined by other authors (Urge-Vorsatz, 2014).

"Resilience to climate change", the fourth most important criterion, is a relatively new aspect that was not considered until the recent years in energy systems assessments. It is also a relatively new concept and objective for LGs. This could mean that there are well informed LGs on this issue, while others are still relatively ignorant. This situation is also reflected in the large divergence of LGs preferences that we observe in this study.

Different LGs, on the other hand, show a high degree of agreement for "ecosystem damages". This could be explained by the fact that LGs have high familiarity with the concept of ecosystem services and have clear objectives on preserving the urban and peri-urban ecosystem services for improving local communities' quality of life.

The high convergence between the different LGs on the "employment generation" could be explained by the fact that creation of jobs has a very strong local perspective, which in current times of European economic crisis is becoming more prominent among the European LGs.

For this study, we also ran a correlation analysis of all evaluation criteria. The results showed very strong positive correlation (r higher than 0.7) between "CO_2 emissions" and "resilience to climate change" as well as between "mortality and morbidity" and "accident fatalities". Moreover, the results showed moderate positive correlation (r higher than 0.4) between GDP *per capita* and criteria related to energy security of supply and innovative ability.

Largely populated cities, in particular, prioritize resilience to climate change which suggests the need to develop strategies to cope with future climatic shocks and stresses. Moreover, large cities

place emphasis on (radioactive) waste which implies the need for cleaner electricity generation sources and the importance of reduced environmental impacts. This can also be explained by the fact that the issue of climate resilience has been recognised as an important issue in the last years by many European LGs, and that there is an increasing number of LGs that are conducting local climate change adaptation
plans (Cinelli et al., 2014)

It is also evident that larger cities with accumulated populations and assets are potentially more vulnerable in cases of energy system disturbances or failure due to climate extremes. This can be explained by the fact that both criteria concern the two sides of the issue of climate change, namely mitigation and adaptation. Moreover, reduction of carbon emissions as well as developing climate resilience both address the actual and potential impacts of climate change in the long-run. Evidently, European LGs are aware about this relationship which is reflected on the way they weight these two criteria.

Based on the positive relationship between GDP *per capita* and awareness on issues related to energy security of supply and technology innovation, wealthy cities tend to prioritize technological innovation at a high level, which could possibly drive further their competitiveness with regard to low-carbon energy technologies. At the same time wealthy cities give high priority to issues related to energy security supply, enhancing their resilience to any energy supply disturbances while minimizing any negative effects to their economy, as it has been also discussed by other authors (O'brien and Hope, 2010; Molyneaux et al., 2012). It needs to be further studied, if there is any causality in these relationships.

6.6 Conclusions

This study, to the best of our knowledge, is the first attempt to map and measure priorities of European LGs on the sustainability evaluation of low-carbon energy technologies. It is critical to consider LGs' priorities as this could further enhance implementability, alignment and coordination of sustainable and low-carbon energy policies at different levels.

This study applied a hybrid weighting methodology which combined two weighting elicitation techniques (pairwise comparisons and swing method) for the elicitation of LGs' priorities. It was carried out through three different means (survey, face to face workshop, webinar) of exploring the preferences of LG representatives.

Further research on comparing different approaches will provide useful insights on how to best elicit LGs' priorities. It would also be useful to further explore how this methodology can be applied in different group decision making contexts to map stakeholders' priorities and further facilitate participation, deliberation, learning and adaptive decision making during low-carbon energy policy and planning processes.

Our study, which targeted LG representatives explored the specific, categorical, and overall priorities as well as analysed preferences based on three variables: population size (large, medium-sized cities), geographical region (northern/western, southern, and eastern European countries) and GDP *per capita*.

With LGs that have prepared SEAPs and are signatories to transnational European networks as respondents, our study was able to elicit preferences among large and medium sized cities that as it seems highly prioritize European climate change mitigation objectives. In that respect, we could conclude that European climate change policy has succeeded to engage LGs in the broader international discourses on tackling global climate change.

While our study may not provide a definitive representation and generalized results for all LGs, we recommend an extensive application of the methodology to a larger sample of European LGs. Moreover, it is deemed necessary to conduct a similar study for other geographical regions (e.g., Asia, North and South America) and compare the priorities of LGs from different regions. Furthermore, a similar approach could be also applied for eliciting LGs' preferences regarding the most important criteria and barriers regarding the actual development and planning of local SEAPs.

Chapter 7: Synthesis and Conclusions

7.1 Answering the research questions

In order to contribute to the advancement of decision making and integrated assessment of low carbon energy options (including technologies and policies) the current PhD thesis tried to investigate the integration of sustainability and resilience aspects in an overall framework of assessment, to deploy a process of validation, and continuous refinement of the integrated assessment framework by including views of different stakeholders and experts. Moreover the research aimed at developing a weighing methodology for consistent construction of stakeholders' preferences in the decision making and assessment process and mapping and assessing priorities of local governments and energy stakeholders with regard to the evaluation criteria of low carbon energy options. Based on the preceding chapters the thesis addressed the main research questions, where the general outcomes are presented in the following sections. The main thesis research questions are as follows:

- How can the assessment of low carbon energy technologies be improved in an integrated way that sustainability and resilience aspects are incorporated?
- How can stakeholders' preferences be incorporated in the evaluation of low carbon energy options in a constructive and iterative way?
- Which are the priorities of European local governments' and other stakeholders with regard to the evaluation of low carbon energy technologies?

7.1.1 How can the assessment of low carbon energy technologies be improved in an integrated way that sustainability and resilience aspects are incorporated

With regard to the integration of resilience and sustainability aspects within an overall assessment framework of low carbon energy options, chapter 2 identified and discussed the main gaps in the literature and needs for further advancements. It became evident that in the field of low carbon energy technologies assessment, there is no explicit framework that addresses both sustainability and resilience aspects. It was found that there have been observed specific attempts to address either sustainability or resilience issues with regard to low carbon energy systems in a distinct, isolated and non- integrative manner. Chapter 3 discusses in details how sustainability and resilience criteria can be incorporated in an overall assessment framework avoiding overlaps and maximising complementarities. Furthermore in chapter 3, I attempted to contextualize the concepts of sustainability and resilience in the field of low carbon energy technologies assessment and operationalize these concepts in specific 5 criteria categories and 21 indicators.

As it has been concluded in chapter 2 of the thesis and based on the literature review that was conducted, there are few specific important aspects of the integrated sustainability assessment of low carbon energy options that could be further improved. Those are:

- the importance and use of validation and refinement of criteria framework by experts and relevant stakeholders through an iterative process, something that in most assessment frameworks for low carbon options is neglected, and
- the incorporation of sustainability and resilience aspects within the overall framework of integrated sustainability assessment of low carbon energy options.

Chapter 3 discusses a systematic way of validation and refinement through a process of experts and stakeholders engagement which was inspired and adjusted from the "3S" approach that was first applied in environmental impact assessment by Cloquell – Ballester, et al. (2006). By combining a top down, based on literature review, and bottom up approaches the following steps have been established:

- Extensive literature review
- Screening of indicators (based on selection principles)
- Self-validation and refinement (based on rigorous internal peer review),
- Scientific validation and refinement (based on energy experts review), and
- Social validation and refinement (based on a survey of local energy stakeholders)

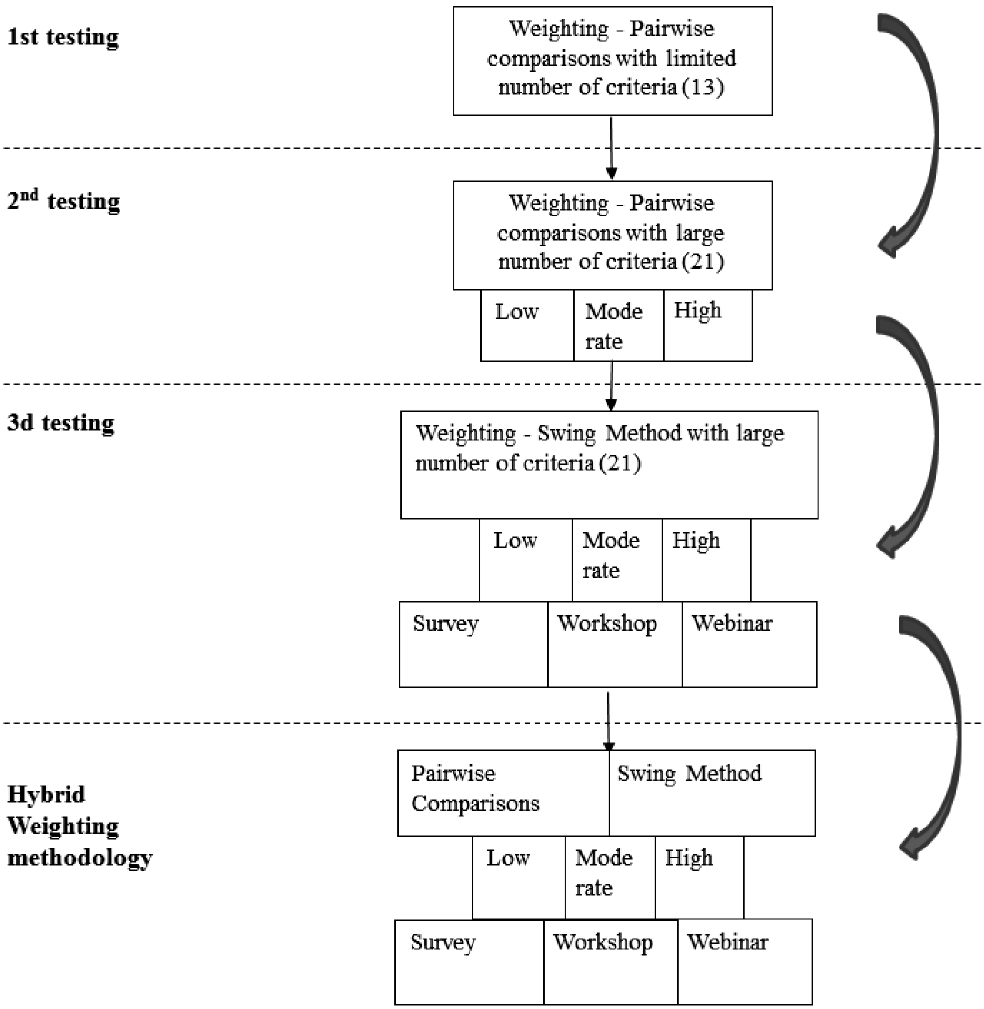
This iterative validation and refinement process along with the involvement of a wide range of experts and stakeholders made possible the development of a refined set of evaluation criteria and indicators for the assessment of low carbon energy options.

7.1.2 How can stakeholders' preferences be incorporated in the evaluation of low carbon energy options in a constructive and iterative way?

The proposed weighting methodology introduced a constructive hybrid weighting technique to incorporate stakeholders' preferences in energy and climate integrated assessment field. The term constructive reflects the gradual process of constructing human preferences for non – familiar issues as sustainability is in our case. Therefore the weighting methodology developed supports and facilitates the respondents, through the weighting process, to gradually construct their preferences with regard to the evaluation criteria of low carbon energy options. The proposed weighting methodology has been developed through an iterative and continuous process of development, application and testing, learning and refinement through the different PhD study stages and chapters. In particular the continuous, iterative development of the weighting methodology went through the following stages as illustrated also in figure 27:

- Based on literature review and identified weights elicitation challenges, a weighting methodology was developed by combining ranking and pairwise comparisons techniques (chapter 3).
- Application and testing of the weighting methodology with limited number of criteria (13) in the field of energy and climate policies (chapter 7). Lessons learned generated by this 1st application/testing of the weighting methodology, were taken into consideration to refine further the weighting methodology in order to be applied at a larger number of criteria.
- Application and testing of the refined weighting methodology to an extended number of criteria (21) in the field of low carbon energy technologies (chapter 5). In this application, I introduced a mechanism of gradual initial ranking of criteria into three groups according to their level of relative importance, aiming to reduce the overall cognitive burden of the respondents, due to the high number of criteria. Lessons learned generated by this 2nd application/testing of the weighting methodology, were taken into consideration to refine further the weighting methodology in order to address the high rate of inconsistencies of respondents' preferences that was observed.
- Application and testing of the further refined weighting methodology by utilizing swing technique, instead of pairwise comparisons, to an extended number of respondents and applications (individuals, group), to the same large set of evaluation criteria (21) in the field of low carbon energy technologies (chapter 6). Lessons learned generated by the third application/testing of the weighting methodology, were taken into consideration to refine further the hybrid weighting methodology.

Figure 27: Learning, testing and iterative process of the weighting methodology



Chapter 4 discusses how at a first stage, stakeholders are introduced to a “warming up” holistic approach for ranking the evaluation criteria and then they are requested to express the relative importance of criteria in pair-wise comparisons by providing an interactive mean with verbal, numerical and visual representation of their references. Stakeholders and experts in the climate policy field (chapter 7) that tested this application approved the co-application of two techniques (initial ranking and pair-wise comparisons), since it permits the gradual approach to the decision problem and the more accurate construction of their preferences. By developing a consistency-ranking index, the use of initial ranking serves also as a mean to test consistency by comparing the initial ranking to the ranking obtained from the pair-wise comparisons (chapters 5 and 7) or swing weighting method (chapter 6). In addition, the development of the proposed weighting approach proved to overcome the main difficulties that lie in criteria weighting methods, namely, impact range sensitivity, consistency, hierarchical bias and the association of linguistic expressions to the standard nine points AHP numerical scale (chapters 2 and 3).
On a policy level, taking into account the multi-disciplinary nature of climate and energy analysis and the multiple stakeholders involved, such an integrated weighting method has been proved a facilitative tool for the elicitation of preferences of respondents. The group of stakeholders, although of diversified synthesis, has in total positively commented on the applicability of the presented tool and its potential to enhance and aid the policy design by providing transparency, multi-dimensionality and inclusion of stakeholders’ preferences to the policy-making process.

7.1.3 Which are the priorities of European local governments’ and other stakeholders with regard to the evaluation of low carbon energy technologies

In chapters 5 and 6 the weighting methodology was applied for the elicitation of European local energy stakeholders’ and local governments’ priorities respectively in the context of evaluation of low carbon energy technologies.

Local energy stakeholders’ priorities

In chapter 5, the developed constructive weighting methodology was applied to elicit European local stakeholders’ preferences on the evaluation criteria of current and future low-carbon energy technologies. Overall, the application of the weighting methodology presented in chapter 5 mapped, albeit in a limited manner, elicited the preferences of local energy stakeholders. The framework applied with the support of the Covenant CapaCITY, a project co-funded by the Intelligent Energy Europe programme, and led by the Local Governments for Sustainability ICLEI.

Chapter 5 mapped three broad categories, namely public authorities, energy industry actors, and technical professionals. Through the elicited stakeholders' preferences, the low-carbon energy technologies that best meet the evaluation criteria prioritized by local energy stakeholders were assessed as well. Chapter 5 presented, on one hand, how local energy stakeholders prioritize certain economic, environmental, social, energy and technological criteria. On the other hand, this chapter showed which low-carbon technologies rank high taking into account local energy stakeholders priorities.

Local stakeholders expressed high preferences for CO_2eq emissions, levelised costs, ecosystem damages, employment generation, resilience to climate change, fuel use, and waste disposal which show implied responsibility towards global and local benefits and negative externalities. Mortality and morbidity, accident fatalities as well as radioactive waste also achieved high preferences from the respondents which show how local stakeholders value the welfare of the public, including workers, during project installation and operation. The potential impacts of energy technologies on human health and safety are considered a priority. Understandably, human health and safety are primary considerations.

Public authorities prioritize public health protection and safety – and in general, certain social criteria - as proven by their high preferences for mortality and morbidity and accident fatalities. Public authorities also give significant priority to ecosystem damages, CO_2eq emissions as well as levelized costs which reflect their concern for local and global environmental protection as well as economic outlays.

In spite of sharing similar preferences with public authorities and energy industry experts, technical professionals have a unique high preference for fuel use. This chapter also concludes that technical professionals, when compared to the weights provided by other stakeholder groups, have higher preferences for certain energy and technological criteria. On the other hand, public authorities provide least priority to certain energy and technological criteria, while technical professionals have provided least preferences for certain social criteria. Figure 28 shows the convergence and divergence of preferences among the three different local stakeholder groups.

However the sample of the stakeholders group does not allow for generalization of the results and indicates the need of applying this methodology to a larger sample of different local stakeholder groups along Europe.

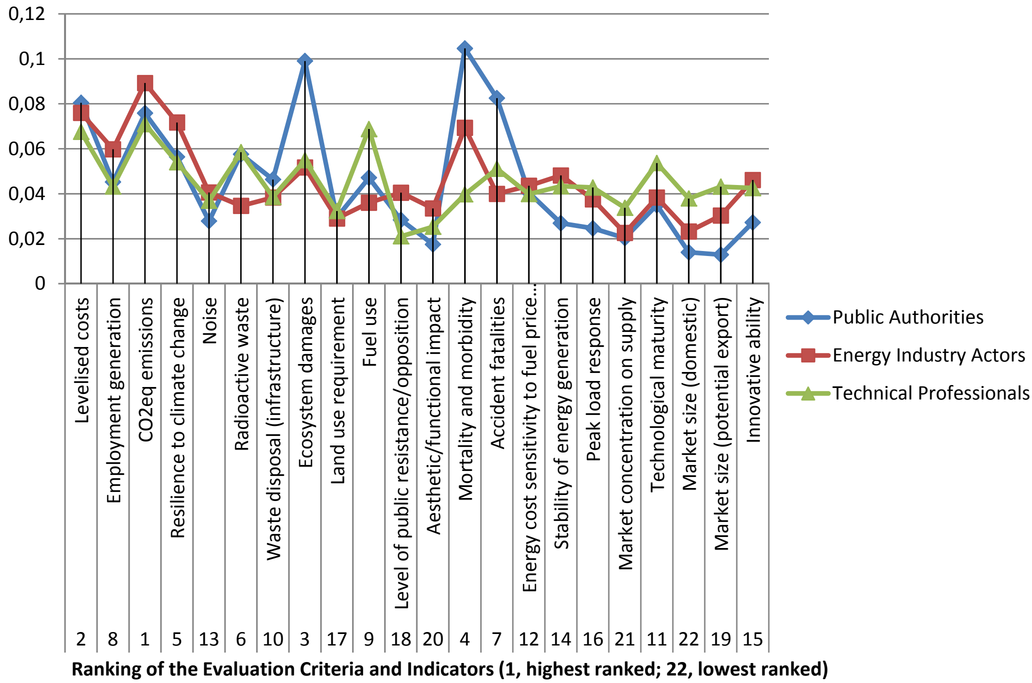


Figure 28. Distribution of weights for all criteria among the three stakeholder groups

Chapter 5 concludes that wind off-shore, solar PV, hydropower, windon-shore, and GTCC are the low-carbon energy technologies that rank highest while considering the preferences of local stakeholders. On the other hand, IGCC with CCS and IGCC were the lowest ranked energy technologies among all three stakeholder groups. Figure 29 below presents the final scores of the low-carbon energy technologies and the contribution of all criteria based on local stakeholders' perspectives.

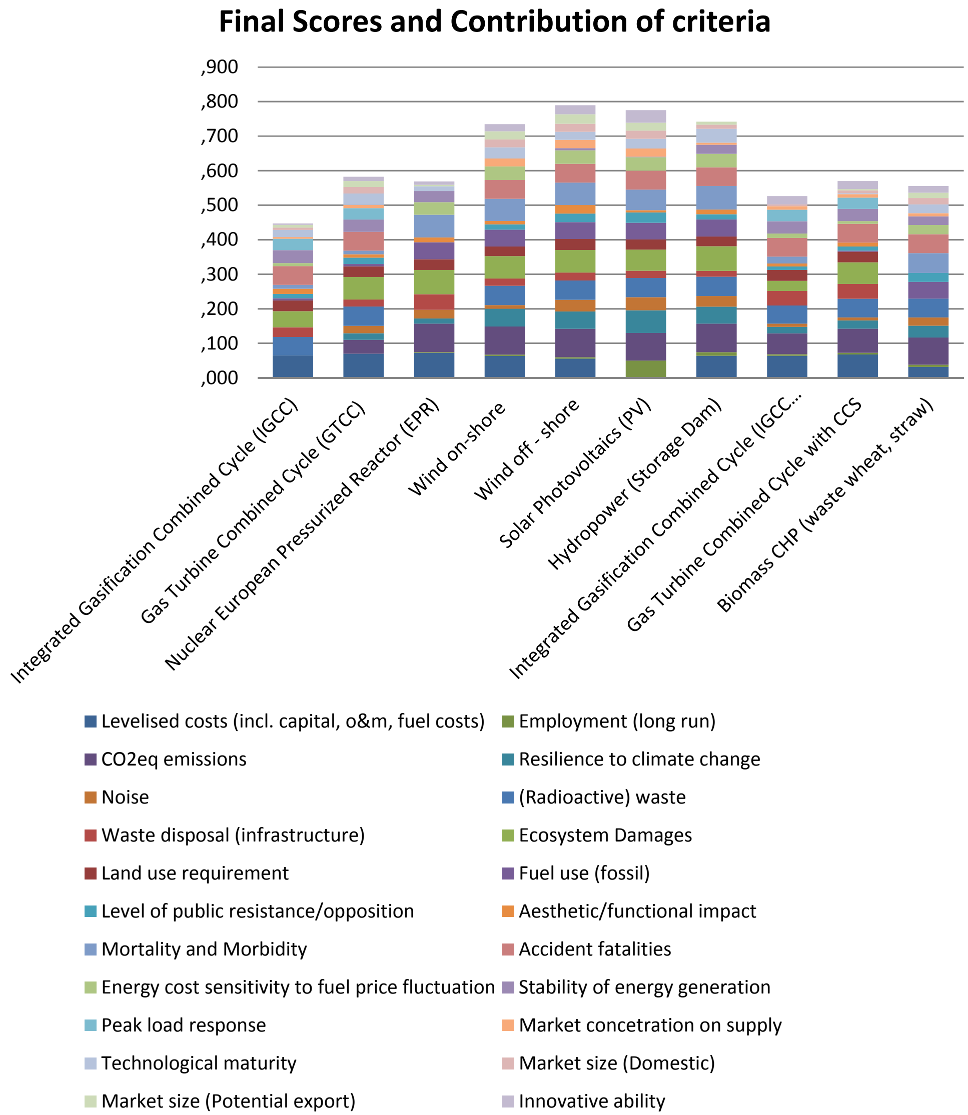


Figure 29.The final scores of the low-carbon energy technologies and the contribution of all criteria based on local stakeholders' perspectives.

Local governments' priorities

According to the 31 European LGs' responses that participated in the survey (chapter 6), the most important criterion, based on the average weights, is the criterion of "CO_2 emissions" (ENV1). "CO_2 emissions" is followed by "mortality and morbidity" (SOC3), "ecosystem damages" (ENV5), "resilience to climate change" (ENE5), "employment generation" (EC2), "accident fatalities" (SOC4), "levelised costs" (EC1), and "radioactive waste" (ENV3) (see also Table 24 below) .

Table 18. Final average weights of criteria, final ranking and standard deviation.

Criteria	Average Weight	Rank	StDev
ENV1: CO_2eq emissions	0.073	1	0.032
SOC3:Mortality and morbidity	0.063	2	0.034
ENV5: Ecosystem damages	0.061	3	0.025
ENE5: Resilience to climate change	0.059	4	0.034
EC2: Employment generation	0.058	5	0.018
SOC4: Accident fatalities	0.054	6	0.023
EC1: Levelised costs	0.054	7	0.027
ENV3: Radioactive waste	0.049	8	0.034
SOC1:Level of public resistance/opposition	0.048	9	0.018
ENV4:Waste disposal (infrastructure)	0.047	10	0.015
ENV7: Fuel use	0.046	11	0.020
ENE1: Energy cost sensitivity to fuel price fluctuation	0.044	12	0.014
ENV6: Land use requirement	0.041	13	0.018
ENE3: Peak load response	0.038	14	0.015
ENE2:Stability of energy generation	0.036	15	0.012
TEC4: Innovative ability	0.036	16	0.015
TEC1: Technological maturity	0.035	17	0.013

TEC2: Market size (domestic)	0.035	18	0.014
ENV2: Noise	0.034	19	0.017
SOC2: Aesthetic/functional impact	0.032	20	0.017
ENE4: Market concentration on supply	0.031	21	0.013
TEC3: Market size (potential export)	0.028	22	0.013

"CO_2 emissions", as the most important criterion among LG representatives and across different geographical regions, clearly shows that the EU climate change mitigation policy objectives have reached the local level.

Interestingly, the second ("mortality and morbidity") and third most important criteria ("ecosystems damages") are both related to air pollution from burning of fossil fuels. According to the results of this study, these issues were affirmed as highly important impacts from a European LGs' perspective. By combining these two highly weighted criteria, the issue of air pollution reduction is becoming the most important co-benefit of low-carbon electricity generation for LGs.

"Resilience to climate change", the fourth most important criterion, is a relatively new aspect that was not considered until the recent years in energy systems assessments. With regard to this criterion a large divergence of LGs preferences was observed in this study. Different LGs, on the other hand, show a high degree of agreement for "ecosystem damages".

High convergence between the different LGs on the "employment generation" has been observed as jobs has a very strong local perspective, which can be explained due to the fact of the observed high rate of unemployment in European countries particularly during the period of current economic crisis.

Largely populated cities, in particular, prioritize resilience to climate change which suggests the need to develop strategies to cope with future climatic shocks and stresses. Moreover, large cities place emphasis on (radioactive) waste which implies the need for cleaner electricity generation sources and the importance of reduced environmental impacts. This can also be explained by the fact that the issue of climate resilience has been recognised as an important issue in the last years by many European LGs, and that there is an increasing number of LGs that are conducting local climate change adaptation plans.

7.2 Scientific findings, contributions and reflections

7.2.1 Findings, contributions and reflections with regard to the integrated assessment framework of low carbon energy options

Integrating sustainability and resilience criteria

One of the main innovative aspects and contributions of the thesis is the integration of sustainability and resilience indicators in an overall assessment framework for low carbon energy technologies which is lacking in the literature. There are numerous studies looking at the sustainability aspects of energy technologies and few that have been conducted the last years focusing explicitly on resilience aspects (O'Brien and Hope, 2010, Molyneaux et al., 2012). It is deemed necessary to develop approaches and frameworks that consider both sustainable development sub-systems and technology development in order to enhance sustainable technology development (Musango and Brent, 2011). Different low carbon energy technologies, particularly in the electricity sector, are versatile with multiple interrelationships with environmental, social and economic dimensions of sustainability, while at the same time are vulnerable to external shocks and disturbances such as energy prices fluctuation, concentration of energy supply, future climate change threats and other natural disasters, reliance on non - renewable resources (O'Brien and Hope, 2010, Molyneaux et al., 2012, McLellan et al., 2012). This integrated assessment framework of indicators is the first attempt to bring together sustainability and resilience aspects, that generally are considered and treated in isolation, providing an analytical tool to policy makers on identifying explicitly the potential sustainability impacts and vulnerabilities of different energy technologies under one overall integrated assessment framework.

The developed integrated MCA framework which combines both sustainability and resilience aspects of energy technologies, strengthens local decision making by a) providing information both on sustainability impacts of energy technologies such as environmental and socio-economic impacts but also on resilience and vulnerability aspects of technologies, b) providing a validated and robust framework that can capture potential impacts, risks and disturbances of the energy systems, c) allowing stakeholders' active participation, while at the same time d) facilitating a flexible and adaptive decision making process that can be easily adjusted to different local circumstances.

During this study and the extensive literature review that was conducted, it was found that often some resilience aspects of energy systems have been considered implicitly in sustainability assessment frameworks (e.g. energy security of supply, fuel price fluctuation). However other types of resilience issues (e.g. potential climate change impacts) were completely neglected. Furthermore, interestingly it was found that specific aspects could be seen either from a sustainability or resilience perspective. For instance the indicator of "GHG emissions" could be considered as an environmental impact through the contribution to GHG emissions and climate change problem but also as a resilience aspect, reflecting the financial risks of carbon intensive technologies, in case of a price is tagged on carbon either through carbon tax or a higher price of carbon emission allowance (Molyneaux et al., 2012). In that case, both perspectives should be considered explicitly by giving emphasis and possibly additional weight to the criteria.

Validation and refinement of evaluation criteria framework

Another contribution of the thesis is the modification and application of the "3S" validation process in the context of low carbon energy planning and assessment consisting of 5 consecutive steps of validation and refinement. This 5 steps validation process along with the involvement of a wide range of experts and stakeholders made possible the development of a refined set of evaluation criteria and indicators.

Although there were few suggestions for the adjustment or removal of criteria, the validation process proved important as it revealed several misinterpretations of criteria descriptions that were addressed at this stage prior to weighting. The descriptions of the criteria were improved and better reflected stakeholders' suggestions minimizing possible misinterpretations of criteria during the weighting phase that might have affected the weighting results and final ranking of technologies. In addition, we could also observe that the misinterpretations were mainly expressed from few individual respondents and none from specific type of stakeholders that could have suggested removal of specific criteria. Furthermore, the validation process allowed stakeholders to express their suggestions for removal or adjustment of certain criteria. This indicated which criteria could be potentially weighted with a low level of relative importance during the weighting process.

Looking both at the results of the stakeholders' validation survey and criteria weights, specifically the correlation between the percentage of removal and the ranking/weighting of criteria, aesthetic/functional impact seemed to be the less preferred – and least important –

criterion. Based on the two aforementioned attributes, aesthetic/function impact was suggested for removal by 10% of the respondents (as well as for adjustment by another 10%) and has ranked 20th in the final ranking. It also ranked last (22nd) in the initial ranking of respondents. In other words, the criterion of aesthetic/functional impact was suggested for removal and also received a very low weight and ranking evaluation.

Most of the times researchers either develop indicators intuitively or consider only experts' judgments during selection of indicators, neglecting stakeholders' perspectives (Cloquell – Ballester et al., 2006; Hak et al., 2012). The proposed approach integrates stakeholders' views in the very initial stage of the assessment process, namely during the selection and validation of indicators. This could effectively reduce the risk of conflict between energy project designers and relevant stakeholders (Cloquell – Ballester et al., 2006).

The scrutiny of the validation process and inclusion of stakeholders a) enhanced the relevance of criteria and indicators, b) contributed to improved and clearly described set of criteria and indicators, c) improved the robustness of the assessment framework by increasing the acceptance of selected criteria, and d) provided a first indication of the potentially least important criteria. As Cloquell – Ballester et al. (2006) argue, these validation stages are complementary so that the indicators' credibility and usability increases as we complete and move from one validation stage to the next.

7.2.2 Findings, contributions and reflections with regard to the hybrid weighting methodology

Weighting biases and difficulties

So far in energy policy decision making, most of the researchers and practitioners dealt mainly with the development of decision aid tools without focusing on the criteria weights elicitation. In addition, researchers usually focus on purely applying certain weighting techniques on energy policy problems ignoring their potential biases. Finally, literature has focused mainly on describing biases and difficulties rather than developing means for eliminating them (Hamalainen and Alaja, 2008). The design and application of the proposed weighting technique attempts to overcome the main challenges that lie in criteria weights elicitation stage, namely, impact range sensitivity, consistency, hierarchical (splitting) bias and the association of verbal expressions to the AHP nine-point numerical scale:

(a) Impact range sensitivity. Different authors (Weber and Borcherding, 1993; Fischer, 1995) have reported the existence of an impact range effect on weights, meaning that the weight of a criterion is normally elicited as a function of the criterion's impact range. A stakeholder should adjust the weights to impact (performance) ranges in order to have stable preferences. Proper adjustment of the weights would have required lowering weights for small-perceived value ranges and increasing them for large ones. If important judgments reflect a generalized social concern rather an appropriate re-scaling of attributes then can remain insensitive (Stillwell et al., 1987). In other words, the weighting procedure should be on certain cases range sensitive. Furthermore, if a value function is normalized relative to the impact range outcomes in the local context, then attribute weights should be range sensitive and adjusted to the impact range of criteria. But, when the value function is normalized relative to the global context, then criteria weights can be range insensitive and can remain unaffected from changes of the range of attributes (Fischer, 1995). In all applications of the different refined versions of the weighting methodology, the impact range was presented explicitly to respondents in order to be taken into account during the elicitation of their preferences. The impact range was presented in different cases where the performances technologies against the evaluation criteria have been estimated in cardinal and ordinal measurement scales.

(b) Splitting or hierarchical bias. The division of criteria in value trees and sub-criteria categories can either increase or decrease the weight of a criterion. Experimental evidence in multi-criteria weighting techniques shows that when a criterion is split into sub-criteria, there is an effect on the weighting outcome and a difference between the weight of the criterion and the sum of the sub-criteria, while they were supposed to be equal (Weber and Borcherding, 1993). The degree of the split of a criterion to sub-criteria enhances the criteria weights (Weber et al., 1988). Furthermore, the various ways of structuring criteria and sub-criteria in value trees may also change the rank of criteria, a phenomenon which is called the unadjustment phenomenon or as it is widely used as splitting bias (Poyhonen et al., 2001). By developing and applying this weighting technique, hierarchical (and splitting) bias is avoided while all criteria are compared in pairs without any hierarchical value tree structure. The division of criteria according to different objectives just illustrates the association between criteria and objectives and does not have any implications to the weighting process of the criteria. All criteria are compared in pairs irrespective of the criteria category they belong. Furthermore the study does not aim to measure the weighting preferences of different criteria categories in an aggregated manner, as this would not provide any additional information to decision makers, but will entail splitting bias risks.

(c) Inconsistency. The stakeholder perceives inconsistencies as mistakes not purposely. They are expressed as discrepancies between stakeholder's judgments and the weighting results. However, they enable stakeholder to learn more about the elicitation procedure and the different aspects of the decision problem. Usually, they are reconciled by requiring the respondent to make a final judgment, reducing the inconsistency. Borcherding et al. (1991) demonstrated that there is a difference concerning the consistency between different weighting methods and this is related to the number of criteria that had to be compared. This is rational and could have been predicted as more criteria require more comparisons for the stakeholders and simply present more opportunities to be inconsistent. Transitivity of preferences, as discussed in more details in chapter 3, is assumed by applying the abbreviated pair-wise comparisons and thus consistency check is not deemed necessary within this type of pair-wise comparisons technique. Nevertheless, during the development of the weighting method, a ranking (in)consistency test has been introduced providing the opportunity to respondents to check the consistency of the ranking orders and revise their initial preferences if necessary. Particularly in methods with high number of criteria and indicators, the use of consistency test is deemed necessary as there is higher risk for preferential inconsistencies. Therefore, a consistency test was introduced in all applications as main part of the overall hybrid weighting methodology.

(d) Numerical evaluation scale. Few of the weighting methods (e.g. AHP and MACBETH) are using numerical evaluation scale to express the importance judgments of stakeholders. The selection of the numerical evaluation scale, which is assigned to verbal expressions at the AHP, is an important factor which influences the criteria weights. The original 1-9 numerical scale overestimates the ratios that assign to the verbal expressions (Poyhonen et al., 1997). This scale has problems because of the lack of steps. Stakeholders focus on the verbal statements to express their preferences while the numerical scale fails to capture the numerical counterparts of the verbal expressions. Thus, a balanced or continuous scale is preferred comparing to the original 1-9 numerical scale in order to have more accurate and consistent weights (Poyhonen and Hamalainen, 2001). As Poyhonen et al. (1997) clearly stated, one possible remedy would be to substitute points estimates assigned to verbal expressions by intervals of ratios. In the current application, the respondent can indicate which ratio of the range better reflects his verbal expressions of relative importance of criteria (Table 19).

Table 19: Verbal and ratio numerical intensity of preferences

Verbal expressions	**Ratio – numerical intensity of preferences**
Equally preferred	1
Almost equally preferred	0.9
Moderately preferred	0.6, 0.7 and 0.8
Strongly preferred	0.3, 0.4 and 0.5
Very strongly preferred	0.1 and 0.2

During the application of the developed methodology, it was required from stakeholders to express their preferences importance between criteria verbally as an introductive step before asking them to further express their preferences' intensity in a ratio numerical scale which was further accompanied by an automatic visual representation of the selected relative importance between the criteria. Certain ratios and ratio ranges were assigned to the verbal statements where the respondent could choose an appropriate value from a list with scale from 0.1 to 1.0 (Table 19). Preferences can be selected numerically by typing in a value but also being represented graphically with a slider. Then one, in fact, uses a continuous scale. By first asking verbal expression of preferences and then asking to state the associated ratios, by providing them with the possibility to choose from a range of numbers, the methodology overcomes the main weakness of associating verbal expression to a standard numerical evaluation scale like Saaty's, one to nine-point numerical scale (Saaty, 1987).

Combination of different techniques

Weighting techniques that allow respondents to give imprecise, rank order information may be a mean to remedy for time consuming, subject to inconsistency weighting techniques and may assist in practical preference elicitation (Hayashi, 2000; Poyhonen and Hamalainen, 2001). Thus, the application and use of the ranking technique as preparatory process to the elicitation of the relative importance of criteria was deemed appropriate. However, holistic approaches and the judgment of all criteria at once make impossible the consideration of the criteria in a careful and insightful manner. Thus, respondents' preference statements cannot be considered as defensible and balanced using only a holistic ranking approach. Therefore, at the first application and testing phase (chapter 7) with a limited set of evaluation criteria (13), a decomposed pair-wise comparisons technique was used to accompany the ranking method. After the development of the integrated framework of sustainability and resilience criteria for low carbon energy technologies the number of criteria increased to 21. In order to deal with the high number of criteria and reduce the cognitive burden on respondents, a mechanism of gradual ranking of criteria according to different groups of importance was introduced (chapter 5 and 6).

Furthermore, the design of the integrated methodology decreases and (where possible) minimizes the burden to respondents. The parallel use of multiple techniques than a single one was preferred in order to foster the users to reconsider their initial preferences, think harder their value systems and deliberate their preferential judgments against the evaluation criteria. The appropriateness and usefulness of combining different techniques has been highlighted in the literature and furthermore facilitates stakeholders to revise their preferences (Hobbs and Horn, 1997; Bell et al., 2001, 2003). The proposed MCA weighting methodology on one hand combines different aspects and strengths of various techniques while on the other hand consists of an interactive and iterative tool that enables the user to revise his initial preferences and check the consistency of ranking order judgments. The methodology provides verbal, ratio and visual means for stakeholders' preferences expression by integrating elements of a ranking (holistic), a pair-wise comparisons (decomposed) and ratio techniques (chapter 7 and 5), whereas chapter 6 introduces the combination of initial ranking and swing weighting method to reduce the complexity and cognitive burden that was observed through the application of the pairwise comparisons with a large set of evaluation criteria (21). Each respondent has individually completed the interactive excel-based questionnaire. The users expressed their comments and feedback on written questionnaires offered after the application of the weighting methodology was completed. The following conclusions were obtained based on users' feedback regarding the weighting methodology. Co-application of both methods (initial ranking and pair wise)

All participants acknowledged that the combination of two methods and their different level of application were practical because it introduced an initial session (the initial ranking step). Being free to rank the criteria in a holistic way without an immediate obligation in expressing their relative weights, users adapted gradually to the problem and the more accurate expression of their preferences through the pair-wise comparisons was facilitated.

As the initial ranking provided the basis for the consistency check, the results of the pair-wise comparisons were checked in order to assure their consistency and reliability. By applying different ranking and weighting techniques, an opportunity for a consistency check was established to enhance the reliability of stakeholders' preferences. Most of the times and as has been pointed out by Bell et al. (2003) this is commonly neglected. By using different methods we were able to detect inconsistencies by comparing the different ranking results. As Bell et al. (2003) concluded such inconsistencies are an opportunity to reflect on results from different framings of the issue at hand. By using a single method such kind of opportunity is lost (Bell et al. 2003).

It is important to note that the application of initial ranking and pair wise comparisosn with high number of criteria (chapter 5) led to 31% rate of respondents low consistency between their initial and final rankings. As it has stated also by Borcherding et al. (1991), Grafakos et al. (2010a) and Riabacke et al. (2012) the study conveyed that the difference in consistency between weighting methods could be related to the large number of criteria for comparison, particularly common in the case of pairwise comparisons. Chapter 5 involved 22 pairs of criteria for comparison which resulted on high cognitive burden to the respondents. Hence, with the large number of pairs for comparison, inconsistencies inevitably arose. This was expected as during prescriptive decision analysis processes, according to Riabacke et al. (2012), perceptions change and evolve, and the representation of these perceptions are not static. The respondents were then asked to modify their preferences should their weighting scores did not reach the consistency threshold value. However, having to repeat the pair-wise comparisons could have been a challenge for some of the respondents since this would have required additional time.

Furthermore it could be observed that due to the cognitive demands as well as time constraints, the respondents were more comfortable with providing the ranking order directly to a list of criteria than selecting the extent to which a criterion is relatively more important for each pair-wise comparison. As Riabacke et al. (2012) suggests for the elicitation of weights, ranking methods using surrogate weights in the interpretational proved to be less cognitively demanding. In chapter 7 (Grafakos, et al., 2010a), a sample of individual stakeholders and experts in the climate and energy policy field has expressed satisfaction as well as approval for combining ranking and pairwise comparisons as approaches in weighting energy and climate criteria. The study showed that the initial ranking facilitated a gradual approach to the evaluation problem. The pair-wise comparisons, on the other hand, enabled a more accurate expression of the respondents' preferences. The number of the criteria (14) in chapter 7 was significantly less than the number of criteria (21) that were selected to be assessed in chapters 5 and 6.

Cognitive limit is one of the challenges in stakeholders' preference elicitation. In a decision problem which involves a small set of alternatives and criteria, most people can make their selection intuitively. However, with a large set of alternatives and criteria, relying on intuition and/or experience seems inadequate and thus needs further support. The conclusions are in accordance with Makowski et al. (2009) about the additional challenge of the mix of qualitative and quantitative indicators as well as of preferences that are often times irregular, non-sequential, and with threshold values. The computerized interaction was considered important in helping stakeholders to construct their preferences. This provided stakeholders with support in analyzing their desired objectives in relation to the outcomes of the elicitation process. As Riabacke et al., (2012) stated, practical techniques for elicitation are to a great extent a matter of balancing the quality of elicitation results with the time available and cognitive burden on the respondents for eliciting all the required information.

The constructive weighting methodology developed and applied in this PhD thesis allows for a thorough process for eliciting weighting preferences. The methodology subjects survey respondents to be consistent in their preferences. Moreover, the use of different techniques enhances the reliability of the results as respondents had the opportunity to check and revise their preferences. MCA practitioners often apply a 'one-size-fits-all' approach even though different methods work better for some people and situations than for others (Bell et al. 2003). Particularly on the low consistencies between the preferences, this could be attributed to the large number of criteria involved and the cognitive burden it imposes to respondents. However, the demonstration of the constructive weighting methodology shows great potential for better decision making as well as for further enhancement in its application.

It should be noted though that the relatively low response rate of LGs to the weighting survey (chapter 6) can be highly attributed to the complex and time consuming process of weighting a high number of evaluation criteria. Considering the fact that the respondents were busy professionals with limited resources and time working in local governments such a kind of complexity and cognitive demand might compromise their participation. Therefore a simpler and less complex weighting approach could be considered in such type of respondents. On the other hand the experience of application of this weighting methodology in group decision making didn't show any similar challenges and issues, indicating the potential of this hybrid methodology in group decision making context.

7.2.3 Findings, contributions and reflections with regard to respondents' preferences and low carbon energy technologies ranking

Ranking results

Experts' impact assessment

The main innovative contribution of chapter 4 was the evaluation of low carbon energy technologies against a selected set of criteria combining sustainability and resilience aspects, along with the application of a large European expert survey for the evaluation of low carbon energy technologies.

Chapter 4 presented and discussed the assessment results of the experts' assessment survey. The selection of criteria was based on a 5 steps approach which included extensive literature review, experts' judgments and stakeholders' validation (Grafakos et al., 2015a). An experts' impact assessment survey was conducted for the assessment of the technologies against 10 criteria that were not yet quantified in the literature. In overall, the experts evaluated solar PV with the highest score in comparison to all the other technologies in 5 (climate resilience, noise pollution, public resistance, innovative ability and domestic market size) out of the 10 criteria. On the other hand, Nuclear power was relatively low evaluated as it performed worst, according to the experts' judgments, in 3 criteria (public resistance, market concentration of supply and domestic market size). It should be noted that the results and conclusions reflect the performance of technologies against a selected sub-set of the overall criteria set, with 4 out of 10 criteria focusing on technological aspects, while excluding economic criteria from the evaluation. The reason is that the other 12 criteria have been quantified by other studies.

The analysis of convergence of experts' evaluations revealed that further research is needed to explore the technological maturity and future deployment of CCS technologies since there is still large uncertainty and disagreement on how they will be deployed in the future. Furthermore it became clearly evident that Nuclear EPR has the highest likelihood to face public resistance. In addition, still experts agree that Wind onshore will have relatively low energy generation stability which points out on further research on how to increase its stability through smart energy grids or other technological means.

Ranking of low-carbon energy technologies

Chapter 5 concludes that wind off-shore, solar PV, hydropower, wind on-shore, and GTCC are the low-carbon energy technologies that rank highest while considering the preferences of local stakeholders for the whole set of 21 evaluation criteria. On the other hand, IGCC with CCS and IGCC were the least significant low-carbon energy technologies among all three stakeholder groups.

The results of the NEEDS project (Schenler et al. 2009) also showed high preferences for renewables, such as solar, wind, and biomass technologies. Centralized gas options (e.g. combined cycle and combined heat and power CHP) as well as nuclear technologies were the mid-performing group of technologies, while coal and lignite technologies were considered the worst performers. In Turkey, Topcu and Ulengin (2004), in their ranking of alternative energy sources, wind power proved to be the most preferred option. Wind was also the highest ranked alternative, followed by biomass and PV, in an MCA by Mourmouris and Potolias (2013) in Greece.

However, considering levelised costs alone, EPR exhibited the lowest costs, followed by fossil fuel-based technologies (GTCC, GTCC with CCS, IGCC, and IGCC with CCS). Renewable energy technologies, such as hydropower, wind, and solar, have higher levelised costs. However, the results of the study also show how certain technologies (e.g. renewables) that rank relatively low in a cost-based assessment are otherwise most preferred and highly ranked if multiple criteria and aspects are considered in the assessment. One can surmise that economic costs certainly play a role in decision making, regardless of stakeholders' propensity for choosing other sustainability criteria. As demonstrated in the results of the study, costs matter, but only up to a certain extent. Other sustainability criteria, such as social and environmental ones, should also drive the assessment process.

Weighting results of local energy stakeholders

Local stakeholders, in chapter 5, expressed high preferences for CO_2eq emissions which is a surprising outcome considering the global scale of this type of benefits that somebody would expect not to be highly weighted at the local context. The fact that the sample of local stakeholders was linked to the European project Covenant CapaCITY, that aims to provide support to local governments to develop SEAPs, could partly explain this surprising result. Furthermore, local stakeholders expressed high preferences for CO_2eq emissions, levelised costs, ecosystem damages, employment generation, resilience to climate change, fuel use, and waste disposal which show implied responsibility towards local benefits and negative externalities. Mortality and morbidity, accident fatalities as well as radioactive waste also achieved high preferences from the respondents which show how local stakeholders value the welfare of the public, including workers, during project installation and operation. The potential impacts of energy technologies on human health and safety are considered a priority. Understandably, human health and safety are primary considerations.

As chapter 5 showed, local stakeholders and society in general, are still concerned about radioactive waste because of its potential to cause – whether likely or unlikely –catastrophic accidents or be used in terrorist attacks. In the aftermath of the Fukushima nuclear disaster in Japan in 2011, radioactive waste and nuclear safety remain controversial topics. Aesthetic/functional impact did not achieve high preference among the local stakeholders. Although debate is inevitable regarding the aesthetics of current infrastructure of specific renewable energy technologies (e.g. wind and solar), mechanisms are available for the deployment of these technologies in unobtrusive ways (Kaldellis et al. 2013b).

The results of chapter 5 indicate that public authorities prioritize public health protection and safety – and in general, certain social criteria - as proven by their high preferences for mortality and morbidity and accident fatalities. Public authorities also give significant priority to ecosystem damages, CO_2eq emissions as well as levelised costs which reflect their concern for local environmental protection as well as economic outlays.

In spite of sharing similar preferences with public authorities and energy industry experts, technical professionals have a unique high preference for fuel use. This research study also concludes that technical professionals, when compared to the weights provided by other stakeholder groups, have higher preferences for certain energy and technological criteria. On the other hand, public authorities provide least priority to certain energy and technological criteria, while technical professionals have provided least preferences for certain social criteria. However the sample of the stakeholders group does not allow for generalization of the results and indicates the need of applying this methodology in a larger sample of different local stakeholder groups along Europe.

Weighting results of local governments with regard to the evaluation criteria of low carbon energy technologies

According to the LGs' responses, as showed in chapter 6, the most important criterion, based on the average weights, is the criterion of "CO_2 emissions" (ENV1), followed by "mortality and morbidity" (SOC3), "ecosystem damages" (ENV5), "resilience to climate change" (ENE5), "employment generation" (EC2), "accident fatalities" (SOC4), "levelised costs" (EC1), and "radioactive waste" (ENV3).

"CO_2 emissions", as the most important criterion among LG representatives and across different geographical regions in Europe, which is profoundly a counterintuitive outcome, clearly shows that the EU climate change mitigation policy objectives have reached the local level (Monni and Raes, 2008). Although reduction of CO2 emissions is considered more of an international and European-level priority issue, this result can be attributed to the growing importance placed on climate change mitigation by European LGs and their conscious attempts to reduce emissions in their own localities as evidenced by their participation in cities' networks and initiatives as the Covenant of Mayors supporting them in the development and implementation of SEAPs (Covenant of Mayors, 2013).

Interestingly, the second ("mortality and morbidity") and third most important criteria ("ecosystems damages") are both related to air pollution from burning of fossil fuels. These criteria are also the two most common energy externalities highlighted in the literature (Roth et al., 2009; PSI, 2010). According to the results of this study, these issues were affirmed as highly important impacts from a European LGs' perspective. By combining these two highly weighted criteria, the issue of air pollution reduction is becoming the most important co-benefit of low-carbon electricity generation for LGs. This further indicates that climate change mitigation policies should seek how to maximize local air pollution reduction co-benefits as was also underlined by other authors (Urge-Vorsatz et al., 2014).

"Resilience to climate change", the fourth most important criterion, is a relatively new aspect that was not considered until the recent years in energy systems assessments. It is also a relatively new concept and objective for LGs. This could mean that there are well informed LGs on this issue, while others are still relatively ignorant. This situation is also reflected in the large divergence of LGs preferences that we observe in this study.

Different LGs, on the other hand, show a high degree of agreement for "ecosystem damages". This could be explained by the fact that LGs have high familiarity with the concept of ecosystem services and have clear objectives on preserving the urban and peri-urban ecosystem services for improving local communities' quality of life.

The high convergence between the different LGs on the "employment generation" could be explained by the fact that creation of jobs has a very strong local perspective, which in current times of European economic crisis is becoming more prominent among the European LGs.

For this study, we also ran a correlation analysis of all evaluation criteria. The results showed very strong positive correlation (r higher than 0.7) between "CO_2 emissions" and "resilience to climate change" as well as between "mortality and morbidity" and "accident fatalities". Moreover, the results showed moderate positive correlation (r higher than 0.4) between GDP *per capita* and criteria related to energy security of supply and innovative ability.

Largely populated cities, in particular, prioritize resilience to climate change which suggests the need to develop strategies to cope with future climatic shocks and stresses. Moreover, large

cities place emphasis on (radioactive) waste which implies the need for cleaner electricity generation sources and the importance of reduced environmental impacts. This can also be explained by the fact that the issue of climate resilience has been recognised as an important issue in the last years by many European LGs, and that there is an increasing number of LGs that are conducting local climate change adaptation
plans (Cinelli et al., 2014).

It is also evident that larger cities with accumulated populations and assets are potentially more vulnerable in cases of energy system disturbances or failure due to climate extremes. This can be explained by the fact that both criteria concern the two sides of the issue of climate change, namely mitigation and adaptation. Moreover, reduction of carbon emissions as well as developing climate resilience both address the actual and potential impacts of climate change in the long-run. Evidently, European LGs are aware about this relationship which is reflected on the way they weight these two criteria.

Based on the positive relationship between GDP *per capita* and awareness on issues related to energy security of supply and technology innovation, wealthy cities tend to prioritize technological innovation at a high level, which could possibly drive further their competitiveness with regard to low-carbon energy technologies. At the same time wealthy cities give high priority to issues related to energy security supply, enhancing their resilience to any energy supply disturbances while minimizing any negative effects to their economy, as it has been also discussed by other authors (O'brien and Hope, 2010; Molyneaux et al., 2012). It needs to be further studied, if there is any causality in these relationships.

Implications for low carbon energy policy

As for low carbon energy policy, it can be concluded that based on the overall preferences of stakeholders and LGs, there should be focus on policies enabling the local deployment of renewable energy technologies that reflect the most preferred local priorities, such as CO_2 emissions reductions, levelised costs, ecosystem damages, and employment generation.

Moreover, key differences regarding local stakeholder preferences could be highlighted during local low carbon energy planning. Within the decision making context, relevant stakeholders and decision makers would have informed opinions about the value judgments of local stakeholders which need to be taken into account in the process of developing low carbon energy policies. Also, knowledge about key issues of the problem at hand could be a topic for knowledge sharing, awareness raising and information dissemination, among other policies.

With LGs that have prepared SEAPs and are signatories to transnational European networks as respondents, the PhD study was able to elicit preferences among large and medium sized cities that as it seems highly prioritize European climate change mitigation objectives (Grafakos et al., 2015b). In that respect, we could conclude that European climate change policy has succeeded to engage LGs in the broader international discourses on tackling global climate change.

7.3: Future research

There are future research prospects concerning the enhancement and further application of this methodology. It should be recognised that further research merits on the application of the methodology on various type of evaluation problems in climate and energy policy with different type of impact measurement scales, either quantitative or qualitative or combination of both.

In addition, the weighting methodology can be tested to a larger sample of stakeholders or different groups of stakeholders to map the perceptions and objectives of distinct groups and identify commonalities and differences. Furthermore, it can be tested to a large sample of the general public and identify certain trends on people's preferences upon climate policy objectives. However the low response rate that was observed from the LGs survey indicates that special attention should be paid on using this methodology in surveys with non-expert type of respondents that are not familiar with such a kind of weighting processes.
This kind of exercise could provide a tool to identify people's views and stakeholders' objectives and indicate synergetic or conflicting perceptions on climate policy. Decision-making process might become more transparent and assist for the formulation of defensible and socially acceptable decisions. Furthermore, there is much space for testing the contribution of the methodology during participatory stakeholders' workshops where its use could assist them to exchange views and thus facilitate an in-depth and informative discussion, valuable for more apparent and reliable decision-making process. The developed methodology could provide a platform for dialogue and communication between different actors in climate and energy decision making highlighting the commonalities and differences of their perspectives. This

would provide a mean for identifying potential conflicts and synergies between stakeholders and, therefore, threats and opportunities for policy implementation during the policy design and development stage. The developed method can provide a policy analysis aid tool complementing traditional and widely used techniques like CBA and/or cost effectiveness analysis by capturing the policy aspects that cannot be considered by the quantitative techniques and thus providing a more complete and multi-objective decision-making process.

Moreover, this framework can be adjusted and used either by local or national policy makers for the integrated assessment of specific energy technologies. The application of the assessment framework aims to enhance guidance and evidence based support of local and national decision makers when planning and developing energy technologies and policies towards a low carbon and resilient development pathways. By this research I hope to further trigger discussion on the importance of explicitly integrating sustainability and resilience aspects and indicators in the assessment of low carbon energy options, technologies and policies.

In this study, a constructive weighting methodology was applied to elicit European local stakeholders' and local governments' preferences on evaluation criteria of future low-carbon energy technologies. However, this research study merited a small number of respondents. As such, there is a need for further application of this weighting methodology to a large number of local stakeholders and local governments at the European level. This research mapped three broad categories, namely public authorities, energy industry actors, and technical professionals. It would be substantive to map the preferences of distinct local stakeholder groups or types of local governments that apply within a larger local energy context in Europe.

It would also be useful to further explore how this methodology can be applied in different group decision making contexts to map stakeholders' priorities and further facilitate participation, deliberation, learning and adaptive decision making during low-carbon energy policy and planning processes.

In situations where decision makers have to engage in the development of low-carbon energy strategies and sustainable energy action plans, local stakeholders' preferences can be mapped out by applying this methodology. This is crucial also for the identification of potential conflicts and resolution of actual ones in order to reach consensus on the development of local sustainable energy strategies.

Lastly, while the current study results may not provide a definitive representation and generalized results for all LGs, an extensive application of the methodology to a larger sample of European LGs will provide valuable contributions to European, National and Local energy and climate policy context. Moreover, it is deemed necessary to conduct a similar study for other geographical regions (e.g., Asia, North and South America) and compare the priorities of LGs from different regions. Furthermore, a similar approach could be also applied for eliciting LGs' preferences regarding the most important criteria and barriers regarding the actual development and planning of local SEAPs.

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Annex 1: Application of the constructive weighting methodology for the assessment of climate and energy policy interactions in Europe

(This chapter has been published in: Grafakos, S., Flamos, A., Oikonomou, V., and Zevgolis, D., (2010), Integrating environmental, socio-political, economic and technological dimensions for the assessment of climate policy instruments. In Leal Filho, W. (ed) "The Economic, Social and Political Elements of Climate Change", part 4, 623-648, Springer Verlag, Berlin)

The energy and climate policy framework of the European Union (EU) consists of a series of regulations and initiatives that aim at different objectives and affect various actors in the energy and climate field. These policies aim to achieve specific objectives set by the United Nations Framework on Climate Change Convention, which assigns Greenhouse Gas (GHG) emissions reduction targets for all Member States. In December 2008, EU leaders reached agreement over an energy and climate change 'package' to deliver the bloc's ambitious objectives of slashing greenhouse-gas emissions by 20%, boosting renewable energies by 20% and increasing energy efficiency to 20% of the primary energy consumption by 2020. The package has multiple objectives and is designed to increase the EU's share to combat climate change, reduce the Union's dependency on imported fuels, promote green technologies and create new jobs.

Policy instruments addressing such targets are present at EU wide level and on national basis. As far as the latter case is concerned, many instruments are currently incorporated into regulations, economic instruments, voluntary agreements, and market based mechanisms. In the EU wide context, a unified emissions trading scheme (EU ETS) was established as from 2005 based on an EU Emissions Trading Directive (CEC, 2003b), followed up by an additional Directive (CEC,

2004) that enables direct links of the EU ETS with the Kyoto Protocol project mechanisms (namely Joint Implementation and Clean Development Mechanism). The climate and energy package lays down certain conditions and requirements for further improvement and amendment of EU ETS specifically for its third phase which starts in 2013. In addition EU policy focuses also on the promotion of renewable energy sources by adopting various Directives, such as the Directive on the promotion of electricity produced from renewable energy sources (CEC, 2001), the biofuels Directive (CEC, 2003a) and the recently agreed energy and climate package, which includes new targets for renewable energy sources for Member States.

Numerous policy instruments are applied simultaneously at an EU, national and regional level, aiming at often contradictory energy, environmental and economic targets. Given this complex policy environment, it is clear that various objectives are pursued in terms of environmental and energy effectiveness, alongside with economic efficiency. As these policies are designed and implemented in an already policy-crowded environment, interactions of their measures are taking place. These interactions can take different forms and shapes and in general can be complementary, overlapping or indifferent. This raises the issue of compatibility of the different policy schemes, which is of crucial importance for further policy design. In this sense, policy interactions can affect the result of the overall targets of climate policy either in a positive or negative way. In addition, policy interactions could be beneficial towards certain policy objectives but on the other hand they might affect negatively other objectives, which consequently would undermine the effectiveness of the overall policy. Thus, during the ex-ante assessment of policy interactions, a systematic way to highlight and analyze trade - offs and synergies between policy objectives, is indispensable. The most common practice in climate policy assessment is the use of quantified tools, models and neoclassical economic approaches to measure the extent of climate mitigation and economic efficiency simultaneously. Therefore, the majority of researchers and practitioners in climate policy evaluation use approaches like cost benefit analysis (CBA) and cost effectiveness analysis (CEA), which normally can capture the economic and the environmental (in terms of greenhouse gas emissions reduction) dimensions of climate policy. In order to complement these approaches and consider other aspects of climate policy, specific studies are being conducted separately targeting to other dimensions and policy objectives as competitiveness, employment, energy security of supply and technological innovation. There is a lack of a unified method that aims to capture the different climate policy objectives in a systematic way and thus reconcile environmental, economic, socio-political and technological aspects.

In order to reconcile the various aspects of climate and energy policy into the evaluation of policy instruments interactions, a Multi Criteria Analysis (MCA) approach is deemed appropriate for the following reasons:

- Multiple instruments and thus multiple combinations of instruments (policy options) for evaluation can be considered and evaluated by MCA;
- Climate and energy policy have various aspects and objectives that should be all considered while evaluating policy instruments, where MCA is capable to deal with multiple often conflicting criteria and objectives;
- Climate policy interaction is a high complex issue whereas MCA has the ability to deal with complex policy issues by decomposing, analysing and structuring them in a transparent way;
- MCA can consider and combine objective (facts or likely performances) and subjective type of information (expression of judgments and preferences);
- MCA can incorporate different stakeholders' perspectives and preferences by the application of a weight elicitation technique;
- MCA is an aid to decision making that assists stakeholders to organise the available information, think the consequences, explore their own objectives and tolerances and thus provide a widely acceptable policy decision.

However, despite the recent interest to participatory and MCA methods, MCA assessments are absent from most of the actual climate policy evaluations due to various reasons. Time constraints, data availability problems, lack of guidelines and general tradition in monetized and cost-benefit analysis methods, misconceptions and large variety of MCA methods comprise some of the main reasons that MCA methods are neglected most of the times in the climate policy evaluation (Borges and Villavicencio, 2004).

MCA methods should be used as decision aid tools rather than techniques for taking decisions. Their outcomes are the result of stakeholders' evaluations and thus are sensitive to their judgments. Therefore, stakeholders should be informed about the tools they use and comprehend their functions and outcome.

MCA, although appropriate for the evaluation of policy interactions, should have a properly modeled preference system in order to facilitate the decision making process. In this respect, special attention is paid to distinct stakeholders who tend to weight differently the employed criteria according to their policy objectives and preferences. Therefore, capturing this essential information could be of significant usefulness, especially if it will appropriately feed-in the decision making process.

To this extent we have developed an integrated assessment tool to evaluate energy and climate policy interactions during the policy design phase, which is able to assess combined policies using multiple criteria and parameters. This decision support tool is qualitative and in an interactive way provides a useful insight of several aspects of policy interactions. It addresses policymakers, policy analysts and stakeholders who can use it in order to identify policy interactions and effects of various policies.

Considering the above and following this introduction, we describe in section 2 the methodology employed in the tool alongside with its basic characteristics and the parts that focus mainly on the selection of evaluation criteria and the weighting factors determination. In section 3 we present an illustrative example of the tool in order to demonstrate its actual function whereas section 4 is dedicated to the presentation and analysis of results obtained from the illustrative case study. Finally, conclusions are drawn and future research areas are identified at section 5.

The developed multi-criteria decision support tool, provides a qualitative framework for analyzing interactions among policy instruments in various policy mixes during the phase of policy design. The key concept is that policymakers and stakeholders are able to examine selected policy instruments for interaction and express their preferences towards certain criteria when assessing options of integrating various instruments. In the ECPI tool a traditional policy condition is assumed that an optimal policy solution preconditions the relationship one policy instrument for one policy target (Tinbergen's rule).

Energy and Climate Policy Interactions (ECPI) consists of certain features and steps that are described in detail by Oikonomou et al. (2010). This chapter focuses on the preference system modeling and more specifically on the elicitation of criteria weights from various stakeholders and the investigation of potential trends according to their specific preferences and objectives.

Design characteristics and areas of policy interaction

Design characteristics refer to parameters that describe several functions of a policy instrument in terms of a measure identification, objectives pursued, scope, market creation, financing, timing, and institutional setup. A detailed explanation of these characteristics is provided in Oikonomou and Jepma (2008). The most important characteristics taken into consideration at this stage are briefly explained in table 18.

Table 20: Design characteristics of policy instruments (Adapted from Oikonomou and Jepma, 2008)

Characteristic	Explanation
Application	The option for a policy target group to participate or not in the instrument's objective accomplishment (mandatory or voluntary)
Level and kind of target	General objective of a policy translated into targets in different ambient levels (GHG reduction, RE, energy efficiency, etc) and Level of target expressed in terms of high or low stringency
Energy target	Targeting sources of energy (e.g. oil, fossil fuels) leads to substitution effect between them and hence to cleaner production, while targeting final energy use stimulates energy efficiency and reduction of energy use

Obligated entities	Entities that comprise the target group that undertakes the fulfilment of the target, distinguished in: energy producers, industry, energy suppliers, and end-users
Market flexibility	The optional choice of excluding or including some entities or sectors or technologies in the course of time of the policy cycle
Linking commodities	Type of commodity generated, exchanged and traded in a parallel to product market, distinguished in: EUA, WhC, TGC, emissions allowance, CHP certificate
Commodity liquidity	Trading participants can be allowed to bank the commodity and use it in the next compliance period. Trading participants can be allowed to borrow or lend a commodity in order to fulfil their target for the current compliance period
Cost recovery	The way that the target group recovers induced policy costs. There is partial, full or no cost recovery and is determined by market structure and market's degree of liberalization
Technologies	Technologies addressed and eligible for the target fulfilment, distinguished in: fossil fuel, renewable energy, nuclear, all, energy efficiency products
Additionality	Effect of policy if the target group would take actions independently of other policies and measures, and these investments would not have taken place in the absence of the specific policy
Institutional Setup	Entities that design, set the rules for the implementation, monitor, verify the eligibility for target fulfilment, register all actions of a policy instrument

EUA stands for Emission Unit Allowance (under the EU emissions trading scheme), WhC for White Certificates, TGC for Tradable Green Certificates and CHP for Co-Heat and Power

Design characteristics of standalone policies are combined and provide options for the formation of unified policy instruments with areas of design interaction. In a combined option of policy instruments A and B, a design characteristic X is compared in pairs and an area of policy interaction is extracted.

Design characteristics and areas of policy interaction are practically the same, but we distinguish them in the tool since they belong to different processes. Design characteristics refer to parameters of individual policy instruments, while areas of policy interaction to shared characteristics of combined policy instruments. In the options of combined policy instruments, based on our selection of design characteristics and on formulation of areas of policy interaction, we classify areas of policy interaction as complementary, overlapping, or indifferent. This principle of redundancy of design characteristics is in accordance with our core assumption of Tinbergen's rule as stated above. Complementary means that a design characteristic of policy A enforces the same characteristic of policy B. Overlapping means that a design characteristic of policy A reduces the value of the same characteristic of policy B. Indifferent means that a design characteristic of A and B do not meet or reinforce each other.

Climate and energy policy objectives and criteria

Policy and decision makers implement policies and measures to achieve specific objectives, taking into account different aspects, that they believe will not be achieved in the absence of government intervention, possibly because of the existence of not internalised externalities and/or public goods supplies. There are various aspects deriving from climate and energy policies that policy makers aim to take into account. The evaluation of climate and energy policies first defines evaluation criteria and second categorises them into, main policy aspect categories. The evaluation criteria are used to measure the extent of the fulfilment of the policy aspects and objectives taken into account. Evaluation criteria are indispensable for both the choice of instruments during the policy design phase and the ex-post assessment of implementation of policy instruments. The main EU climate and energy policy objectives which the EU climate and energy package aim to achieve are the following:

- to combat climate change and reduce GHG emissions,
- to secure energy of supply and diversify the energy fuels,

- to reduce the energy consumption by increasing the energy efficiency within the economy,
- to boost technological innovation and competitiveness,
- to create new jobs

In this context, different studies have also identified criteria for the evaluation of climate and energy policy instruments (IPCC, 2001; 2007; OECD, 1997, 2001; Bondansky, 2003; Oikonomou and Jepma 2008; Gaiza – Carmenates *et al*. 2010) addressing the different dimensions of climate and energy policy evaluation. Following a bottom – up process of selection of criteria and based on review of these studies we have selected the most relevant criteria and clustered them in the following five main categories trying to capture all possible aspects of climate and energy policy interactions evaluation:

1) Environmental category

Environmental effectiveness has been emphasized broadly in the environmental and climate change literature as the main criterion able to capture the extent that a policy instrument achieves the environmental goal, such as a GHG emissions reduction target (IPCC 2001, 2007; Bodansky, 2003; Oikonomou and Jepma, 2008). How reliable is the instrument in achieving that objective? In addition does the instrument create continual incentives to improve products or processes in ways that reduce GHG emissions? Furthermore, OECD (1997) and Bodansky (2003) identify 'soft' effects, which relate to the impact of environmental policy instruments on changes in attitudes and awareness. Thus 'environmental awareness' is another environmental criterion which complements the criterion of 'reduction of GHG emissions' in environmental category.

2) Socio – political category

Considering socio – political aspects is often an important issue of climate and energy policies. Blyth and Lefevre (2004) carried out a quantitative study on the interactions between energy security and climate policies highlighting the significance of 'security of energy supply' as an evaluation criterion. Decoupling economic growth and energy use is one of the main EU objectives and thus 'reduction of energy intensity' has been added as a criterion in this category.

3) Financial category

The second assessment report (IPCC, 2001) identifies cost-effectiveness as one of the main criteria for the evaluation of climate policies. Whether the policy instrument achieves the environmental objective (e.g. reduction of GHG emissions) at the lowest cost, taking transaction, information, and enforcement costs into account? 'Administration' and 'compliance' costs have been defined as separate evaluation criteria of climate and energy policy interactions by Oikonomou and Jepma (2008) additional to 'transaction' costs. OECD (1997) identifies 'governmental revenues' raised in the case of market mechanisms, for instance, may constitute a second source of benefits from their use, over and above their direct environmental impact, depending on if and how the revenues are recycled.

4) Macroeconomic category

Administrative and political feasibility includes considerations such as flexibility in the face of new knowledge, understandability to the general public, impacts on the 'competitiveness' of different industries, and other government objectives. "Wider" economic effects include potential effects on variables such as inflation, competitiveness, 'employment', trade, and growth (OECD, 1997). One of the priorities of EC energy policy is the enhancement of energy market liberalization (e.g. Directive 2003b) which can be captured by the 'market competition' criterion (Oikonomou and Jepma, 2008).

5) Technological category

OECD (1997) identifies dynamic effects, which relate to the impact on learning, innovation, technical progress, and dissemination and transfer of technology. Stimulating technological change is stressed also by Bodansky (2003) as one of the main criteria for evaluating climate policies. In the long run, the development and widespread adoption of new technologies can greatly ameliorate what, in the short run, sometimes appear to be overwhelming conflicts between economic well-being and environmental quality. Therefore, the effect of public policies on the development and spread of new technologies may be among the most important determinants of success or failure in climate policy.

The evaluation criteria should fulfil some qualitative attributes as described in chapter 3 and emphasized by different authors Belton and Stewart (2002) and Hajkowicz et al. (2000), Grafakos et al. (2010a) such as *Value relevance, Operationality*, *Reliability, Measurability, Decomposability, Non-redundancy, Minimum size, Preferential independence and Completeness*.

The selection of evaluation criteria as described is based on a bottom up approach. By reviewing the relevant literature and assuring that the selected set of criteria meets the above conditions the criteria are categorised according to their association with the climate and energy policy aspects discussed above. At the final stage stakeholders and experts were asked to approve and refine the set of criteria. Figure 30 illustrates the main climate and energy policy aspects and criteria categories, whereas table 21 provides a brief explanation of each selected criterion employed within the tool.

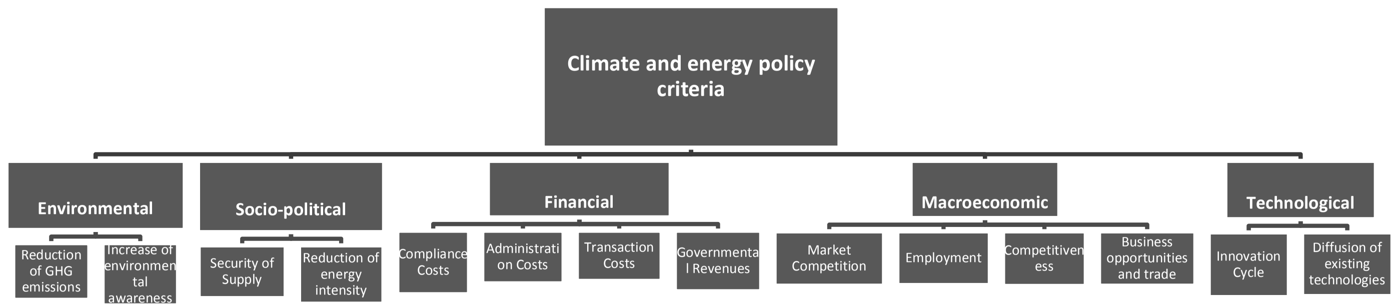

Figure 30: Major criteria categories and selected criteria

Table 21: Explanation of selected criteria

	Criterion	Explanation	Comments	Objective
Environmental category	Reduction of GHG emissions	Reduction of emissions through policy	A positive sign refers to an **increase** in reduction of GHG emissions	max
	Increase of environmental awareness	All economic actors become more environmental aware through policy	A positive sign refers to an **increase** in environmental awareness	max
Socio-Political category	Security of supply	Non interruption and security of energy supply through policy	A positive sign refers to an **increase** in security of supply	max
	Reduction of energy intensity	Reduction of energy use as input for a given output in total economy due to	A positive sign refers to an **increase** of reduction in energy intensity	max
Financial Category	Compliance costs	Direct costs for obligated parties that need to fulfill policy goals	A positive sign refers to a **decrease** in compliance costs	min
	Administration costs	Costs required from public bodies for implementing a policy based on the institutional set up	A positive sign refers to a **decrease** in administration costs	min
	Transaction costs	Search, information, negotiation, approval, monitoring, insurance costs undertaken by obligated parties due to	A positive sign refers to a **decrease** in transaction costs	min
	Governmental revenues	Revenues generated through policy that can be redistributed for an environmental or other cause	A positive sign refers to an **increase** in governmental revenues	max
Macro - economic Category	Market competition	Compatibility with market liberalization and transparency that enhance competition through policy	A positive sign refers to an **increase** in market competition	max
	Employment	New positions in sectors through policy	A positive sign refers to an **increase** in employment opportunities	max
	Competitiveness	Effects on market prices of domestic industrial products due to policy	A positive sign refers to an **increase** in competitiveness	max
	Business opportunities and trade	Enhancement of trade (national or international) and of investment opportunities (beyond the direct policy goals) due to policy	A positive sign refers to an **increase** in business opportunities and trade	max
Technological Category	Innovation Cycle	Innovation, Invention and Diffusion of new technologies can be enhanced	A positive sign refers to an **increase** in innovation activity	max
	Diffusion of existing technologies	Besides innovation, diffusion of existing efficient technologies in stock due to	A positive sign refers to an **increase** in diffusion of existing technologies	max

It is unavoidable that some overlaps between the criteria might exist within a category and between the different categories of criteria. They are not necessarily consistent, but give room for synergies and conflicts. This leads us to the necessity not to see the criteria or groups as separated formulas but as parts of the overall aim and to incorporate them whenever possible into the integrated climate and energy policy concept. Coming from the overall aim to the criteria is one step of operationalising, whereas the next would be to measure the criteria through quantitative - if possible - otherwise qualitative measurement scales.

Assessment of policy mixes (scoring of policy options)

The criteria selected in the ECPI tool receive specific values that range from -2 to +2 and reflect the positive or negative effect of each policy instrument on the specific criterion. A zero value reflects that there is no influence on the criterion, which could also illustrate that a policy instrument is not related to targets that the specific criterion represents. As the numbers -2 to 2 are taken as mathematical numbers and as ordinal ones (having a meaning), the distance between the numbers must be the same as between the associated answers (see table 20). This overcomes the problem of using an ordinal scale (answer possibilities) for a weighted sum aggregation.

Table 22: Measurement scale of criteria performance

Measurement Scale of Criteria performance	Explanation *
-2	Significant decrease of criterion performance
-1	Moderate decrease of criterion performance
0	No change of criterion performance
1	Moderate increase of criterion performance

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2	Significant increase of criterion performance
	* this refers to max criteria and the opposite stands for the min criteria

A positive or negative effect does not always mean an increase of a positive or negative value of a criterion. The effect of the value is in accordance with the interpretation of criteria as explained in table 2.

The tool provides the user with performance values of policy instruments towards the evaluation criteria, as they are assessed from various literature studies and experts' judgements. The performance values for the option of integrating the policy instruments result from the design areas of integrated policy instruments and the degree of influence of areas of policy interaction on the criteria. The measurement scale is the same as of the scale of standalone policy instruments (-2 / +2). We should stress here that these performance values cannot give more than a preliminary idea about the direction and the probable range of the impact on all criteria.

Weighting of criteria

Each policy maker and stakeholder may apply different weights to the evaluation criteria according to policy objectives and preferences while evaluating climate and energy policy options. There are numerous methods to determine criteria weights which can be used in various ways for different policy evaluation purposes according to different interpretations of weights (Grafakos et al., 2010a). Weights can have different meanings, they can either be perceived as relative importance coefficients stating importance of the criteria, or as scaling factors reflecting impact trade-offs between criteria. The weighting method that has been developed to derive factors of relative importance of criteria is a combination of pair wise comparisons with an initial ranking technique.

Ranking of criteria

The methodology combines an initial simple ranking criteria exercise and a pair wise comparison technique which results in criteria weights determination and a new criteria ranking. The former is a direct ranking whereas the latter one is indirect which is determined by the weights derived by the pair wise comparisons of criteria. The introduction of the initial holistic ranking technique has a twofold meaning and use. It is introduced first to help stakeholders to comprehend the concept of criteria importance and second to provide the means to respondents to resolve any conflicts and discrepancies that may be detected between the two rankings.

Pair wise comparisons of criteria

Respondents' weighting judgments regarding the criteria are derived by comparing the criteria in pairs in a structured and constructive manner. We use the abbreviated pair wise comparison format and thus n-1 pair wise comparisons are performed. Pairs are sequentially assigned (as a-b, b-c, c-d, etc.), where the initial criterion a is the first ranked criterion by the respondent, criterion b is the second ranked criterion, c is the third ranked criterion and sequentially the order of pairs of criteria is according to the initial criteria ranking. This means that first, randomness is assured in the sense that each subsequent pair is selected differently according to respondents' initial ranking and thus problems with path dependency are being minimized (Saaty, 1987) and second, the ranking consistency of stakeholders' preferences is being maximized.

Description

An illustrative application of the methodology is presented in this section by comparing the option of implementing two stand alone policy instruments to the option of their combined application. The policy options are evaluated by the weighted summation of each option based on their scores and criteria weights that have been assigned by the stakeholders. We compare the option of applying feed in tariffs for renewable energy (feed in RE) to energy suppliers in combination with the application of EU ETS to energy producers for CO2 emissions reduction with the option to keep them as standalone policy instruments. The main characteristics of the policy instruments and policy options are illustrated at table 21 as presented to stakeholders.

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Table 23: Areas of policy interaction

Areas of policy interaction	Feed-in tariffs for Renewable Energy	EU ETS	Status of interaction
Application in market (Mandatory (M) or Voluntary (V))	Voluntary	Mantadory	Complementary
Level of targets (High or Low)	Low	High	Complementary
Energy (primary or final)	Final	Final	Overlapping
Obligated entities (energy producers, energy suppliers, industry, consumers)	suppliers	producers	Complementary
Market flexibility for entities (Optional in/Optional out)	Optional out	Optional out	Indifferent
Linking commodities (EU allowance, Tradable Green Certificate (TGC), White Certificate (WhC))		EUA	Indifferent
Commodity liquidilty (Banking and Borrowing (Y/N))		Yes	Indifferent
Cost recovery (Full tariff, Limited tariff)	limited tariff	full tariff	Complementary
Technologies (Fossil Fuels, Renewable Energy (RE), Nuclear)	RE	Fossil fuel	Complementary
Additionality (no, baseline)	No	No	Overlapping
Institutional setup (number of bodies required)	6	3	Overlapping

As was described at the methodology section, the policy instruments are compared to their combined application based on the selected evaluation criteria. The performance values (scores) of the policy options have been determined from literature studies and experts' judgments. The measurement scale of the performance values is common for all criteria and ranges from -2 to 2 as discussed above. Table 22 depicts the evaluation impact matrix which contains the scores of policy options towards the evaluation criteria.

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Table 24: Evaluation impact matrix

	Environmental category		Socio-Political category		Financial Category				Macroeconomic Category				Technological Category	
criteria / policies	Reduction GHG emissions	Increase of environmental awarenes	Security of supply	Reduction Energy intensity	Compliance costs	Administration costs	Transaction costs	Governmental revenues	Market competition	Employment	Competitiveness	Business opportunities and trade	Innovation cycle	Diffusion of existing technologies
Feed-in tariff for RE	1	1	2	0	1	0	0	-1	1	0	1	0	1	2
EU ETS	1	1	0	0	-1	-1	-1	1	1	1	-1	2	0	2
Result of Interaction	2.0	2.0	2.0	0.0	0.3	-1.0	-1.0	0.1	2.0	1.0	0.2	2.0	1.0	2.0

It can be noticed from table 5 that none of the policy options is superior to others with respect to all evaluation criteria. EU ETS and the interaction policy options have negative scores at the criteria of 'administration costs' and 'transaction costs'. On the other hand, these two options achieve the best performance (score 2) at the criterion of 'business opportunities'. Feed in tariff for RE policy option has also negative score at the 'governmental revenues' criterion whereas performs best (score 2) at the criterion of 'security of supply'. Therefore, the weighting factors that stakeholders assign to criteria would determine the most desirable policy option with the highest score.

The tool was distributed to various stakeholders to elicit their preferences on criteria weights. The tool includes specific instructions to assist the stakeholders to use it in an easy way and minimize the cognitive burden to users and time to be spent by them. The sample was small and the response rate judged as moderate (50%). The tool was sent to 38 stakeholders while 19 by them responded. The sample was divided into two main categories: academics (9) and market players (10) (e.g. energy and climate experts, consultants) in the climate and energy policy field. The completion of the tool was performed individually in an interactive way in the sense that each respondent could see and revise the output of his preferences.

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Assigning criteria weights

First step: Initial Ranking

The respondent is required to rank criteria according to his preferences, from the most preferred to the least preferred criterion. The initial ranking is used also for a consistency test of user's preferences by being compared to the ranking determined by the pair – wise comparisons of criteria.

Second step: Pair wise comparisons

The respondent is required to express his preferences in three consecutive step - requests: a) which criterion he prefers at each pair wise comparison, b) how much he prefers a criterion to the other verbally and c) how much preference intensity he assigns arithmetically to the most preferred criterion against the other. Five levels of preferences have been defined in verbal expressions. The five levels of preferences verbally expressed are associated to 10 levels of numerical preference values:

Table 25: Verbal and ratio numerical intensity of preferences

Verbal expressions	**Ratio – numerical intensity of preferences**
Equally preferred	1
Almost equally preferred	0.9
Moderately preferred	0.6, 0.7 and 0.8
Strongly preferred	0.3, 0.4 and 0.5
Very strongly preferred	0.1 and 0.2

The user is assisted by a developed computer aided excel tool. A graph automatically reflects his preferences providing him with the visual representation of the resulted relative importance between the pair of compared criteria. When the respondent completes the whole series of pair wise comparisons across criteria, then relative scores, weighting factors and ranking of criteria are determined automatically by the tool.

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Final step: Consistency test and revision of preferences

During the final stage the respondent can observe the derived weights and ranking of criteria, and revise his preferences if necessary. The obtained ranking of criteria during the pair wise comparisons is compared with the initial ranking. The consistency indicator, which is calculated automatically by the tool, suggests whether or not the respondent needs to revise his preferences.

Results and discussion

The analysis of results focuses mainly on how different stakeholders weight various objectives and criteria during the climate policy interactions evaluation. Figure 31 illustrates the spread of criteria weights for confidence level 95%. It can be clearly noticed from figures 31 and 32 that the criterion which has been assigned with the highest average weighting value is the 'reduction of GHG emissions'. 'Reduction of energy intensity' and 'security of supply' follow as second and third most significant criteria respectively. The least significant criteria according to stakeholders are 'governmental revenues', 'transaction costs' and 'administration costs'. This could be expected since there were no representatives from governmental institutions that returned the tool within the sample and thus their views are not represented in these results.

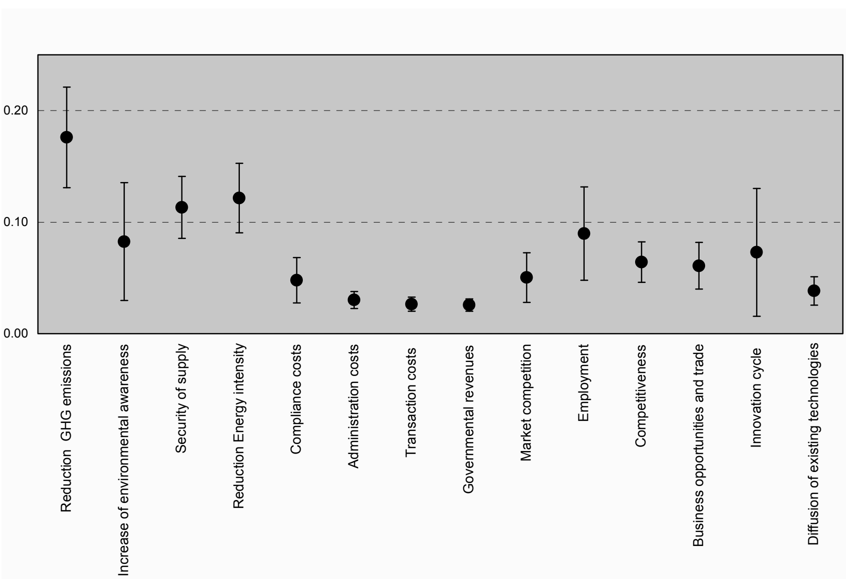

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Figure 31: Spread of criteria weights (95% confidence level)

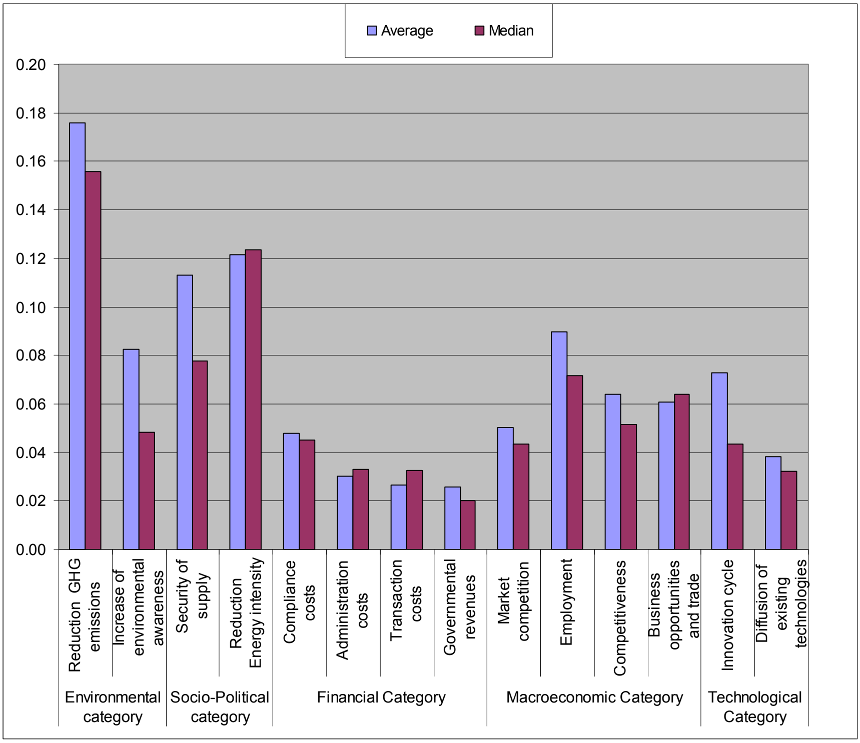

Figure 32: Average and median criteria weights

It can be observed in figure 32 that there is significant deviation between average and median value of some criteria weights. In particular, the criteria of 'increase of environmental awareness', 'security of supply' and 'innovation cycle' obtain the highest deviation between average and median which means that few respondents assigned high weights and force the average values upwards. On the contrary, the criteria with less variation of the assigned weights by the stakeholders are those of 'reduction of energy intensity', 'business opportunities' and 'compliance costs'.

In case we would like to explore how stakeholders value and weight different criteria categories we can simply add the criteria weights for each specific category (see figure 33). However, we should be aware of the risk of splitting bias that exists while there is a tendency to weight more the categories with more criteria than the categories with fewer criteria. Therefore, we should interpret these data with care and be cautious about the conclusions that can be drawn. Nevertheless, we can observe that financial category is being weighted with the second lowest value factor even if includes four criteria. In addition environmental and socio-political categories have been weighted with high values and much higher than the technological category (which also includes two criteria).

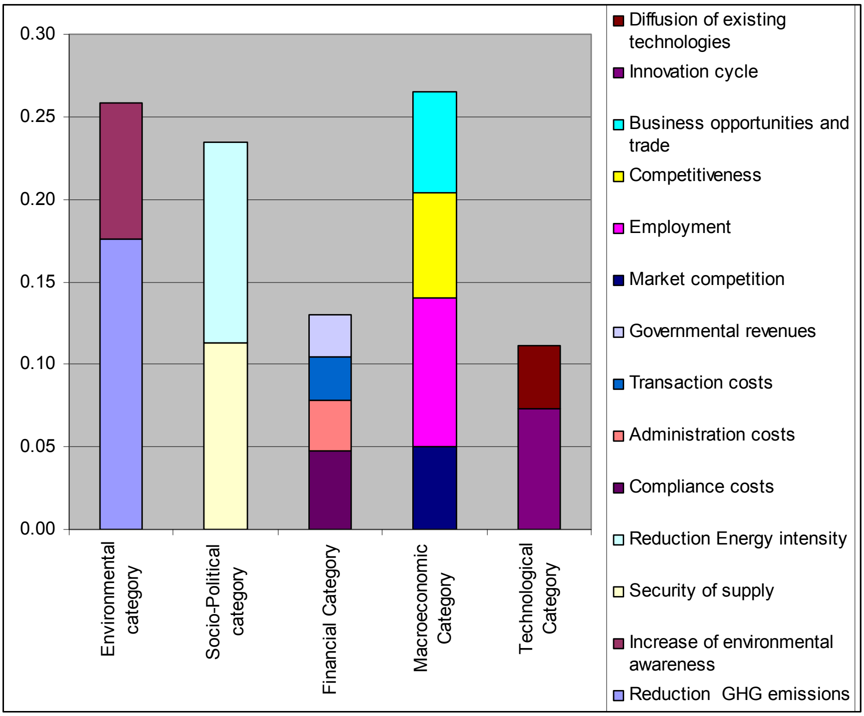

Figure 33: Criteria categories' weights

Figure 34 shows the differences of criteria weights that have been assigned between different stakeholder groups. In our application we have distinguished two stakeholder groups: 1) academics and 2) market players (energy experts, consultants etc.). It can be observed from figure 35 that the group of market players perceives some criteria much more significant than the group of academics do.

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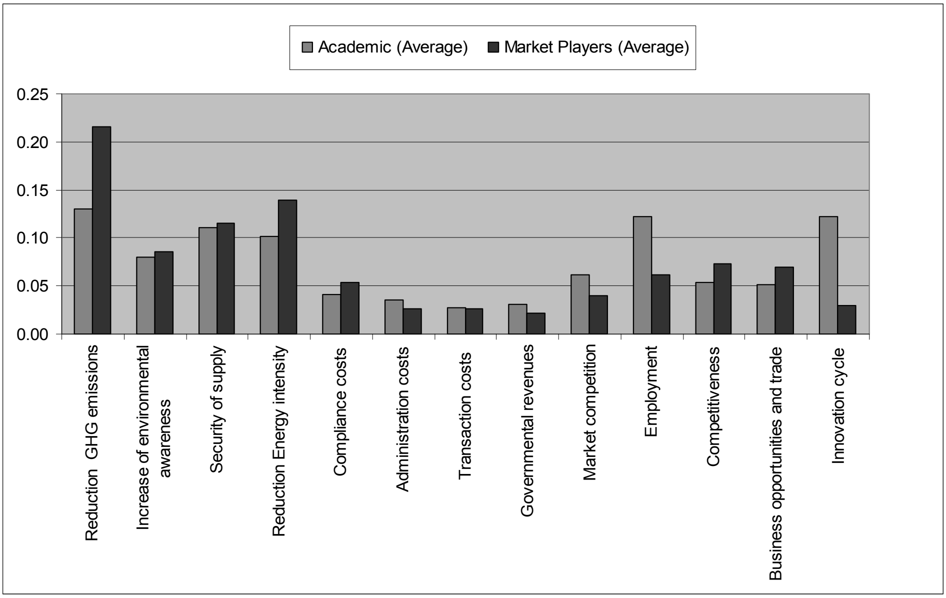

Figure 34: Criteria weights of different stakeholder groups

In particular, 'reduction of GHG emissions', 'reduction of energy intensity', 'compliance costs', 'competitiveness' and 'business opportunities and trade' assigned with much higher weights by market players than by academics. On the contrary 'market competition', 'employment' and 'innovation cycle' have been considered with more significance by the group of academics than by the group of market players. In order to have more robust results or to explore the views and preferences of other type of stakeholders, a bigger sample of respondents would be essential to be involved in the study.

It can be observed from figure 35 that some average and median values of criteria weights had significant differences within the group of academics.

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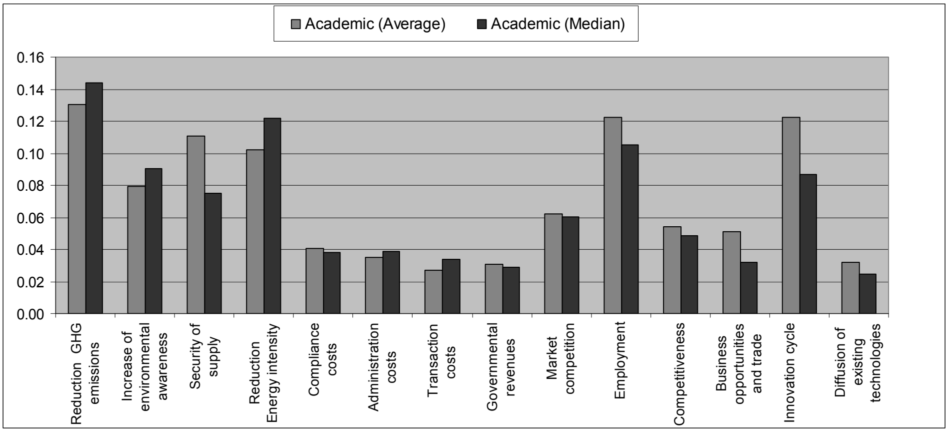

Figure 35: Average and median weights of group of academics

On the other hand the differences between average and median weights were mainly insignificant within the group of market players, as shown in figure 36.

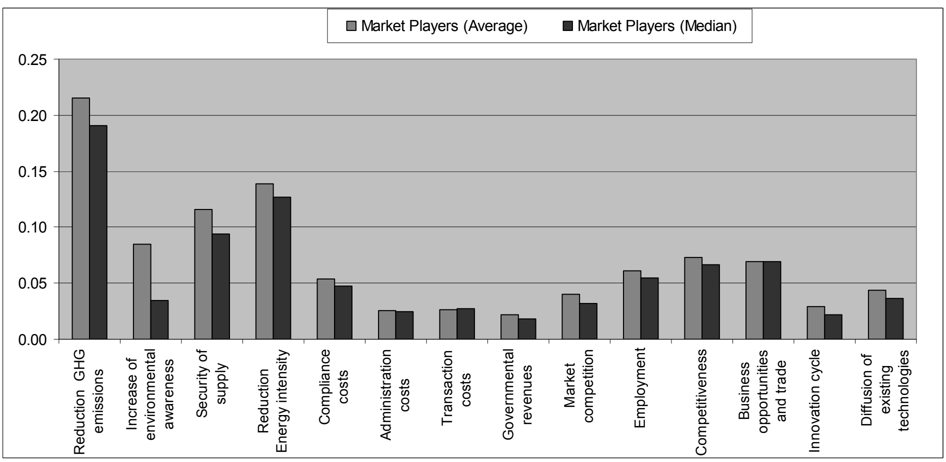

Figure 36: Average and median weights of group of market players

This probably could be explained from the fact that market players represent more unified preferences than the group of academics. In particular, the median weight of the 'reduction of GHG emissions' is estimated higher than the average weight, which means that few academics

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assign very low values to this criterion and consequently drive the average value downwards. Therefore, this may also explain the major difference between the average weighting values of the two groups for the criterion of 'reduction of GHG emissions'.

Regarding the policy options' final scores and ranking, the policy option of combining the policy instruments (interaction) performed best for all stakeholders irrespective their background and the particular group they belong (see figure 37). This result coincides with many practices in EU countries where EU ETS has been complemented by the feed in tariff for renewables.

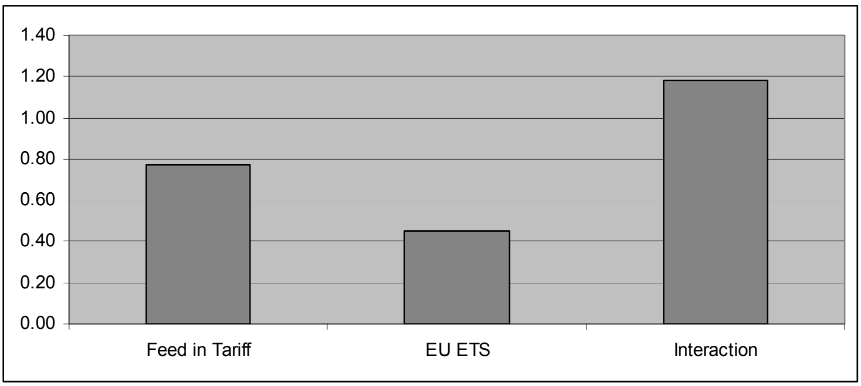

Figure 37: Average weighted scores of policy options

Figure 38 demonstrates how different criteria contributed to the final score of the most desirable policy option taking into account their weighted scores. It can be noticed that the criterion of 'reduction of GHG emissions' has the highest contribution to the final average score of the interaction policy option. This figure can illustrate also the main synergies and conflicts between certain criteria concerning the particular examined policy option. For instance, we can clearly observe that this policy option performs high score simultaneously on specific criteria (synergies) like 'reduction of GHG emissions', 'security of supply', 'increase of environmental awareness' and 'business opportunities and trade'. On the contrary, this achievement is being realized on the expense of other criteria (e.g. administration and transaction costs) highlighting conflicts between criteria.

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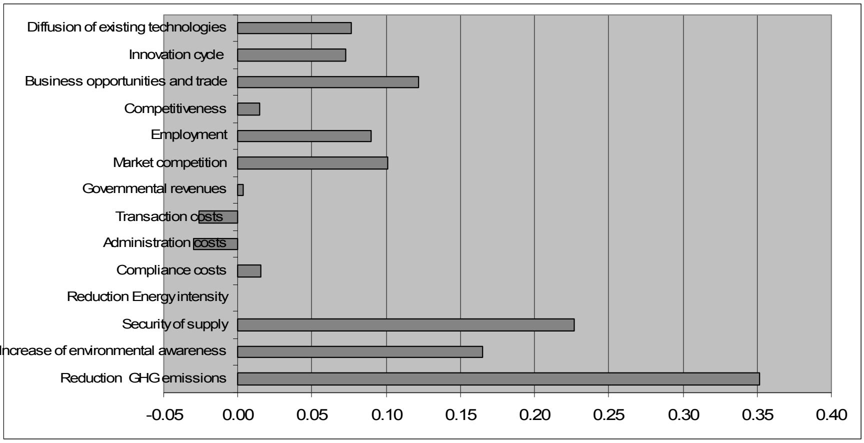

Figure 38: Contribution of criteria to the final score of the interaction policy option

The share of each criterion to the final score can be further analyzed and categorized into individual components of criteria weights and scores and thus indicate the main policy drivers of the policy design process and the different perspectives affecting the policy outcome.

The development and application of this weighting methodology contributed also to the improvement of weighting methods for mapping stakeholders' preferences in climate and energy policy evaluation:

- It has the capability to consider a high number of criteria.
- It is user friendly weighting procedure (structured, simple, transparent), it does not require a lot of time and effort from stakeholders and it therefore reduces the cognitive burden required by them.
- The weighing method has been applied by the use of excel tool which has been developed for this purpose and provide the appropriate automated modules.
- It provides the ability to respondents to interact with the results and revise their initial preferences whereas a ranking consistency index gives them the opportunity to check the consistency of their rank order preferences

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- It can be used by many and different individuals simultaneously either in a form of individual interview or by electronic communication
- It can be used within groups to identify trends, preference differences and conflicts, and raise a discussion for the evaluation problem at hand.

Conclusions

In a policy environment where EU ETS has been introduced since 2005 and renewable energy targets have been set for all EU Member States (MSs) as laid down within the recently agreed climate and energy package, the assessment of interactions between energy and climate policy instruments is essential. The Energy and Climate Policy Interactions (ECPI) framework can serve these need in a quite satisfactory way by considering different aspects and objectives within the analysis and furthermore with the ability to embed stakeholders' preferences and weights towards certain policy objectives. Our analysis of ECPI characteristics and the testing applications are illustrative of the following aspects:

Integration of different aspects

ECPI includes specific parts to decompose the issue of assessing policy instruments' interactions into structural elements of the climate policy problem and then to integrate and synthesize them within one unified policy analysis framework. We have distinguished 5 main aspects as main criteria categories: 1) environmental, 2) socio – political, 3) financial, 4) macroeconomic and 5) technological that are taken into account and have been further decomposed into 18 evaluation criteria. Apart from the integration of various aspects of climate policy the tool incorporates stakeholders' preferences as well. In addition, one of its greatest strengths is the capability to integrate normative judgements (e.g. stakeholders' preferences) and technical expertise (e.g. experts' judgements).

Transparency

Transparency of the impacts, the preferences and the conflicts between the criteria is extremely important for every decision maker. The policy makers and stakeholders need insight into the nature of these parameters in order to make the decision. Transparency of the decision process is again important for the acceptance of the decision and the implemented climate and energy policy strategies by the affected people. As MCDA improves this transparency, it can improve the decision process and the design of climate and energy policies. The result of a MCDA is usually a ranking or a set of rankings of policy options. This ranking is not unequivocal; it is dependent among others on the preference structure of the stakeholders involved. In our case study, MCDA does not provide only one exact ranking, but it provides the background of the ranking and the information about its formation.

Learning and awareness process for stakeholders

The tool comprises of certain interactive elements that keep the respondent aware about the specific characteristics and areas of policy instruments interactions, the likely impacts of interactions towards certain evaluation criteria, his own preferences and how these preferences affect the final outcome.

Identification of synergies and conflicts

By the application of the tool synergies and conflicts between criteria can be identified and therefore areas for further improvement can be highlighted. By categorising the policy problem into structural elements we can observe which elements and parts function as potential conflicts and thus try to improve them for optimizing the policy design.

The stakeholders who have tested ECPI and its weighting module have expressed positive opinions about the its usefulness, especially with regard to its characteristic to identify policy instruments interactions that should be further analysed and the improvement of the decision making process transparency.

Some conclusions can be drawn also based on the application of the tool:

- Based on the application of the tool, the criteria of ‘GHG emissions reduction’, ‘reduction of energy intensity’, ‘security of energy supply’ performed as the most significant, whereas ‘transaction costs’, ‘governmental revenues’ and ‘administration costs’ performed as less significant.

- Different groups of stakeholders, namely academics and market players weight differently the evaluation criteria. Furthermore, market players' preferences, regarding the criteria, proved to be more unified and less dispersed as was the case with the group of academics where significant variations observed between their responds.
- The policy option of interaction of the examined policy instruments (EU ETS and feed in tariff) performed best for each one of the respondents.

The overall Energy and Climate Policy Interactions (ECPI) framework and its weighting technique should not be considered as static. On the contrary, it is a dynamic instrument that is open to changes, improvements, adaptations. It has an evolutionary character, which lies in the concept of integrated climate and energy policy. Being aware of certain limitations of the current version of the tool we can draw specific directions for further improvement.

- In the current version of the tool the selected list of criteria is based on the analysis of climate and energy policy aspects by the research team whereas stakeholders' involvement is limited to the final refinement of the set of criteria. The possibility of including stakeholders more actively in the process of selection of criteria could also be explored, where criteria can be discussed, added, changed or removed. This prospect could also minimise the risk of any personal or institutional bias that might arise during the predefined selection of the criteria.
- This case study was limited in terms of number of respondents contacted and answered. More robust results could be derived by engaging a wider range of stakeholders and to form more groups of stakeholders and then map their perceptions based on the elicitation of criteria weights.
- Furthermore, the tool can be examined at group decision making context and serve stakeholders as communication and mapping tool. Then participants can shape and share information in order to reach a reciprocal understanding, highlight differences, identify potential conflicts and strive towards building upon a communicative consensus. Thus it could be used as a communication and dialogue tool which should improve negotiation process through better understanding and more transparent dialogue which consequently enhance the overall policy design.

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Annex 2: Results of the stakeholders' indicators validation survey

Thirty (30) respondents from 18 European countries participated in the survey on refinement and validation of evaluation criteria and indicators. Almost half (43%) of the respondents represented Southern Europe (Italy, Greece, Spain, Portugal, and Croatia). Twenty (20%) of the respondents came from Eastern Europe (Georgia, Bulgaria, Romania, and Turkey), while another 20% were from Northern Europe (United Kingdom, Denmark, Sweden, Ireland, and Lithuania). Seventeen percent (17%) of the respondents represented Western Europe (Belgium, Austria, France, and Germany).
The survey respondents were associated with five (5) stakeholder groups. These were: 1) civil society and non-government organizations (27%), 2) energy agencies (27%), 3) governmental organizations both local and national (23%), 4) academic/research institutes and consultants/advisors (14%), and 5) market players (i.e. electricity and energy associations, regulators and network administrators, electricity producers) (9%).
Majority of the respondents opted for the retention of all 23 criteria and indicators for evaluating low-carbon energy technologies. After the completion and analysis of the survey results on refinement and validation, there was a modification in the final selection. Two (2) economic criteria, namely employment (short run) and employment (long run), were integrated into one as (local) employment generation. No additional criteria and indicators were added into the final selection. The number of criteria and indicators for evaluation were reduced from the original list of 23 to 22.
Since majority of the respondents supported and validated the selected criteria, no significant changes were made. However, the researchers tried to integrate most of the respondents' comments and suggestions by streamlining the description of criteria. This is to highlight the scope of the study and to justify why certain criteria were included in the end. In addition, it became obvious that certain comments from the respondents were due to misinterpretation of the description of criteria and therefore, the streamlining also aimed to remove all possible misinterpretations that could occur during the stage of technologies impact assessment and criteria weighting.

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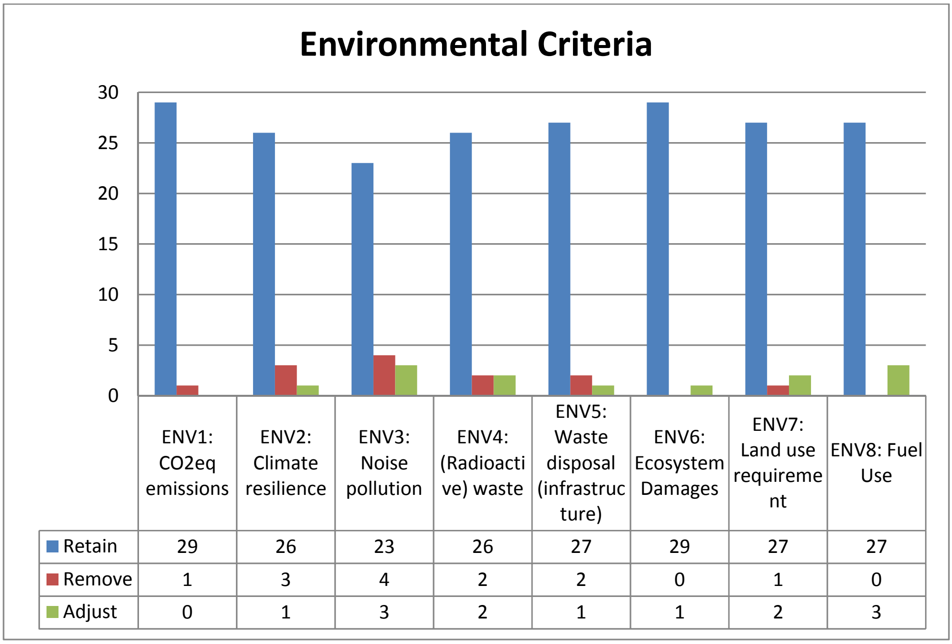

	ENV1: CO2eq emissions	ENV2: Climate resilience	ENV3: Noise pollution	ENV4: (Radioactive) waste	ENV5: Waste disposal (infrastructure)	ENV6: Ecosystem Damages	ENV7: Land use requirement	ENV8: Fuel Use
Retain	29	26	23	26	27	29	27	27
Remove	1	3	4	2	2	0	1	0
Adjust	0	1	3	2	1	1	2	3

Figure 39. Survey results for environmental criteria.

CO_2eq emissions and ecosystem damages were the most favored with majority (97%) of the respondents voting for the retention of each criterion (see figure 39).

According to the respondents, "noise pollution is not important in global warming" and it is "difficult to assess and explain (to public) for the different technologies", hence, the suggestion for removal. However, noise pollution is directly related to sustainability and therefore is relevant to the sustainability assessment of low-carbon energy technologies. According to Hirschberg (2007) noise pollution is considered an important criterion when evaluating energy technologies. The level of importance in any case would be elicited during the weighing process. Furthermore, noise pollution impacts have been assessed by experts (See Annex 4 for the impact assessment matrix).

Climate resilience was favored by the 87% of the respondents whereas one (1) respondent stated that the criterion needed adjustment with the explanation that "climate change in the future might be less gradually altered" and that "changes will be more sudden". Three (3) respondents who voted for the removal of this indicator mentioned

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its irrelevance “as nobody can predicate climate change” and that the objective is to “mitigate climate change”.

The main objective of the assessment is not only to look at the climate mitigation objective but also to consider all other important sustainability aspects, such as environmental, social and technological ones, in an integrative manner. Therefore, the resilience of the energy systems to future climate is an important aspect to be taken into account even with certain degree of uncertainty of the future climate (The Royal Academy of Engineering, 2011). There are already climate models providing scientific evidence on climate predictions for the coming decades in the European continent (IPCC 2007; Christiensen et al. 2011) and good indications on the likely impacts on future energy systems (Ebinger and Vergara 2011; Dowling 2013).

Regarding the criterion of (radioactive) waste 87% opted for its retention. Seven percent (7%) of the respondents were in favor of the removal of (radioactive) waste as one explained that it is “not relevant”. (Radioactive) waste is an important criterion as this poses potential harmful impacts to environment and even when handled properly, is still subject to human aversion. Also, 7% of the respondents were in favor of adjustment with one respondent suggesting that waste and radioactive waste should be separated because it is not one and the same. The criterion under evaluation pertains solely to radioactive waste and thus, adjusted accordingly.

With regards to waste disposal (infrastructure), 90% of the respondents favored its retention, whereas 7% of the respondents opted for its removal with one respondent explaining that it is “not widely acceptable”. Just one (1) respondent was in favor of adjustment with the comment of “no dangerous wastes can be treated as common waste”.

As for fuel use, 90% of the respondents were in favor of keeping it as it is, whereas 10% were in favor of adjustment with the following suggestions: “amount of primary energy should be used instead" and “fossil energy use (gas, coal, etc.)". The notion of this criterion is to express the availability or scarcity of the fuel. Apart from fossil fuels used in gas turbine combined cycle (GTCC) and integrated gasification combined cycle (IGCC), uranium is used as a fuel in nuclear power plants. Renewable energy sources, on the other hand, require minimum use of fossil fuels during their production phase.

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Similarly, the vast majority of respondents (90%) favored the retention of land use requirement criterion. Three percent (3%) of the respondents were in favor of the removal of land use requirement as it is considered of “minor importance compared to the others”. Seven percent (7%) of the respondents said that it needed adjustment as it is “not very important” and “not only environmental criteria, [but] it is one of the most pressing social criteria as well’’. However, for this research study, the methodology allows for the provision of factors of relative importance of criteria, depending on stakeholders’ preferences, and therefore respondents determine the level of importance of criteria. Land use requirement remains a relevant criterion according to different authors (e.g. Afgan and Carvallo 2002; Beccali et al. 2003; Flamos et al. 2004), and it is conventionally classified under environmental category with clear social implications as well.

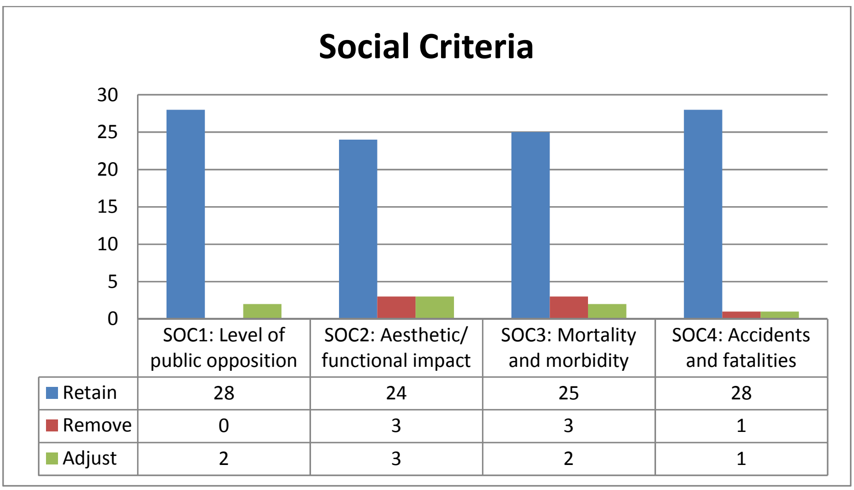

Figure 40. Survey results for social criteria.

Level of public resistance/opposition and accidents and fatalities were the most favored social criteria by the vast majority of respondents (93%) (see figure 40). However, 2 respondents thought that the level of public resistance/opposition needed adjustment as “there should be differences between resistance to nuclear or wind”. The latter comment, however, is already captured by the experts' judgments which are reflected in the impact assessment matrix.

Eighty percent (80%) of the respondents were in favor of keeping the criterion of aesthetic/functional impact. Ten percent (10%) of the respondents deemed that aesthetic/functional impact needed adjustment. The respondents thought that aesthetic/functional impact "fits better with the environmental indicators". Aesthetic/functional impact is an important criterion that combines both aesthetic and landscape impacts and is also related to perceptions of citizens. Therefore, it entails both social and environmental components. The research team decided to keep it in the social criteria category for a better balance between social and environmental categories. One of the respondents who voted for the removal questioned how aesthetic/functional impact is measured. As provided in the general definition, aesthetic/functional impact is measured in relative ordinal scale, and it was assessed by experts during the experts' impact assessment survey which is included in the impact assessment matrix (Annex 4). Also, two (2) of the respondents deemed necessary to adjust the indicator mortality and morbidity. Three (3) of the respondents, on the other hand, suggested its removal. However, mortality and morbidity was favored by the vast majority (83%) of the respondents. Furthermore, it is certainly relevant as a criterion in the evaluation of energy technologies as it also reflects the health impacts of air pollutants. Certain pollutants, such as particulate matter, for example, are main causes for mortality and morbidity of people near power plants (Chatzimouratidis and Pilavachi 2008).

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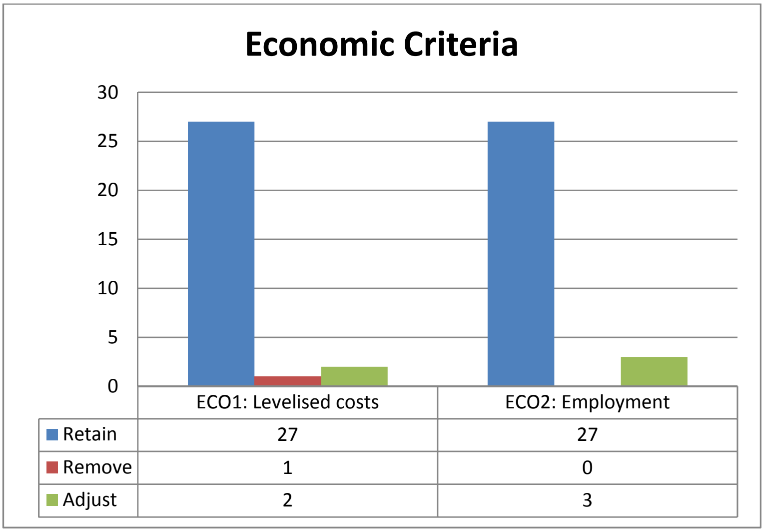
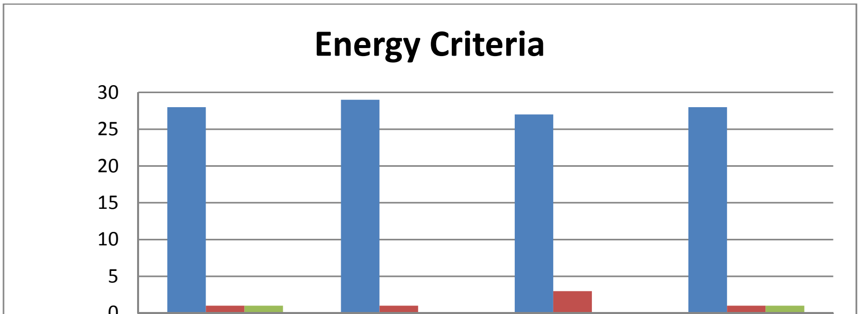


Figure 41. Survey results for economic criteria.

For levelised costs, 90% of the respondents opted for retaining the criterion as it is (see figure 41. For the same criterion, 2 respondents (7%) opted for its adjustment with the explanations that “costs need to be compared with the costs of another solution and/or of not acting” as well as the need “to identify costs and benefits” and “subsidies (for fossil fuels) and environmental cost should be included”. The comparison between the costs of technologies is already being addressed by this research study. Moreover, the MCA approach addresses the costs and benefits, including environmental-related ones (e.g. ecosystem damages, reduction of GHG emissions) of the different low-carbon energy technologies. Within the context of electricity generation, levelised costs of energy reflect the costs of building, operating, and maintaining a facility within the life cycle of the project (IEA 2010).

As for employment, again 90% of the respondents opted for keeping the criterion. Three respondents opted for the adjustment of this criterion whereas one expressed the comment that “local jobs solution (is) less interesting if the jobs are created elsewhere.” One conventional view conveys that renewable energy generation, creates additional jobs as decentralization provides more labor intensive employment. Moreover, it is argued that this sector puts the employment opportunities in the energy industry in domestic terrains where fossil resources are low (IEA 2012).



	ENE1: Energy cost sensitivity to fuel price fluctuation	ENE2: Stability of energy generation	ENE3: Peak load response	ENE4: Market concentration on supply
Retain	28	29	27	28
Remove	1	1	3	1
Adjust	1	0	0	1

Figure 42.Survey results for energy criteria.

With regard to the energy criteria, the vast majority of respondents confirmed the selection of criteria and favored their selection (figure 42). The most favored energy criteria were stability of energy generation (96%), followed by energy cost stability/sensitivity to fuel price fluctuation (93%), market concentration on supply (93%), and peak load response (90%). Three percent (3%) of the respondents said that energy cost stability/sensitivity to fuel price fluctuation needed adjustment as "[to] renewable’s fuel prices fluctuation is not very significant". Energy cost stability/sensitivity to fuel price has already been studied, and the estimates were derived from expert’s judgments as reflected in the impact assessment matrix. Indeed, renewables are the least sensitive to such fuel price fluctuations whereas fossil based fuel technologies are highly sensitive. Therefore, the criterion was included in the assessment.

Three respondents thought that peak load response should be removed with one respondent explaining that it "can be solved by smart grids or other energy production". Smart grids would not be fully operationalized in the whole European continent.

Therefore, we decided to keep this indicator in the current set and let the respondents during the weighting stage to decide on its importance, depending on the local context. Market concentration on supply needed to be adjusted according to 3% respondents as the "criterion is not very significant to renewable”. The weighting elicitation that has been applied enables one to derive the relative importance of one criterion compared to another. One respondent was also in favor of its removal with the explanation that is "(already) included in energy cost stability”. As it has been described, the criterion of “energy cost stability to fuel fluctuation” refers only to sensitivity to fuel price sensitivity and not to the power that certain suppliers may enjoy due to their oligopolistic market position since this is captured at a different criterion namely “market concentration”. To avoid similar misinterpretations during the weighting stage, clarifications were added on the descriptions of the “energy cost stability to fuel fluctuation” and “market concentration” criteria.

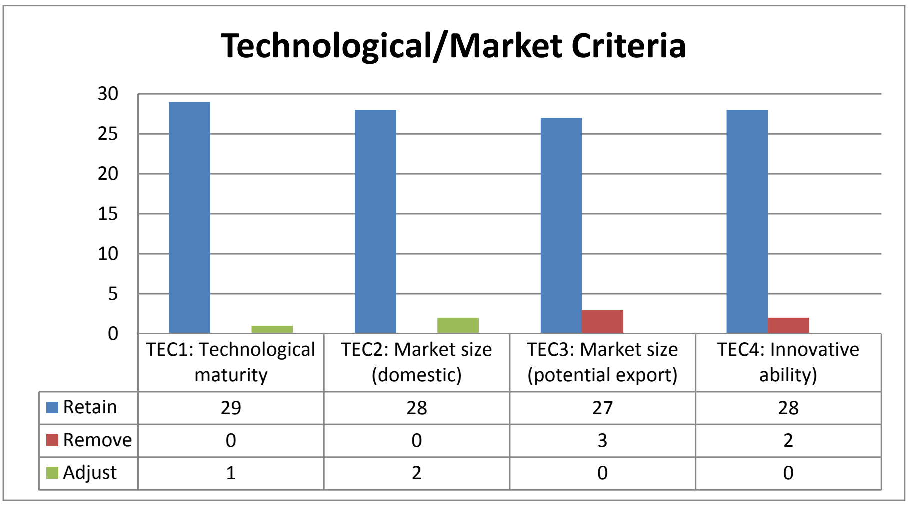


Figure 43.Survey results for technological criteria.

Most of the respondents expressed their clear preference of retaining all technological criteria (see figure 43). The most favored technological criterion was technological maturity (96%), followed by market size- domestic (93%), innovative ability (93%), and market size - potential export (90%). Three (3) of the respondents thought that market size (potential export) needed to be removed, with one respondent explaining that it is "not relevant". The relevance of market size – in general – and potential export in particular, should not be understated as it would provide potential economic opportunities and possibly further technological advancements as well. A larger market size attracts more investments. Many countries, also in Europe, aim to expand their market shares not only domestically but internationally as well while developing local business opportunities to meet the demand (Lewis and Wiser 2007, Shen et al. 2010). Only 2 respondents suggested the removal of innovative ability as it is "not necessary [as] we need stable production." Stable production, as was suggested, is captured by energy category criteria. There was no additional indicator suggested by the survey respondents for inclusion under the technological criteria.

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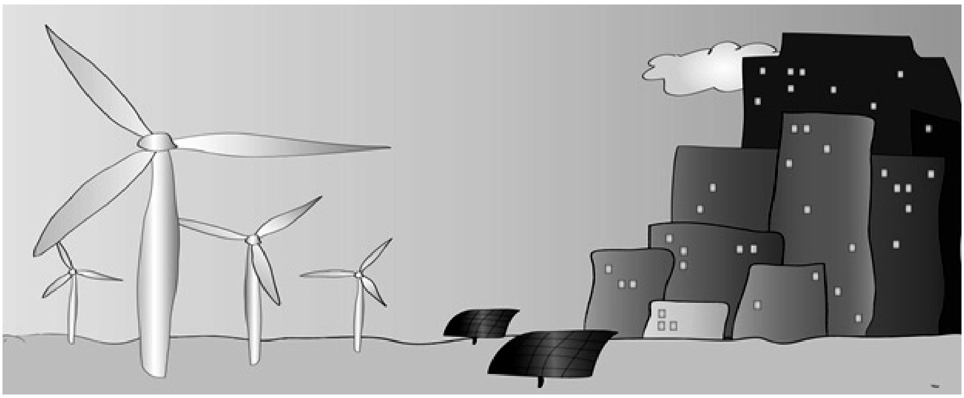
Annex 3: Developed Excel based tool of weighting methodology



Profile of Respondent

Kindly provide your name, organization, country of residence as well as indicate the stakeholder group you belong to. We assure you that individual responses will be kept confidential and will only be used for this research study alone.

Name (optional): ______________________________

Organization (optional): ______________________________

Country and city of Residence: ______________________________

Select the the stakeholder group you belong to by putting an X sign:

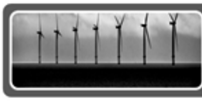
a. Government (National level) ________

b. Government (Regional level) ________

c. Government (Local level) ________

d. Other (Please specify) ________

Step 1. Study the descriptions of the low-carbon energy technologies under investigation.



Wind Offshore

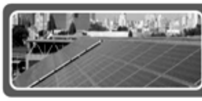
The shortage of land sites for onshore wind energy has spurred the interest in exploiting offshore wind energy. Offshore wind farms consisting of multiple wind turbines all connected to a single transformer station are more financially viable than individual turbines. Offshore sites also enjoy the advantage of having significantly more stable and higher wind speeds than onshore sites and which leads to a longer turbine life.

Wind Onshore

The exploitation of wind energy has increased exponentially during the last decades, and there is still large unexploited wind energy potential in many parts of the world – both onshore and offshore. However, the success story of onshore wind energy has led to a shortage of land sites in many parts of Europe, particular in north-western Europe.

Hydropower

The hydro plant Illanz/Panix (Switzerland) is used as the reference reservoir site. Lifetime of the dam is assumed to be 150 years.



Solar Photovoltaic

The PV installation is small and integrated onto a new or existing building. At 420 kW, this is suited to the roof of a public or commercial building and is too large for most domestic residences. Photovoltaic (PV) reference technology for crystalline silicon is the laminated, integrated slanted-roof multicrystalline-Si module in, which is adapted to the electricity production of 850 kWh kWp.

Biogas

Biogas (SNG) from forest wood gasification is assumed to fuel CHP units. Basis for the production of SNG via wood gasification is the assessment of a 50 MW demonstration plant. A commercialized methanation unit with double capacity and increased efficiency, as well as improved CHP unit SNG combustion, reflect the expected technology development until 2030.

Gas Turbine Combined Cycle (GTCC)

GTCC power plant involves the direct combustion of natural gas in a gas turbine generator. The waste heat generated by this process is then used to create steam for use in a steam generator, in a similar manner to that of IGCC technologies. In this combined cycle power plant around two-thirds of the overall plant capacity is provided by the gas turbine.

GTCC with Carbon Capture and Storage (CCS)

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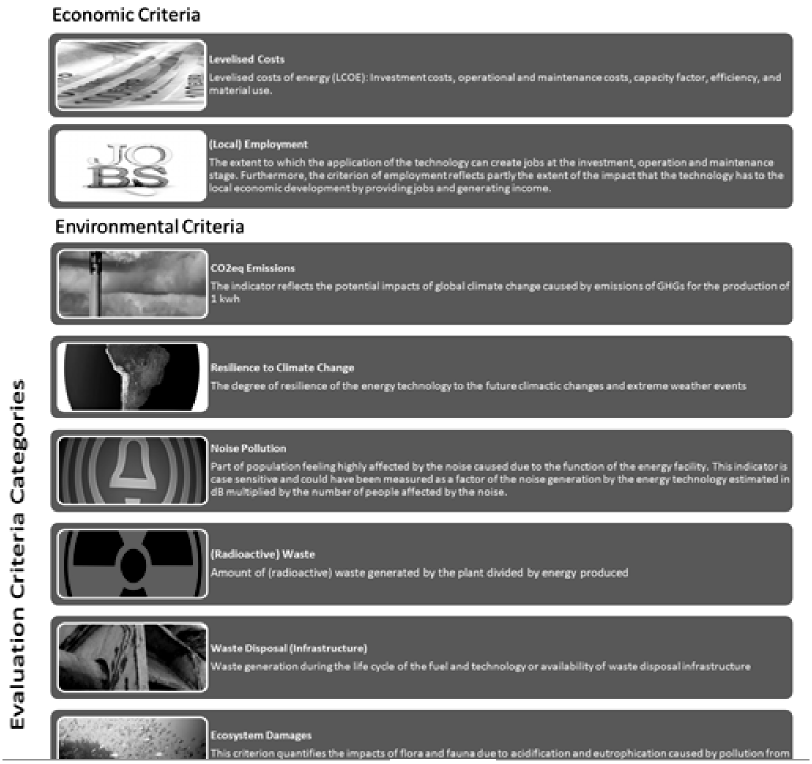
Step 2. Check the different criteria and indicators for assessing low-carbon energy technologies.



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Step 3: Rank all evaluation criteria and indicators based on their relative importance.

This initial ranking is a major step in the weight elicitation process. This step will allow you to be familiarized with the ranking process as well as in how to compare the different evaluation criteria. Start by clicking the first cell under the column 'level of importance'. Using the dropdown menu, rank the first evaluation criteria as to whether it is of high, moderate, or low importance. Continue the ranking process until you reach the last evaluation criteria.

Note: The **impact range** shows the difference between the **best** and **worst** performance of the energy technologies against a specific criterion. Therefore this range shows the potential for improvement moving from the technology with the worst performance to the technology with the best performance. It is essential to consider this when deciding on the level of relative importance of criteria!

	List of Criteria	Unit	Min Score	Max Score	Impact Range	Level of Importance
1	Levelised costs (incl. capital, o&m, fuel costs)	euros/Mwh	69,3	381,5	312,2	High
2	Employment generation	Jobs - year/GWh	0,11	0,87	0,76	High
3	CO2eq emissions	g/kwh	4,0	753	749,0	High
4	Resilience to climate change	"1-5"	2,8	3,8	1,0	Moderate
5	Noise	"1-5"	1,16	3,24	2,1	Moderate
6	Radioactive waste	m3/kwh	3,5E-11	2,3E-08	0,00	High
7	Waste disposal (infrastructure)	kg/kwh	0,037	3,64	3,6	High
8	Ecosystem Damages	PDF*m2*a/kWh	0,00031	0,037	0,04	High
9	Land use requirement	km2/TWh-year	0,00	543	543,0	Moderate
10	Fuel use	Mj/kwh	0,00	7,87	7,9	High
11	Level of public resistance/opposition	"1-5"	1,8	4,6	2,8	Moderate
12	Aesthetic/functional impact	"1-5"	1,7	5	3,3	Low
13	Mortality and Morbidity	YoLL/kWh	1,4E-09	8,7E-08	0,000	High
14	Accident fatalities	deaths	5	50000	49995,0	High
15	Energy cost sensitivity to fuel price fluctuation	%	0	69	69,0	High
16	Stability of energy generation	"1-5"	1,8	3,825	2,0	Moderate
17	Peak load response	%	10	70	60,0	Moderate
18	Market concetration on supply	"1-5"	2,87	3,39	0,5	Moderate
19	Technological maturity	"1-5"	2,73	4,75	2,0	Moderate
20	Market size (Domestic)	"1-5"	2,23	4,11	1,9	Moderate
21	Market size (Potential export)	"1-5"	2,6	4,0	1,4	Moderate
22	Innovative ability	"1-5"	2,1	4,4	2,3	Moderate

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Step 3a: Rank the evaluation criteria that are considered of high-importance.

After ranking all 23 evaluation criteria and indicators, these will be grouped together according to their level of importance - whether high, medium, or low. For this sub-step, check the list of the high-importance criteria below, and assign their rankings specific to this grouping. Start by looking under the green column labelled 'rank high importance criteria'. Assign numbers, with 1 as the most important criterion, 2 as the second most important, 3 as the third most important, and so on. Note: Do not enter a number that is previously selected, and assign rankings specific **ONLY** to high-importance criteria.

	List of Criteria	Min Score	Max Score	Level of Importance
1	Levelised costs (incl. capital, o&m, fuel costs)	69,3	381,5	High
2	Employment generation	0,1	0,9	High
3	CO2eq emissions	4,0	753,0	High
6	Radioactive waste	0,0	0,0	High
7	Waste disposal (infrastructure)	0,0	3,6	High
8	Ecosystem Damages	0,0	0,0	High
10	Fuel use	0,0	7,9	High
13	Mortality and Morbidity	0,0	0,0	High
14	Accident fatalities	5,0	50000,0	High
15	Energy cost sensitivity to fuel price fluctuation	0,0	69,0	High

High Importance Criteria	Select HIGH from the Droplist	Rank HIGH Importance Criteria
Levelised costs (incl. capital, o&m, fuel costs)	High	4
Employment generation	High	9
CO2eq emissions	High	8
Radioactive waste	High	6
Waste disposal (infrastructure)	High	7
Ecosystem Damages	High	1
Fuel use	High	10
Mortality and Morbidity	High	2
Accident fatalities	High	3
Energy cost sensitivity to fuel price fluctuation	High	5

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Step 3b: Rank the evaluation criteria that are considered of moderate-importance.

Check the list of the moderate-importance criteria below, and assign their rankings specific to this grouping. Start by looking under the column 'rank moderate importance criteria'. Assign numbers, with 1 as the most important criterion, 2 as the second most important, 3 as the third most important. Note: Do not enter a number that is previously selected, and assign rankings **ONLY** to moderate-importance criteria.

	List of Criteria	Min Score	Max Score	Level of Importance
4	Resilience to climate change	2,8	3,8	Moderate
5	Noise	1,2	3,2	Moderate
9	Land use requirement	0,0	543,0	Moderate
11	Level of public resistance/opposition	1,8	4,6	Moderate
16	Stability of energy generation	1,8	3,8	Moderate
17	Peak load response	10,0	70,0	Moderate
18	Market concetration on supply	2,9	3,4	Moderate
19	Technological maturity	2,7	4,8	Moderate
20	Market size (Domestic)	2,2	4,1	Moderate
21	Market size (Potential export)	2,6	4,0	Moderate
22	Innovative ability	2,1	4,4	Moderate

Moderate Importance Criteria	Select Moderate from the Droplist	Rank Moderate Importance Criteria
Resilience to climate change	Moderate	11
Noise	Moderate	10
Land use requirement	Moderate	9
Level of public resistance/opposition	Moderate	4
Stability of energy generation	Moderate	5
Peak load response	Moderate	8
Market concetration on supply	Moderate	2
Technological maturity	Moderate	1
Market size (Domestic)	Moderate	6
Market size (Potential export)	Moderate	7
Innovative ability	Moderate	3

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Step 3c: Rank the evaluation criteria that are considered of low-importance.

Check the list of the low-importance criteria below, and assign their rankings specific to this grouping. Start by looking under the column 'rank low importance criteria'. Assign numbers, with 1 as the most important criterion, 2 as the second most important, 3 as the third most important. Note: Do not enter a number that is previously selected, and assign rankings **ONLY** to low-importance criteria.

	List of Criteria	Min Score	Max Score	Level of Importance
12	Aesthetic/functional impact	1,7	5,0	Low

Low Importance Criteria	Select LOW from the droplist	Rank LOW Importance Criteria
Aesthetic/functional impact	Low	1

Step 3d. Check the over-all results of the initial ranking.

The outcome of the previous sub-steps, Step 3d provides you with the over-all results of the initial ranking in the weight elicitation process. Check the ranking below to check whether the results match your preferences. You can go back to the previous sub-steps to modify your preferences in order to achieve consistency as well as satisfaction with the results.

	List of Criteria	Min Score	Max Score	Level of Importance
1	Levelised costs (incl. capital, o&m, fuel costs)	69,3	381,5	High
2	Employment generation	0,1	0,9	High
3	CO2eq emissions	4,0	753,0	High
4	Resilience to climate change	2,8	3,8	Moderate
5	Noise	1,2	3,2	Moderate
6	Radioactive waste	0,0	0,0	High
7	Waste disposal (infrastructure)	0,0	3,6	High
8	Ecosystem Damages	0,0	0,0	High
9	Land use requirement	0,0	543,0	Moderate
10	Fuel use	0,0	7,9	High
11	Level of public resistance/opposition	1,8	4,6	Moderate
12	Aesthetic/functional impact	1,7	5,0	Low
13	Mortality and Morbidity	0,0	0,0	High
14	Accident fatalities	5,0	50000,0	High
15	Energy cost sensitivity to fuel price fluctuation	0,0	69,0	High
16	Stability of energy generation	1,8	3,8	Moderate
17	Peak load response	10,0	70,0	Moderate
18	Market concetration on supply	2,9	3,4	Moderate
19	Technological maturity	2,7	4,8	Moderate
20	Market size (Domestic)	2,2	4,1	Moderate
21	Market size (Potential export)	2,6	4,0	Moderate
22	Innovative ability	2,1	4,4	Moderate

Criteria	OVERALL INITIAL RANKING OF CRITERIA
Levelised costs (incl. capital, o&m, fuel costs)	4
Employment generation	9
CO2eq emissions	8
Resilience to climate change	21
Noise	20
Radioactive waste	6
Waste disposal (infrastructure)	7
Ecosystem Damages	1
Land use requirement	19
Fuel use	10
Level of public resistance/opposition	14
Aesthetic/functional impact	22
Mortality and Morbidity	2
Accident fatalities	3
Energy cost sensitivity to fuel price fluctuation	5
Stability of energy generation	15
Peak load response	18
Market concetration on supply	12
Technological maturity	11
Market size (Domestic)	16
Market size (Potential export)	17
Innovative ability	13

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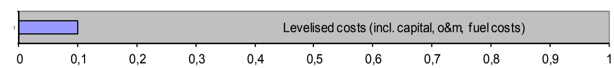
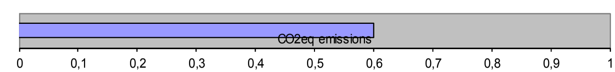
Step 4: Carry out a series of pair-wise comparisons.

At this step of the weight elicitation process, specify which criterion you prefer at each pair-wise comparison (1, 2, 3, etc.). Also, indicate verbally as well as numerically the level of your preference.
The blue horizontal bar in each pairwise comparison shows a graphical representation of your preference.

This step involves three tasks:
(a) Select the criterion you prefer betwen two criteria (**"Between these two criteria, which do you prefer?"**)
(b) Indicate *verbally* the level of your preference (**"How much?"**)
(c) Specify *numerically* the level of your preference (**"Try to score your preference!"**)
Oncer you are finished, observe the over-all results in the next sheet [Step 5].

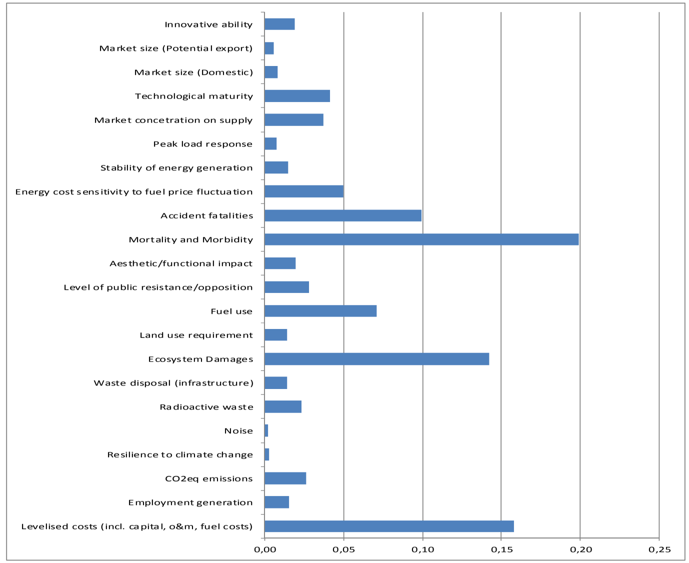
Note: All light green cells below represent the above-mentioned tasks. Click each cell, and a dropdown menu appears. Tick the option that best suits your preference.

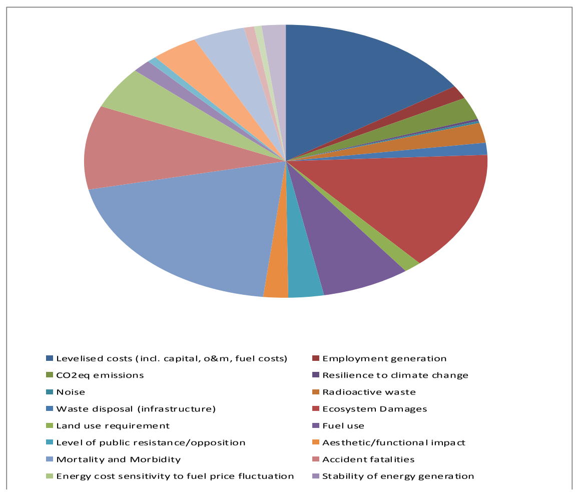
Order	Select the preferred criterion and indicate the level of your preference.		Try to score your preference!			
1	Levelised costs (incl. capital, o&m, fuel costs)	Employment generation	Employment generation	=	0,1	Levelised costs (incl. capital, o&m, fuel costs)
	a) Between these two criteria which do you prefer?	Levelised costs (incl. capital, o&m, fuel costs)	Levelised costs (incl. capital, o&m, fuel costs)	=	10,0	Employment generation
	b) How much?	very strongly				
2	Employment generation	CO2eq emissions	Employment generation	=	0,6	CO2eq emissions
	a) Between these two criteria which do you prefer?	CO2eq emissions	CO2eq emissions	=	1,7	Employment generation
	b) How much?	moderately				

Step 5: Observe the over-all results based on your preferences.
Observe the over-all rankings, including the weighting factors, of the different evaluation criteria under investigation. Also, check the graphic representation of the criteria weights.

	Criteria	Relative Scores	Weighting Factors	RANK (based on pairwise comparisons)
1	Levelised costs (incl. capital, o&m, fuel costs)	1	0,16	2
2	Employment generation	0,1	0,02	14
3	CO2eq emissions	0,2	0,03	10
4	Resilience to climate change	0,0	0,00	21
5	Noise	0,0	0,00	22
6	Radioactive waste	0,2	0,02	11
7	Waste disposal (infrastructure)	0,1	0,01	17
8	Ecosystem Damages	0,9	0,14	3
9	Land use requirement	0,1	0,01	16
10	Fuel use	0,5	0,07	5
11	Level of public resistance/opposition	0,2	0,03	9
12	Aesthetic/functional impact	0,1	0,02	12
13	Mortality and Morbidity	1,3	0,20	1
14	Accident fatalities	0,6	0,10	4
15	Energy cost sensitivity to fuel price fluctuation	0,3	0,05	6
16	Stability of energy generation	0,1	0,01	15
17	Peak load response	0,0	0,01	19
18	Market concetration on supply	0,2	0,04	8
19	Technological maturity	0,3	0,04	7
20	Market size (Domestic)	0,1	0,01	18
21	Market size (Potential export)	0,0	0,01	20
22	Innovative ability	0,1	0,02	13

Go to the next sheet "OVERALL RESULTS"





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Step 6: Check the Consistency Index

Study the index below to to check the consistency of your preferences. A remark at the bottom of the table would indicate whether you need to modify your preferences to achieve consistency or not. If you find inconsisteny, go back to either Step 3 or Step 4 and modify your preferences. Should you have any questions about the consistency index, please do not hesitate to contact us through our email addresses.

Constistency Check

Criteria	Initial Rank	Final Rank
Levelised costs (incl. capital, o&m, fuel costs)	4	2
Employment generation	9	14
CO2eq emissions	8	10
Resilience to climate change	21	21
Noise	20	22
Radioactive waste	6	11
Waste disposal (infrastructure)	7	17
Ecosystem Damages	1	3
Land use requirement	19	16
Fuel use	10	5
Level of public resistance/opposition	14	9
Aesthetic/functional impact	22	12
Mortality and Morbidity	2	1
Accident fatalities	3	4
Energy cost sensitivity to fuel price fluctuation	5	6
Stability of energy generation	15	15
Peak load response	18	19
Market concetration on supply	12	8
Technological maturity	11	7
Market size (Domestic)	16	18
Market size (Potential export)	17	20
Innovative ability	13	13
	0,815	High consistency
	Ranking Consistency Index	

Go to the next step

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SWING weighting technique

- Observe the results of the overall initial ranking (column R) of criteria based on previous steps
- You are now requested to give **values of relative importance** - in descending order.
- Start by assigning the maximum value of **100** points to the **first (1)** ranked criterion that you selected to move first from its **worst to best** performance.
- Then express the relative importance of the **2nd selected** criterion you selected to move from **worst** to **best** performance by providing points between 0 and 100. *(Note: The closer the value of a criterion you assign to 100, the higher its relative importance is in comparison to the most important criterion. For example, assigning 50 points to criterion X means that moving the 1st selected criterion from its worst to best performance is 2 times more important (worthy) than moving criterion X from its worst to best performance.)*
- Continue the process until all criteria are given values (from 0 to 100) expressing the relative importance of moving from their **worst** to **best** performance in comparison to the most important criterion.

Task 1:
Assign 100 points to the highest ranked criterion and then assign points to the other criteria to reflect their relative importance in comparison to the most important criterion

	List of Criteria	Unit	Worst Performance Value	Best Performance Value	Potential improvement	Potential improvement (%)	Level of Importance
1	Levelised costs (incl. capital, o&m, fuel costs)	euros/Mwh	381,5	69,3	312,2	82%	Low
2	Employment generation	Jobs - year/GWh	0,1	0,9	0,8	691%	High
3	CO2eq emissions	g/kwh	753,0	4,0	749,0	99%	High
4	Resilience to climate change	"1-5"	2,8	3,8	1,0	35%	High
5	Noise	"1-5"	3,2	1,2	2,1	64%	Low
6	Radioactive waste	m3/kwh	0,0	0,0	0,0	100%	Moderate
7	Waste disposal (infrastructure)	kg/kwh	3,6	0,0	3,6	99%	Low
8	Ecosystem Damages	PDF*m2*a/kWh	0,0	0,0	0,0	99%	High
9	Land use requirement	km2/TWh-year	543,0	0,0	543,0	100%	High
10	Fuel use	Mj/kwh	7,9	0,0	7,9	100%	High
11	Level of public resistance/opposition	"1-5"	4,6	1,8	2,8	61%	High
12	Aesthetic/functional impact	"1-5"	5,0	1,7	3,3	66%	Low

Criteria	OVERALL RANKING OF CRITERIA (based on previous steps)	VALUE OF IMPORTANCE - Give 100 points to most important criterion and then express the relative importance of all other criteria (0
Levelised costs (incl. capital, o&m, fuel costs)	16	20
Employment generation	4	40
CO2eq emissions	3	100
Resilience to climate change	5	50
Noise	20	10
Radioactive waste	11	20
Waste disposal (infrastructure)	17	40
Ecosystem Damages	6	80
Land use requirement	1	60
Fuel use	2	80
Level of public resistance/opposition	7	50
Aesthetic/functional impact	18	10

Annex 4: Impact Assessment Matrix

		Economic Category		Environmental category								Social Category				Energy Category				Technological Category			
	Criteria / Technologies	Levelized costs (1)	Employment (long-term) (2)	CO2eq emissions (3)	Climate resilience (4)	Noise pollution (3)	Radioactive waste (3)	Waste disposal (infrastructure) (3)	Ecosystem damages (3)	Land use requirement (5)	Fuel use (3)	Level of public resistance/ opposition (4)	Aesthetic/functional impact (4)	Mortality and morbidity (3)	Accidents and fatalities (3)	Energy cost sensitivity to fuel price fluctuation (3)	Discontinuity of energy generation (4)	Peak load response (6)	Market concentration on supply (4)	Technological maturity (4)	Market size (domestic) (4)	Market size (potential export) (4)	Innovative ability) (4)
	Measurement Unit	euros /Mwh	Jobs - year/ GWh	g/kwh	"1-5"	"1-5"	m3/kwh	kg/kwh	PDF* m2*a /kWh	km2/ TWh-year	Mj/kwh	"1-5"	"1-5"	YoLL/ kWh	deaths	%	"1-5"	%	"1-5"	"1-5"	"1-5"	"1-5"	"1-5"
1	IGCC	99,9	0,11	753	2,8	3,0	1,1E-09	2,3	0,013	9,7	6,90	3,4	3,4	7E-08	434	53	1,8	70	3,2	3,8	2,8	3,0	2,4
2	GTCC	78,9	0,11	388	3,0	2,2	3,5E-11	1,7	0,0033	18,6	6,79	2,9	2,8	7E-08	109	69	1,9	70	3,1	4,4	3,7	3,5	2,8
3	EPR	69,3	0,1	4,0	2,9	2,0	0,0	3,6	0,0	2,4	0,07	4,6	3,4	0,0	50000	4,5	2,1	10	3,5	3,4	2,2	2,8	2,7
4	Wind on-shore	107,2	0,17	16	3,5	2,7	8,4E-11	1,7	0,0034	72,1	0,06	3,2	3,6	7E-09	5	0	3,8	10	2,6	4,4	4,1	3,8	3,4
5	Wind off - shore	140,1	0,17	10	3,4	1,5	6,3E-11	1,9	0,0034	0	0,05	2,3	2,6	6E-09	10	0	3,5	10	2,9	3,9	4,1	4,0	3,8
6	Solar Photovoltaics (PV)	381,5	0,87	30	3,7	1,3	2,7E-10	1,7	0,0054	37	0,14	1,8	2,3	1E-08	10	0	3,8	10	2,7	4,2	4,1	3,8	4,3
7	Hydropower (Storage Dam)	104,8	0,27	4	3,5	1,7	4E-11	1,4	0,0003	54	0,00	3,2	3,5	1E-09	285	0	2,4	10	3,0	4,8	3,2	3,1	2,1
8	IGCC with CCS	105,5	0,18	205	3,0	2,7	1,4E-09	3,5	0,022	9,7	7,87	3,6	3,4	6E-08	434	47	1,9	70	3,2	2,7	2,7	2,6	3,3
9	GTCC with CCS	87,8	0,18	120	3,1	2,3	8,6E-10	3,5	0,0045	18,6	7,44	3,5	3,1	9E-08	109	55	1,9	70	3,2	2,9	2,9	2,8	3,3
10	Biomass	244,9	0,2	37,0	3,3	2,0	0,0	0,0	0,0	543,0	0,11	2,2	2,0	0,0	5	22,0	2,5	10	2,9	4,0	3,7	3,4	3,4

Annex 5: Experts impact assessment survey for selected sustainability criteria

IHS
Making cities work

Drift
Dutch Research Institute for Transitions

Experts' Judgment Impact Assessment Survey

1 / 24 | 4%

1. Survey Invitation

Dear Madame/Sir,

I would like kindly to invite you to participate in the Experts' Judgment Impact Assessment Survey of future mitigation technologies in the energy sector against selected evaluation criteria and indicators.
This survey is part of my PhD research which has as its objective the "development of an integrated assessment framework for the evaluation of climate mitigation technologies in the energy sector in Europe for the year 2030".
Based on your knowledge, expertise and experience you are kindly requested to judge the likely impacts of selected technologies in the energy sector in EU in the year 2030 against the evaluation indicators.

We anticipate that completing this questionnaire should take approximately thirty (30) minutes of your time. We can share with you the results (i.e. reports, publications, thesis) of the study as a kind gesture for your time spent on participating in the survey.

Only the researcher will have access to your responses, which will remain confidential and private. Names, addresses and other Personal / Organisational details will not be identified, or divulged to any third party.

I would like to thank you in advance for taking the time to participate in this survey.

Stelios

--
Stelios Grafakos,
Researcher
Institute for Housing and Urban Development Studies (IHS) and
Dutch Research Institute for Transitions (DRIFT)
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phone: + 31 (0)10 4089871
Website:www.ihs.nl

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Experts' Judgment Impact Assessment Survey

2 / 24 | 8%

2. Background and Objective of the survey

The energy sector in European Union is responsible for large amounts of CO2 emissions and can play a crucial role in the efforts towards mitigating climate change along with delivering significant sustainable development benefits. Numerous studies have been conducted to analyse the techno-economics of energy technologies or to estimate their abatement potential mainly from an individual decision maker's point of view neglecting how different views of various groups of stakeholders could result in different outcomes and eventually lead to different rankings of the climate mitigation technologies in the energy sector.

The following survey represents the second phase of a three-stage research process with mainly aiming to provide a qualitative assessment by experts' judgments on the likely impacts of the climate mitigation technologies in the energy sector against selected evaluation criteria and indicators.

The **three phases of the research** are as follows:

Phase 1: Selection of evaluation criteria and indicators (completed)

The list of selected indicators is the outcome of a long process of scrutinizing relevant indicators through a comprehensive literature review and is validated and refined by various stakeholders and experts in the field of electricity technologies in Europe. In addition, all indicators have been screened and filtered by using the principles of comprehensiveness, non redundancy, measurability, availability of data, relevance, understandability and operationality.

Phase 2: Experts' judgment impact assessment survey (current survey)

The objective of the survey is to elicit experts' judgments for the impact assessment of specific climate change mitigation technologies in the energy sector in Europe in 2030 against selected indicators.

Phase 3: Weighting of criteria process (to be followed)

The third phase of the process will aim to determine the criteria/indicators weights that different groups of stakeholders assign to them and consequently result in different rankings of the technologies within a multi stakeholder multi criteria analysis framework.

Objective of the survey

The objective of the survey is to elicit experts' judgments for the assessment of specific **reference European climate mitigation technologies in the energy sector in 2030** against selected indicators. The quantification of the indicators will be based on a relative qualitative scale from **very low (1) to very high (5)**. In addition the survey aims to seek validation of specific indicators that have been assessed qualitatively by other studies.

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Experts' Judgment Impact Assessment Survey

3 / 24 — 12%

3. Expert's Profile

1. It is optional to fill in your personal data

Name ____________

Surname ____________

Email ____________

2. Please fill in the following information *

Country of Residence ____________

Job description (i.e. engineer, economist, social scientist, etc) ____________

3. Organization *

- ☐ University
- ☐ Research Centre
- ☐ Energy Association
- ☐ Energy Production
- ☐ Governmental
- ☐ Other (Please Specify) ____________

4. Scale of Organization

- ☐ Up to 50 employees
- ☐ Between 50 - 100 employees
- ☐ More than 100 employees

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Experts' Judgment Impact Assessment Survey

4 / 24 — 16%

4. Technical Expertise

You are requested to state the type and level of your expertise

1. **Please indicate the area(s) of your expertise with regard to the following energy technologies**

*

- ☐ Coal energy technologies
- ☐ Natural gas energy technologies
- ☐ Carbon Capture and Storage
- ☐ Nuclear Power
- ☐ Wind energy
- ☐ Solar PV
- ☐ Hydropower
- ☐ Biogas

2. **Please indicate the level of your expertise regarding the energy technologies**

*

- ☐ Low
- ☐ Medium
- ☐ High

3. **Please indicate the area(s) of your expertise with regard to the following energy impacts/aspects** *

- ☐ Climate impacts to energy systems
- ☐ Functional/aesthetic/noise impact of energy systems
- ☐ Social aspects (e.g public acceptance) of energy systems
- ☐ Energy market aspects
- ☐ Technological aspects

4. **Please indicate the level of your expertise regarding energy impacts/aspects** *

- ☐ Low
- ☐ Medium
- ☐ High

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Experts' Judgment Impact Assessment Survey

5 / 24 20%

5. Description of Energy Technologies

The **average European reference mitigation technologies** in the energy sector under investigation in **2030** are:

1.1 Integrated Gasification Combined Cycle (IGCC) coal

Future reference technology for 2030 is an Integrated Gasification Combined Cycle (IGCC) power plant. Integrated Gasification Combined Cycle (IGCC) technology is an emerging advanced power generation system having the potential to generate electricity from coal with high efficiency and lower air pollution (NOx, SO2, CO and PM10) than other current coal-based technologies.

1.2 Integrated Gasification Combined Cycle (IGCC) coal with CCS

IGCC technology lends itself very well to carbon capture and storage (CCS) due to the higher pressure of the gas stream and the possibility to achieve the highly concentrated formation of CO2 prior to combustion. In order for this to be possible then after having been cleaned of particulates the syngas then enters a shift reaction unit in which the methane reacts with steam to produce hydrogen and CO2. The preferred technique for CO2 separation in applications at higher pressure (i.e. IGCC) is currently physical absorption using solvents commonly used in commercial processes. Once captured, the CO2 can then be treated in the same way as the other technologies incorporating CCS. The resulting power plant net efficiency for this technology scenario is 48.5%. CO2 transport and storage is modelled in the same way that Pulverized Coal power plants are modelled.

1.3 Gas Turbine Combined Cycle (GTCC)

A gas turbine combined cycle (GTCC) power plant involves the direct combustion of natural gas in a gas turbine generator. The waste heat generated by this process is then used to create steam for use in a steam generator, in a similar manor to that of IGCC technologies. In this combined cycle power plant around two-thirds of the overall plant capacity is provided by the gas turbine. Reference technology for large natural gas power plants is a 500 MW Combined Cycle (CC) unit. The analysis focuses on a base load power plant and location of the plant is in Switzerland. Technology development until 2030 is taken into account with higher power plant efficiencies.

1.4 Gas Turbine Combined Cycle (GTCC) with CCS

The electricity generation aspect of this technology is exactly the same as the GTCC without CCS. The flue gas from the GTCC then enters the same CO2 separation, stripping, drying, transportation and sequestration process that is used for coal and lignite CO2 capture.

1.5 Nuclear European Pressure water Reactor (EPR)

This "Generation III" design of nuclear reactor uses either uranium oxide enriched to 4.9% fissile material (uranium-235) or a mix of uranium-235 and mixed uranium plutonium oxide (MOX), with pressurized water as the moderator and cooling agent. The heat from the reaction is used to produce steam to drive a steam turbine generator. It features not only superior reliability and safety over its current "Generation II" counterparts but also higher efficiency. This results in less high-level radioactive waste per unit of electricity generated that requires either reprocessing or long term storage in geological repositories.

1.6 Wind onshore

The exploitation of wind energy has increased exponentially during the last decades, and there is still large unexploited wind energy potential in many parts of the world – both onshore and offshore. However, the success story of onshore wind energy has led to a shortage of land sites in many parts of Europe, particularly in northwestern Europe.

Vestas' V80 2 MW turbine serves as current reference technology for onshore wind power in Germany. The capacity factor for a generic optimal site near to coast of the North Sea is assumed to be 0.29. Future wind turbines in 2030 with higher capacities are assumed to be located at the same or similar sites.

1.7 Wind offshore

The shortage of land sites for onshore wind energy has spurred the interest in exploiting offshore wind energy. Offshore wind farms consisting of multiple wind turbines all connected to a single transformer station are more financially viable than individual turbines. Offshore sites also enjoy the advantage of having significantly more stable and higher wind speeds than onshore sites and which consequently leads to a longer turbine life.

Future wind turbines in 2030 with higher capacities than the current ones are assumed to be located at the Danish part of the North Sea (HornsRev) or similar sites. The whole park is assumed to consist of eighty Vestas V80 turbines with monopile steel foundations.

1.8 Solar Photovoltaics – crystalline silicon (PV)

The PV installation is small and integrated onto a new or existing building. At 420 kW, this is suited to the roof of a public or commercial building and is too large for most domestic residences. Photovoltaic (PV) reference technology for crystalline silicon is the laminated, integrated slanted-roof multicrystalline-Si module in (Jungbluth and Tuchschmid, 2007), which is adapted to the electricity production of 850 kWh kWp at the reference site of Baden, Switzerland. Not only efficiency increase for the PV-cells as such, but also reduced energy demand in the production steps of the PV chains are taken into account for the modelling of the future 2030 reference PV units according to (Bauer et al. 2008, Rot et al. 2009).

1.9 Hydropower

The hydro plant Ilanz/Panix (Switzerland) is used as the reference reservoir site. Lifetime of the dam is assumed to be 150 years (Bauer et al., 2007).

1.10 Biogas

Biogas Synthetic Natural Gas (SNG) from forest wood gasification is assumed to fuel CHP units. Basis for the production of SNG via wood gasification is the assessment of a 50 MW demonstration plant. In this study, the plant is assumed to be located at a Swiss location with sufficient wood available within a radius of 25 km.

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Experts' Judgment Impact Assessment Survey

7 / 24

7. Selected Criteria for assessment

Description of selected criteria

Criteria categories	Indicators	Description
Environmental	Climate resilience	The degree of resilience of the energy technology to the future climatic changes and extreme weather events.
	Noise pollution	Part of population feeling highly affected by the noise caused due to the function of the energy facility. This indicator is case sensitive and could have been measured as a factor of the noise generation by the energy technology estimated in dB multiplied by the number of people affected by the noise. However since we are investigating different energy technologies and systems at a European scale we cannot measure precisely this indicator and therefore we will use an ordinal relevant scale to measure the perceived noise.
Social	Level of public resistance/opposition	Energy system induced conflicts that may endanger the cohesion of society (e.g. nuclear, wind, CCS). Opposition might occur due to the perceptions of people regarding the catastrophic potential or other environmental impacts (aesthetic, odor, noise) of the energy technology/system. This indicator also integrates the aspect of participatory requirement for the application of the technology. The higher the public opposition, the higher the participatory requirement is.
	Aesthetic/functional impact	Part of population that perceives a functional or aesthetic impairment of the landscape area caused by the energy system. The aesthetic impairment is judged subjectively and therefore this criterion fits in the social category than the environmental one. In addition this is also a very location specific indicator and therefore an average metric will be determined measured in relative ordinal scale.
Energy	Stability of energy generation	Stability of output of electric power generated depending on the technology used. This reflects whether the energy supply is being interrupted. The presence of these interruptions impacts the electricity network stability. This criterion reflects whether the energy supply faces any interruptions due to the type of energy technology.
	Market concentration on supply	The market concentration on the supply of primary sources of energy that could lead to disruption due to economic or political reasons.
Technological	Technological maturity	The extent to which the technology is technically mature. The criterion refers to the level of technology's technological development and furthermore the spread of the technology at the market.
	Market size (Domestic)	Demand for final products (of energy technologies) and potential market size domestically (in European Union). The potential market size plays an important role to establish industrial competitiveness and stimulate economic growth.
	Market size (Potential export)	Demand for final products (of energy technologies) and potential market size internationally (outside of European Union).
	Innovative ability	Flexibility and potential of the technology to integrate technological innovations.

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Experts' Judgment Impact Assessment Survey

8 / 24 — 33%

8. Assessment of Energy Technologies

Please answer the following questions by assessing the impact that the selected energy technologies will have against the evaluation criteria

1. **Climate Resilience:**
Consider the **level of resilience** that the energy technology under question will have in 2030 against **climate change and climate variability impacts** such as extreme heat and cold, extreme wind, stress on water resources, floods, coastal erosion and sea level rise. Evaluate the **relative level of resilience** of the energy systems under question from **very low (1) to very high (5).**

	Very low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)
Integrated Gasification Combined Cycle (IGCC) coal	○	○	○	○	○
Integrated Gasification Combined Cycle (IGCC) coal with CCS	○	○	○	○	○
Gas Turbine Combined Cycle (GTCC)	○	○	○	○	○
Gas Turbine Combined Cycle (GTCC) with CCS	○	○	○	○	○
Nuclear European Pressure water Reactor (EPR)	○	○	○	○	○
Hydropower (Storage Dam)	○	○	○	○	○
Wind Onshore	○	○	○	○	○
Wind Offshore	○	○	○	○	○
Solar PV	○	○	○	○	○
Biogas	○	○	○	○	○

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Experts' Judgment Impact Assessment Survey

9 / 24 — 37%

9. Noise Pollution

1. Assume that each energy system in question has the same distance from the residential area in the year 2030. Evaluate the **extent that residents will be disturbed by noise** caused during the energy generation or the transport of materials to and from the plant. Evaluate the (relative) level of **perceived noise** from very low (1) to very high (5).

Before answering this question we present you the **average values** that have been assessed by past experts' studies (Roth et al. 2009 and Gallego and Mack, 2010).

Do you **agree/validate ALL the values** of the past experts' assessment studies of the selected energy technologies against the criterion of **noise**?

Integrated Gasification Combined Cycle (IGCC) - Coal: 3,1

Integrated Gasification Combined Cycle (IGCC) with CCS: 2,6

Gas Turbine Combined Cycle (GTCC): 2,1

Gas Turbine Combined Cycle (GTCC) with CCS: 2,3

Nuclear Power European Pressurized water Reactor: 2

Hydro power (Storage dam): 1,6

Wind Onshore: 2,7

Wind Offshore: 1,4

Solar PV: 1,2

Biogas: 1,9 *

☐ YES, I AGREE WITH ALL
☐ NO, I DO NOT AGREE WITH ALL

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Experts' Judgment Impact Assessment Survey

23 / 24 — 95%

23. THANK YOU very much for completing the Questionnaire!

There is one more step to submit your answers!

1. Would you like to receive the results (i.e. reports, publications) of this study? If yes, please fill in your e-mail address:

2. Would you like also to participate at the **stakeholders' preferences elicitation survey** for **weighting** the evaluation criteria?

☐ YES
☐ NO

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Experts' Judgment Impact Assessment Survey

24 / 24 — 100%

24. Evaluation of the survey

Please provide feedback regarding the e-survey

1. How would you rate the **ease** for filling in the questionnaire?
- ☐ Low
- ☐ Medium
- ☐ High

2. How would you rate the **sufficiency of the information** provided for filling in the questionnaire?
- ☐ Low
- ☐ Moderate
- ☐ High

3. Please provide any comments you may have regarding the survey

You have **successfully completed** the Questionnaire!
Please click on the **SUBMIT** option and we will receive your answers!
According to the preference you expressed before we were **share the results with you!**
THANK YOU very much for your time and participation!

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Annex 6: Webinar on evaluation of low carbon energy technologies

P R I O R I T I Z I N G L O W - C A R B O N ENERGY TECHNOLOGIES F O R S U S T A I N A B L E A C T I O N P L A N N I N G :

A webinar for local stakeholders

P R O G R A M M E O V E R V I E W :

Local urban energy actors have varied interests at stake when selecting low-carbon technologies for imple-mentation. For example, governments purchase energy services to meet the needs of their constituents, whi-le energy producers are responsible for electricity generation. Meanwhile, the local population is directly or indirectly affected by these energy-related decisions.

Nevertheless, the multiple, often conflicting views of stakeholders have to be taken into account in energy planning and decision making. Moreover, it is equally important to prioritize low-carbon energy technology options, particularly in formulating Sustainable Energy Action Plans (SEAPs). All these are crucial in order to reach a consensus, establish legitimacy, and carry out a participatory process.

W H A T D O Y O U G E T F R O M T H E W E B I N A R :

A European study, which provides insights on how local stakeholders value different evaluation criteria and indicators as well as low-carbon energy technologies, will be presented. The webinar aims to enhance know-ledge and learning of participants in multi-stakeholder processes. In addition, the webinar seeks to provide insights on how local energy stakeholders provide their preferences during the prioritization process of low-carbon energy options when conducting SEAPs.

W H O S H O U L D A T T E N D :

The webinar is designed for local stakeholders in the energy context in Europe. These include representatives of the following local stakeholders groups: public authorities (government - both national and local), techni-cal professionals (academe - research, consultants - advisors), energy industry actors (electricity and energy associations, producers, consumers, regulators and network administrators), private sector (financial and tra-ding sector), and civil society (non-government organizations).

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PROGRAMMEDESIGN:

Session 1: HOW LOCAL STAKEHOLDERS CAN PRIORITIZE TECHNOLOGIES IN THEIR SEAPS

FEBRUARY 3, 2014 (MONDAY) AT 3 PM (CET)

Local energy stakeholders highly value economic, environmental, and social criteria which show implied responsibility to-wards local environmental protection, human health and safety, and economic and employment returns. Specific local sta-keholder groups, moreover, have their own set of preferences. With these interests in mind, local energy stakeholders give priority to specific low-carbon energy technologies in formulating their SEAPs. Which technology then best reflects the prefe-rences of local energy stakeholders? Is it wind, solar, hydropower, or biogas, among other options? This session highlights the results of a European study, provides knowledge on integrated evaluation process, and generates feedback from partici-pants.

Time	Activity
5 minutes	**Opening**: Welcome Remarks, Agenda Presentation, General Introduction of Participants
10 minutes	**Introduction to the Prioritization Process**: This highlights the importance of an integrated evaluation process in prioritizing low-carbon energy technologies and how it can be applied in sustainable energy action planning. Also, this provides an over-view of the weighting methodology that enabled the elicitation of preferences of local energy stakeholders.
5 minutes	**Preferences of Public Authorities**: The selected preferences of government representatives (both at the national and local levels) in terms of the criteria for evaluating low-carbon energy technologies will be presented. This group prioritizes public health protection and safety as proven by their high preferences for mortality and morbidity.
5 minutes	**Preferences of Energy Industry Actors**: Energy industry actors expressed high preferences for CO2eq emissions, levelised costs, resilience to climate change, mortality and morbidity, employment generation, ecosystem damages, stability of energy generation, innovative ability, energy cost sensitivity to fuel price fluctuation, and noise.
5 minutes	**Preferences of Technical Professionals**: This group of stakeholders conveyed preferences for CO2eq emissions, fuel use, levelised costs, radioactive waste, ecosystem damages, resilience to climate change, technological maturity, accident fatali-ties, stability of energy generation, and employment generation.
5 minutes	**Q & A**
5 minutes	**Over-all Evaluation about Stakeholder Preferences:** All three groups of local stakeholders expressed high preferences for CO2eq emissions, levelised costs, ecosystem damages, and resilience to climate change. This portion will also highlight the convergence and divergence of preferences among the three local stakeholder groups.
10 minutes	**Evaluation of Low-Carbon Energy Technologies:** Based on local stakeholders' preferences of the evaluation criteria and indicators, the results of the evaluation of low-carbon energy technologies will be presented. The highest-ranked technologies are renewables, namely wind off-shore, solar photovoltaics, hydropower, and wind on-shore.
5 minutes	**Q & A**
5 minutes	**Feedback Session**
10 minutes	**Closing**: Wrap Up, Feedback Session, Invitation to the Second Session, Closing Remarks

HOWTOJOIN:

1. Go to www.iclei-events.webex.com by clicking the link. (Note: Session 2 requires another registration procedure.)
2. Click register. Use the registration password capacit, and submit.
3. Fill out the needed information.
4. You will receive a confirmation email message.
5. Take note of your registration ID and event password.

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Session 2: INTERACTIVE LEARNING PROCESS AMONG LOCAL ENERGY STAKEHOLDERS

FEBRUARY 5, 2014 (WEDNESDAY) AT 3 PM (CET)

Local energy stakeholders express their views about low-carbon energy technologies especially when it directly or indirectly impact their own territories. Through this session, local energy stakeholders will participate in an interactive learning process which will elicit their preferences for the different criteria and indicators for evalua-ting low-carbon energy technologies. An integrated weighting tool that is able to collect preferences on low-carbon energy technologies is introduced and applied together with the participants. This process provides use-ful insights on how to prioritize low carbon energy options when conducting SEAPs.

Time	Activity
5 minutes	**Opening:** Welcome Remarks, Agenda Presentation, General Introduction of Participants
10 minutes	**Overview of the Interactive Preference Elicitation Process:** This section provides a review of the interactive learning pro-cess, including the steps that the participants have to go through. This also highlights the importance of an integrated evalu-ation process in prioritizing low-carbon energy technologies in sustainable energy action planning.
5 minutes	**Q & A**
15 minutes	**Presentation of Initial Results:** The initial results will be presented to the participants. The participants will also have time to discuss among themselves what they think about the initial results, whether they agree with it, and if the group preferen-ces hold true. Emphasis will be provided to large discrepancies in the preferences.
15 minutes	**Revision of Initial Preferences:** This round entails a revision of the stakeholders' weighting process based on the results of the previous discussion. After the participants have carried out discussions and knowledge exchange about the weighting process and the results, they will undergo the process again and revise their preferences.
5 minutes	**Q & A**
10 minutes	**Presentation of Results and Conclusions:** After the revision, the weighting results will be presented to participants. The presentation will show the convergence and divergence of preferences and conclusions shall be generated from the over-all results. The iterative process should enable the participants to know more about other stakeholder judgments, refine their preferences, and learn about multi-stakeholder processes in an interactive way.
5 minutes	**Q & A**
5 minutes	**Closing:** Feedback Session, Closing Remarks

HOWTOJOIN:

1. Go to www.iclei-events.webex.com by clicking the link. (Note: Session 1 requires another registration procedure.)
2. Click register. Use the registration password capacit, and submit. 3. Fill out the needed information.
4. You will receive a confirmation email message.

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5. Take note of your registration ID and event password.

Reminder: Make sure that you have speedy internet connection and that your speaker/ headphones work. We will start the event on time. Please join it at least 10 minutes before the scheduled starting time so you won't miss valuable information. 3

BACKGROUNDINFORMATIONON
Low-Carbon Technologies

Technology	
Integrated Gasification Combined Cycle (IGCC) coal	Future reference technology for 2030 is an IGCC power plant. IGCC technology is an emerging advanced power generation system having the potential to generate electricity from coal with high efficiency and lower air pollution (NO x, SO2, CO and PM10) than other current coal-based technologies.
IGCC coal with Carbon Capture and Storage (CCS)	IGCC technology lends itself very well to CCS due to the higher pressure of the gas stream and the possibility to achieve the highly concentrated formation of CO2 prior to combustion. For this to be possible then after having been cleaned of particulates the syngas enters a shift reaction unit in which the methane is reacted with steam to produce hydrogen and CO2. The preferred technique for CO2 separation in applications at higher pressure (i.e. IGCC) is currently physical absorption using solvents commonly used in commercial processes. Once captured, the CO2 can then be treated in the same way as for the other technologies incorporating CCS. The resulting power plant net efficiency for this technology scenario is 48.5%. CO2 transport and storage is modelled in the same way as for Pulverized Coal power plants.
Gas Turbine Combined Cycle (GTCC)	GTCC power plant involves the direct combustion of natural gas in a gas turbine generator. The waste heat generated by this process is then used to create steam for use in a steam generator, in a similar manner to that of IGCC technologies. In this combined cycle power plant around two-thirds of the overall plant capacity is provided by the gas turbine. Reference technology for large natural gas power plants is a 500 MW Combined Cycle (CC) unit. The analysis focuses on a base load power plant. Technology development until 2030 is taken into account with higher power plant efficiencies.
GTCC with CCS	The electricity generation aspect of this technology is exactly the same as the GTCC without CCS. The fuel gas from the GTCC then enters the same CO2 separation, stripping, drying, transportation and sequestration process to that used for coal and lignite CO2 capture.
Nuclear European Pressure Water Reactor (EPR)	This 'Generation III' design of nuclear reactor uses either uranium oxide enriched to 4.9% fissile material (uranium-235) or a mix of uranium-235 and mixed uranium plutonium oxide (MOX), with pressurized water as the moderator and cooling agent. The heat from the reaction is used to produce steam to drive a steam turbine generator. It features not only superior reliability and safety over its current 'Generation II' counterparts but also higher efficiency. This results in less high-level radioactive waste per unit of electricity generated that requires either reprocessing or long term storage in geological repositories.
Wind onshore	The exploitation of wind energy has increased exponentially during the last decades, and there is still large unexploited wind energy potential in many parts of the world – both onshore and offshore. However, the success story of onshore wind energy has led to a shortage of land sites in many parts of Europe, particular in north-western Europe. Vestas' V80 2 MW turbine serves as current reference technology for onshore wind power in Germany The capacity factor for a generic optimal site near to the coast of the North Sea is assumed to be 0.29. Future wind turbines in 2030 with higher capacities are assumed to be located at the same or similar sites.
Wind offshore	The shortage of land sites for onshore wind energy has spurred the interest in exploiting offshore wind energy. Offshore wind farms consisting of multiple wind turbines all connected to a single transformer station are more financially

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	viable than individual turbines. Offshore sites also enjoy the advantage of having significantly more stable and higher wind speeds than onshore sites and which leads to a longer turbine life. Future wind turbines in 2030 with higher capacities than the current ones are assumed to be located at the Danish part of the North Sea (HornsRev) or similar sites. The whole park is assumed to consist of eighty Vestas V80 turbines with monopile steel foundations.
Solar PVs—crystalline silicon	The PV installation is small and integrated onto a new or existing building. At 420 kW, this is suited to the roof of a public or commercial building and is too large for most domestic residences. Photovoltaic (PV) reference technology for crystalline silicon is the laminated, integrated slanted-roof multicrystalline-Si module in, which is adapted to the electricity production of 850 kWh kWp. Not only efficiency increase for the PV-cells as such, but also reduced energy demand in the production steps of the PV chains are taken into account for the modeling of the future 2030 reference PV units.
Hydropower	The hydro plant Illanz/Panix (Switzerland) is used as the reference reservoir site. Lifetime of the dam is assumed to be 150 years.
Biogas	Biogas (SNG) from forest wood gasification is assumed to fuel CHP units. Basis for the production of SNG via wood gasification is the assessment of a 50 MW demonstration plant. A commercialized methanation unit with double capacity and increased efficiency, as well as improved CHP unit SNG combustion, reflect the expected technology de-velopment until 2030.

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BACKGROUNDINFORMATIONON

Evaluation Criteria

The following are the criteria and indicators identified for evaluating low-carbon energy technologies. Classified under five categories, namely, economic, environmental, social, energy and technological, the following criteria and categories were drawn from a review of literature as well as a validation process.

Category		
Economic	Levelised costs	Levelised costs of energy (LCOE): investment costs, operational and maintenance costs, capacity factor, efficiency, material use
	(Local) employment	The extent to which the application of the technology can create jobs at the investment, operation and maintenance stage. Furthermore, the criterion of employment reflects partly the extent of the impact that the technology has to the local economic development by providing jobs and generating income
Environment	CO2eq emissions	The indicator reflects the potential impacts of global climate change caused by emissions of GHGs for the production of 1 kwh
	Climate resilience	The degree of resilience of the energy technology to the future climactic changes and extreme weather events
	Noise pollution	Part of population feeling highly affected by the noise caused due to the function of the energy facility. This indicator is case sensitive and could have been measured as a factor of the noise generation by the energy technology estimated in dB multiplied by the number of people affected by the noise. However, since we are investigating different energy technologies and systems at a European scale we cannot measure precisely this indicator and therefore we will use an ordinal relevant scale to measure the perceived noise
	(Radioactive) waste	Amount of (radioactive) waste generated by the plant divided by energy produced
	Waste disposal (infrastructure)	Waste generation during the life cycle of the fuel and technology or availability of waste disposal infrastructure
	Ecosystem damages	This criterion quantifies the impacts of flora and fauna due to acidification and eutrophication caused by pollution from the production of 1 kWh electricity by the energy system and technology
	Land use requirement	The land required by each power plant and technology to be installed
	Fuel use	Amount of fuel use per kWh of final electricity consumption
Social	Level of public resistance/opposition	Energy system induced conflicts that may endanger the cohesion of society (e.g. nuclear, wind, CCS). Opposition might occur due to the perceptions of people regarding the catastrophic potential or other environmental impacts (aesthetic, odor, noise) of the energy technology/system. This indicator also integrates the aspect of participatory requirement for the application of the technology. The higher the public opposition, the higher the participatory requirement is.

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		Aesthetic/function al impact	Part of population that perceives a functional or aesthetic impairment of the landscape area caused by the energy system. The aesthetic impairment is judged subjectively and therefore this criterion fits in the social category than the environmental one. In addition this is also a very location specific indicator and therefore an average metric will be determined measured in relative ordinal scale.
		Mortality and morbidity	Mortality and morbidity due to air pollution caused by normal operation of the technology. This indicator is considered as an impact and composite indicator since it integrates all human health impacts caused from air pollution emissions as NOx, SO2, and PM.
		Accidents and fatalities	Loss of lives of workers and public during installation and operation. Surrogate for risk aver- sion. This criterion partly integrates the catastrophic potential of the energy system/ technology.

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BACKGROUNDINFORMATIONON

Evaluation Criteria

Category	Indicators	Description
Energy	Energy cost stability/ sensitivity to fuel price fluctuation	The sensitivity of technology costs of electricity generation to energy and fuels prices fluctuations. The fraction of fuel cost to the overall electricity generation cost.
	Stability of energy generation	Stability of output of electric power generated depending on the technology used. This reflects whether the energy supply is being interrupted. The presence of these interruptions impacts the electricity network stability. This criterion reflects whether the energy supply faces any interruptions due to the type of energy technology. This criterion reflects whether the energy supply faces any interruptions due to the type of energy technology.
	Peak load response	Technology specific ability to respond swiftly to large variation of demand in time/% representing the possibility to satisfy the required load.
	Market concentration on supply	The market concentration on the supply of primary sources of energy that could lead to disruption due to economic or political reasons
Technological	Technological maturity	The extent to which the technology is technically mature. The criterion refers to the level of technology's technological development and furthermore the spread of the technology at the market.
	Market size (domestic)	Demand for final products (of energy technologies) and potential market size domestically. The potential market size plays an important role to establish industrial competitiveness and stimulate economic growth.
	Market size (potential export)	Demand for final products (of energy technologies) and potential market size internationally.
	Innovative ability	Flexibility and potential of the technology to integrate technological innovations.

WEBINARORGANIZER:

The webinar is conducted by the Institute for Housing and Urban Development Studies (IHS) and supported by the ICLEI – Local Governments for Sustainability, European Secretariat (ICLEI Europe) and the Intelligent Energy Europe project, Covenant CapaCITY.

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Annex 7: List of Participating Local Governments

	Country	Local Government	Geographical Location	Population	Gdp (Euros)/*Capita*
1	Italy	**Rome**	Southern Europe	2,638,842	29,900
2	France	**Paris**	Western Europe	2,249,977	25,200
3	Romania	**Bucharest**	Eastern Europe	1,883,425	15,500
4	Austria	**Vienna**	Western Europe	1,794,770	45,600
5	Poland	**Warsaw**	Eastern Europe	1,724,404	15,700
6	Spain	**Barcelona**	Southern Europe	1,620,943	26,600
7	Turkey	**Gaziantep**	Eastern Europe	1,376,352	4000
8	Finland	**Helsinki (greater city)**	Northern Europe	1,059,631	46,200
9	Spain	**Asturias**	Southern Europe	1,006,000	21,300
10	Netherlands	**Rotterdam (greater city)**	Western Europe	978,040	35,400
11	Greece	**Crete**	Southern Europe	620,000	16,000
12	Switzerland	**Zürich (greater city)**	Western Europe	605,812	44,640
13	United Kingdom	**Worcestershire**	Northern Europe	566,500	23,300
14	Belgium	**Antwerp**	Western Europe	512,230	38,900
15	Netherlands	**Utrecht**	Western Europe	321,916	42,300
16	Italy	**Bari**	Southern Europe	313,213	17,100
17	Serbia	**Nis**	Eastern Europe	255,518	4922
18	Spain	**Vitoria-Gasteiz City**	Southern Europe	242,223	30,500
19	Switzerland	**Lausanne (greater city)**	Western Europe	220,846	50,829
20	Italy	**Padova**	Southern Europe	207,245	30,200
21	Georgia	**Batumi**	Eastern Europe	170,000	2936
22	Spain	**León**	Southern Europe	131,680	22,300
23	Bosnia and Herzegovina	**Tuzla**	Eastern Europe	125,000	3837
24	United Kingdom	**Wychavon**	Northern Europe	117,100	22,700
25	Greece	**Thessaloniki**	Southern Europe	111,703	14,400
26	Croatia	**Osijek**	Eastern Europe	108,048	10,400
27	France	**Colombes**	Western Europe	83,220	25,200
28	Denmark	**Roskilde**	Western Europe	81,800	30,200
29	Greece	**Amarrousion**	Southern Europe	72,480	24,800
30	Italy	**Mantua (Mantova)**	Southern Europe	48,353	33,900
31	Denmark	**Vordingborg**	Western Europe	46,600	30,200

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Annex 8: List of publications

Article/publication	Relevance to PhD	Status	Year	Type of publication
Grafakos, S, Ensenado, E., and Flamos, A., 2016, Developing an Integrated Sustainability and Resilience Framework of Indicators for the Assessment of Low Carbon Energy Technologies at the Local Level, *International Journal of Sustainable Energy, doi:10.1080/14786451.2015.1130709*	High	Published	2016	Peer reviewed Article in journal
Grafakos, S, Ensenado, E., Flamos, A., Rotmans, J., 2015, Mapping and measuring European Local Governments' priorities for sustainable and low carbon energy future, *Energies, 8(10), 11641-11666; doi:10.3390/en81011641*	High	Published	2015	Peer reviewed Article in (open access) journal
Grafakos, S, Flamos, A., and Ensenado, E., 2015, Preferences Matter: A Constructive Approach of Incorporating Local Stakeholders' Preferences in the Sustainability Evaluation of Energy Technologies, *Sustainability, 7(8), 10922-10960; doi:10.3390/su70810922*	High	Published	2015	Peer reviewed Article in (open access) journal
Grafakos, S., and Flamos, 2015, A., Assessing low-carbon energy technologies against sustainability and resilience criteria: results of a European experts survey, *International Journal of Sustainable Energy, doi: 10.1080/14786451.2015.1047371*	High	Published	2015	Peer reviewed Article in journal
Oikonomou, V., Flamos, A., Grafakos, S., (2013), Combination of Energy Policy Instruments: Creation of Added Value or Overlapping?, *Energy Sources, Part B: Economics, Planning, and Policy*, 9 (1), 46-56	Moderate	Published	2013	Peer reviewed Article in journal
Grafakos, S., Zevgolis, D. and Oikonomou, V., 2012, Towards a process for eliciting criteria weights and enhancing capacity of stakeholders in ex ante evaluation of climate policies. In: A. Martinuzzi and M. Sedlako eds., 2012, Governance by evaluation for sustainable development : institutional capacities and learning. Cheltenham: Edward Elgar.	High	Published	2012	Peer reviewed Article in a Book
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