SUSTAINABLE ENERGY TRANSITIONS IN AUSTRIA

A PARTICIPATORY MULTI-CRITERIA APPRAISAL OF SCENARIOS

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I hereby declare that this thesis has not been and will not be submitted, in whole or in part, to another University for the award of any other degree.

Signature:………………………………………

This work is dedicated to my daughter Ylva and her generation!
It is she and her peers who will be the ones living with new energy systems and who will wonder about the wasteful and inefficient lifestyle of their parents' generation. I am confident that resource-mindful lifestyles will evolve for their generation, sustaining quality and joy of life.

Abstract

In the light of advancing climate change and the anticipated scarcity of affordable fossil fuels, a transition towards more sustainable energy systems is vital to allow for the long-term sustainability of human wellbeing. Energy is a key sustainability issue, at the heart of the complex interactions of socioeconomic and biophysical systems. The overall aim of this study is to contribute to furthering the understanding of these systems interactions. It intends to deliver methodological insights on how to identify and appraise favourable energy futures in a changing and uncertain world. In order to cope with the complexity and uncertainty of future developments and with the plethora of partly contradictory social preferences, a participatory approach was combined with scenario development and the application of an appraisal tool that takes account of the multidimensionality of system interlinkages. In a case study for Austria, favourable renewable energy scenarios were developed in a participatory setting, involving key Austrian energy stakeholders. The scenario development consisted of two stages: first an exploratory stage with stakeholder engagement and second a modelling stage generating forecasting-type scenarios. Accordingly, the scenarios consist of a narrative part, the storyline, and a modelled, quantitative part. The application of Multi-Criteria Analysis (MCA) allowed the integration of multi-dimensional sustainability information (social, environmental, economic, and technological criteria) and the social preferences of the stakeholders into the appraisal of the energy scenarios. In the case study presented, five renewable energy scenarios for Austria for 2020 were compared against 17 sustainability criteria. The study illustrates how the combined use of participatory scenario building techniques and MCA acknowledges and integrates inherent complexity, irreducible uncertainty, multi-dimensionality, and, a multiplicity of legitimate perspectives in the appraisal. The main empirical result of the sustainability appraisal undertaken shows that, contrary to the current energy policy in Austria, a profoundly decentralised energy system (scenario E) and an innovative long-term investment strategy (scenario C) rank highest, whereas the renewable strategy based on biomass (scenario D), which represents the dominant political trajectory in Austria's renewable energy policy, ranks very low. The research demonstrates the integration of biophysical, social, economic, and, technological appraisal criteria, presents and discusses best practice criteria, and, illustrates the challenges and opportunities to incorporate bio-physical aspects into the concept of socio-technical systems and their transitions in the light of a more sustainable development.

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Foreword

Not for the first time in human history, a structural change of overall energy systems and consequently societal structures is taking place. But for the first time, our generation is a knowing witness to such a process.

Energy, an integrative key issue of both natural and socioeconomic systems, has also been my personal bridge between my initial education in biology, specialising as an ecologist, and my later training in social science. Many years of interdisciplinary work have blurred the boundaries between these disciplines now, but a fascination for systems understanding still persists. As a politically-aware person, the question for me always was and is: what can be done? Working in interdisciplinary fields teaches painful lessons that certain perspectives on “reality” are not ”true”, but constructed - what a surprise for a natural scientist! The step towards transdisciplinarity, i.e. moving beyond the academic realm, has been another consequence of this personal realisation. A combination of gaining systems understanding, an acquired humility as a scientist, and the pleasure of working closely with other people are my motivation for transdisciplinary research.

There are several people without whom this thesis would not have been possible and whom I would like to thank at this point.

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[1] Further details can be found at http://www.project-artemis.net/

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Thank you to my partner, Heinz Erb, - without him I wouldn’t have found the strength and discipline to finish the thesis. Many inspiring discussions contributed to my work in a profound way. He felt the time and energy that was put into this work the most. Taking over, alongside his own career, the very practical workloads of housekeeping and childcare allowed me to focus on the research. I am deeply happy and thankful to have a partner who respects my wish to accomplish such a work and supports me fully, as he sincerely did.

Introduction

Acknowledging the crucial role of a transition to more sustainable energy systems, international and national policy makers in most OECD countries have developed strategy papers (e.g. UK Renewable Energy Strategy; DECC 2009; Germany's Renewable Action Plan 2010; BMU 2010) and have begun to implement credible policies (e.g. EU Climate and Energy Package announced in April 2009) aiming at fostering integration of renewable energy technologies. The change of existing technological systems as a necessary part of the transition towards more sustainable development has been recognised (Vollebergh and Kemfert 2005). The severe effects of the present energy systems and life styles of developed countries on the global climate make an energy transition necessary. To achieve more sustainable future energy systems, the interactions between the socioeconomic systems and the natural systems have to be anticipated. (Kates et al. 2001, Kemp and Rotmans 2005)

Since 1992, when the United Nations assembled the UN Conference on Environment and Development UNCED in Rio de Janeiro, sustainable development has remained at the top of the agenda in all political fields and has become an overall goal for the 21st century. Sustainable development requires the increased substitution of modern renewables for conventional non-renewable (fossil, nuclear) fuels and energy technologies will play a paramount role. IPPC 2007c Nevertheless, the actual transition towards more sustainable energy systems is still in a pre-development phase. (Polatidis et al. 2003)

Problem statement

Peak oil[2] is already occurring. "The ten largest producers in the group of countries with declining production are the US (peak in 1970), Iran (1974), Norway (2001), Venezuela (1968), the UK (1999), Indonesia (1977), Lybia (1970), Oman (2001), Egypt (1973), and Argentina (1999)." (Zittel and Schindler 2005)

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[2] Peak oil is defined as the point in time when „the production decline in already producing fields gets so steep that it can no longer be compensated by the development of new fields". (Zittel & Schindler, 2005)

The effects of global climate change, caused by the accumulation of anthropogenic greenhouse gases in the atmosphere, are already being experienced IPPC 2007a and the full extent of the anticipated effects are among the most threatening developments of our times. These changes in the global climate system may be irreversible and have severe social, environmental and economic impacts. New scientific insights also suggest that climate change will not be a gradual process, but will be characterized by thresholds, tipping points and sudden systemic collapses. (Lenton et al. 2008) The impacts of climate change will probably be more severe in economic terms, and the means of adaptation more cost intensive than the investment necessary for a carbon neutral energy systems. (Stern 2006)

The average concentration of carbon dioxide in the atmosphere has risen by about 30% from the pre-industrial level of 280ppm in 1750 to a level of app. 380ppm (IPPC 2007b, Canadell et al. 2007) The concentration of 450ppm CO_2 is assumed to be a “sustainability maximum”, a concentration which would cause an average temperature increase of 2°C. (IPPC 2007c) The worst-case IPCC scenario trajectories (or even worse) are now being realized, a fact presented by the Copenhagen Climate Science Congress which was attended by over 2,000 scientists, in 2009. (Richardson et al. 2009)

These two facts indicate the incontestable necessity of a transformation of the present energy systems. However, it is not clear what this future will look like. Questions about the point in time as to when the transitions will happen, and where the transition will lead to, are bound to remain open. Whether and in what ways a transition towards more sustainable energy systems can be managed remains uncertain.

When?

When exactly a transition away from fossil fuel-based energy systems in industrialised societies will happen and whether we are already in the middle of this transition process is highly disputed in scientific literature and policy making. The fact of peak oil in several oil producing countries is a strong indication of a foreseeable end of easily available and thus inexpensive fossil fuels. Reserves of unconventional oil, mainly oil from tar sand, and the potentials of enhanced oil recovery (EOR) are associated with significantly higher economic, ecological and social costs. The recent oil spill in the Gulf of Mexico demonstrates essentially that higher environmental and economic risks are already being taken to produce oil on, for instance, open sea floating derricks. The magnitude of conventional as well as unconventional oil sources is determined by the interplay of many factors such as technological and economic feasibility which further increases the uncertainty of when exactly the transition will happen. (Rowlands 2005)

Where to?

Three main alternatives of energy futures are currently being discussed:

a) prolonging the fossil fuel era by switching to increased production of coal and EOR (already ongoing)
b) using another finite energy resource, uranium, investing into nuclear energy systems again,
c) switching to renewable energy resources, which means returning partly to an area-based energy system.

There are highly controversial discussions on the role and importance of these alternatives, and which ones can contribute in the light of long-term sustainable development. A key strategy for any future energy system is energy conservation, i.e. reduction of energy demand and increase of technological efficiency, (Lund 2007) as the times of vast energy overabundance due to the cheap availability of fossil fuels, are over[3]. Wasteful standards regarding energy demand, primarily minimising labour effort and maximising economic profit, can most probably not be sustained under any of the future energy systems.

Alternative c, switching to renewable energy is commonly acknowledged as being of central importance in this context of sustainable development. Rowlands states "Renewable energy has the potential to make a significant contribution to meeting the challenges of global climate change." (2005) There are two convincing arguments for a transition to renewable energy systems. One is the pressing threat of climate change (Lauber 2005). The other is the massive investment necessary for a structural change of energy infrastructure and capacity building that can probably be made only once in the long-term future. Furthermore, renewable energy plays an important role in creating new businesses and local employment, enhancing social and economic cohesion and improving the security of supply, and is also able to reduce the dependence on imported (mainly fossil) energy sources. (Haas, 2006)

Nevertheless, the increased use of renewable energy sources faces many barriers, partly because of existing market distortions (e.g. subsidisation of nuclear power or coal), technological lock-in

[3] Symptoms of the over-abundance of energy in industrial civilisations are not only single ineffective products, such as private cars, but whole energy-inefficient production sectors, e.g. agricultural production at negative energy-return-on-investment (EROI;, Cleveland et al. 1984, Pimentel and Pimentel 1979).

situations[4], capital-intensity of many RETs (renewable energy technologies), and regulation and institutions favouring well-established energy technologies. However, renewable energy is inexhaustible and in principle carbon neutral and offers diverse energy sources with substantial potential to meet the energy demand.

The continuation of a fossil fuel-based energy system with a focus on coal and EOR will create severe environmental, social and economic problems due to climate change. Technological solutions such as "clean coal technology" are currently neither energetically nor economically efficient, and the risks of pumping, storing, and guarding large amounts of CO_2 in former fossil fuel production fields is rated rather high. (Spreng et al. 2007) A nuclear-based energy system does not contribute directly to the accumulation of greenhouse gases, but binds very large amounts of investment to a highly risky technology that can only be sourced in the medium term due to the scarcity of uranium. Some scholars go even that far to consider fossil fuel and nuclear energy systems as mere transitional stages due to the limited resource availability. (Sieferle, 1997) The nuclear accident in Fukushima, Japan 2011 demonstrated that nuclear power is a threat even in highly technologically developed and economically strong countries.

However, the impacts of renewable energy systems on a large scale are also potentially damaging to the environment as well as harmful to society in several respects. In particular, the area demand of biomass sources and the potential area competition with food production and natural conservation areas, together with the overall lack of efficiency of decentralised energy systems, are key potential problems from a system's perspective. There are numerous challenges to creating decentralised renewable energy systems: categorically reducing energy demand; increasing efficiency; resolving political debates; and solving infrastructure problems. These challenges seem to have boosted the current new wave of arguments in favour of nuclear power and fossil power plants.

Given the future relevance and the high heterogeneity of renewables and their complex impacts on nature this thesis focuses on renewable energy futures. It is beyond the scope of the thesis. To elaborate on optimization strategies or analyses the the spatio-temporal interplay of all the three future energy alternatives listed above. Rather, the focus of this thesis is to identify and appraise alternative renewable energy futures in Austria in a participatory research setting.

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[4] In Austria but also in other countries with e.g. power supply systems based on centralised large-scale electricity generation, transmission schemes that have been heavily subsidised in the past in times of regional monopolistic markets.

Clearly, any structural change of the energy systems will lead to drastic effects on our current way of life, with respect to industry and business as well as for private households and individuals. (McNeill 2000) Looking back into the 17^{th} century to the historic transition towards fossil fuel-based energy systems demonstrates convincingly the major changes induced by the energy transition. They extend from fundamental changes in production and transport modes to cover major social and cultural changes such as housing (urbanisation) and family structures, etc. In the case of an energy transition, similar fundamental change is inevitable, and the ultimate questions arise: how will we judge and who shall judge which road should be taken?

How to manage?

The industrial period, based on fossil fuels, has never provided a long-term sustainable energy system and its finiteness has always been part of the deal. Now that a transition is indisputably necessary, it brings up the questions of whether such a process can be managed or influenced in a beneficial direction, and, if so, how this can be done and by whom. Meanwhile, one threat seems to be that the later the structural change is anticipated and new institutions are set up, the easier it will be for the most powerful players to push changes beneficial for them in the last “fossil” minutes and the developments will not necessarily be in the most socially beneficial way.

After all, the potential success of attempts to foresee and, furthermore, to manage complex adaptive systems has to be approached with realistic (and therefore modest) aims. Relevant questions for science are therefore based on how much and which aspect of the complexity, uncertainty and ambiguity of the perception of reality can be addressed and still be able to inform action. The precautionary principle provides a key approach in this (O’Riordan and Cameron 1995, Stirling 2001, Stirling 2008) especially because there are irreversible processes which have to be taken into consideration.

From a historical perspective, however, this is not the first time that a transformation of the overall energy system has occurred. From a universal-historical perspective, two major structural energy changes have happened: the first a transition around 10,000 BC from hunters and gatherer towards agrarian civilisations, and the second a transition in the 17^{th} century towards industrialised civilisations. (Sieferle 1997, Sieferle 2001) Nevertheless, a fundamental difference between our current situation and these past energy transitions will occur under the influence of advanced information networks and a global economy. Moreover, an informed public is currently aware that something will (have to) happen. Consequently, an adequate form of governance is both possible and necessary, integrating diverse interest groups across several institutional levels. Another significant difference is the starting position of industrialised countries for the current level of energy consumption, made possible by the relative overabundance of energy. This overabundance has enabled and still enables vast technological innovations and advances which can and should be a useful investment in the future.

Attempts at management of the situation require the future and consequences of current decisions to be accurately anticipated. Science has no methodology to arrive at knowledge of the future. The complexity and uncertainties involved in writing new scenarios prevent science from describing future events with acceptable accuracy. (Funtowicz and Ravetz 1992, Geels and Smit 2000) Models, which usually extrapolate past development in some way, and the identification and understanding of drivers and their mechanisms, do give toeholds for insights into future developments, due to their limitations in handling non-linear developments. Even when uncertainty is reduced with respect to certain aspects learnt from models and drivers, anticipations of the future have to deal with an irreducible amount of uncertainty. Limited knowledge und uncertainty should not deter research from informing decision-making today, but this challenge should be met with the appropriate methodological handling. There are and will be others taking the chance to inform and to take action, or, in Hajer's words, there are opposing 'discourse coalitions' influencing the political process. (Hajer 1995)

Different perspectives and different interests make consensus complicated when regarding the movement or direction a transition should take. There are several legitimate perspectives as to why certain developments are more favourable than others, each true in their own right, yet inconsistent with an overall picture. Approaching this requires to move beyond simple applications of optimisation processes. Rather, it is a matter of analysing different underlying assumptions which lead to a number of valid arguments that stand in contradiction to each other. (Dryzek and Niemeyer 2006)

Apparently, in interacting complex systems there is no comprehensive knowledge and most probably no means of steering directly towards any intended targets. Nevertheless, theoretical concepts exist that are able to deal with these uncertainties and at least discern more or less likely futures.

Thus, the role of science is to improve theoretical understanding of energy systems and to learn to apply innovative methodology adequate for dealing with uncertainty and integrating social preferences. The use of participatory approaches can help to identify and tackle barriers, and to better exploit driving forces in a way that allows the integration of a multiplicity of legitimate perspectives. The transition of energy systems has profound effects on socioeconomic systems as well as natural systems. These highly complex and uncertain processes call for an integrated and participatory approach.

Aims and scope

Ongoing efforts to progress towards more sustainable energy systems are often unsuccessful. The study presented here is built on the premise that this is due to the high degree of complexity of social and natural systems and their interactions. Changes of the energy systems must not be understood as a simple, price-driven change in technological applications but are much more far reaching. (Hughes 1987, Geels 2004a, Kemp and Rotmans 2005, Smith and Stirling 2007) On the one hand, they rely on social innovation and entail changes in social practices, organisations, institutions, discourses, cultural codes and norms. (Wynne 1988) On the other hand, such changes affect ecosystem process and patterns and biogeochemical cycles, as well as the life-sustaining systems of the biosphere. These changes profoundly alter the interactions of society and nature. Individual technology plays an essential role but is only one part of these interactions between society and nature.

Not all renewable energy technologies are equally beneficial in this complex feedback-loop system. Moreover, benefits are different for different interest groups. Therefore, an appraisal of the performance of renewable energy technologies based on a wide range of sustainability criteria in the light of the respective social preferences is essential for a reasonable decision-making process. Furthermore, it is necessary to structure this information in a transparent way to allow wide recognition of the appraisal. Due to the high degree of uncertainty and complexity involved, future developments can not be based on expert opinion alone. Rather, scientists and experts themselves are part of a discursive space, together with key decision makers and lay persons. The definition and delineation of solutions to concrete problems is the outcome of a negotiating process. This makes participatory processes highly desirable: it ought to reflect the opinions of experts, stakeholders and decision makers, and move beyond traditional mode 1 science. (Funtowicz and Ravetz 1993, Nowotny et al. 2001, Nowotny et al. 2003)

A central aim of this dissertation is to explore the potential of participatory research related to the appraisal of renewable energy systems by combining participatory multi-criteria analysis and techniques of scenario analyses which, in turn, ought to further advances regarding sustainability projects. The construction of scenarios for exploring alternative future developments under a set of assumed conditions has a long tradition in strategic decision-making (WBCSD 1997; Shell 2008), and especially in decision-making in an energy context (e.g. Ito et al. 1997, Haldi 2000, Nakicenovic 2000, Oniszk-Poplawska et al. 2003, International Energy Agency 2003, BMUNR 2004, Ghanadan and Koombey 2005). Scenarios have been developed for different temporal and spatial scales, from global and (inter-)national long-term scenarios (IIASA 1981, Nakicenovic et al. 1998, Raskin et al. 1998, Eames 2002, IPCC 2004) to local mid-term scenarios (Georgopoulou et al. 1997). Among the non-energy scenarios, climate change and land-use change scenarios are most prominent (Nakicenovic 1998, Nakicenovic 2000). In most cases, however, scenario development is based on expert knowledge, but the normative nature of sustainability target settings calls for a stronger integration of the preferences and values of non-academic stakeholders. This is increasingly acknowledged in the literature. (Schot and Rip 1997) On the other hand, participatory MCA has a great potential to structure discourses and interests in a transparent way and to account for the multi-dimensional nature of sustainability issues. (Stagl 2007) The obvious value added from combining participatory scenario building and participatory MCA has only fragmentarily been investigated in the literature. (but see MacDowall and Eames 2006, Anderson et al. 2006, and Stagl and Stirling [personal communication] on energy future of the South-East of England, and Konrad et al. 2004b for transformation processes in net-based supply systems)

Based on an in-depth case study, the research presented here aims to gain new insights into the combined use of methodological approaches such as scenario building and multi-criteria analysis, attended by a stakeholder participatory process that takes social preferences explicitly into account. In the case study, operational questions of the adequate process of eliciting and of appraising energy options with respect to all sustainability dimensions are discussed. National renewable energy scenarios are developed on the basis of a participatory stakeholder process and a sustainability appraisal applied in this regard. On the basis of these energy scenarios, the aim is to generate learning and discussion (van de Graaf and van de Graaf 1996, Berkhout et al. 2002) on certain aspects of future energy alternatives and their respective consequences.

Austria will serve as the empirical case study. Austria is a highly industrialized country in central Europe with a territory of 83,000 km^2 and a population above 8.3 million. Austria has a long tradition of using renewable energy sources, not least due to the extensive water systems and a vast forest resource base. There are no commercial nuclear power plants in Austria and public opinion is strongly against these. In 1978 a nuclear power plant was under construction in Zwentendorf, yet the plant never went into operation because of the protests and the resulting referendum. New construction of large hydropower plants is also unlikely. Public opinion is opposed to large hydropower plants. The total energy use per year was 302,372 GWh in 2008, whereas households use 25%, traffic 33.7%, and industries & services & agricultural sector use 41.3%. The share of renewable energy is 28.1% of the total energy use in the year 2008. 72.1%

of the total electricity demand is from renewables, stemming mainly from large hydro power, which in an EU comparison puts Austria on rank two after Norway. 34% of the heat demand is met by renewable heat generation, which is stemming mainly from solid biomass combustion. (Biermayr 2009)

One consequence of the single-case study approach is that the empirical results and insights are not transferable without caveats to other contexts. Due to the particular regional supply logic of sustainable renewable energy systems, countries or regions with geographic similarities such as Switzerland or Japan might yield comparable results and the developed scenarios would, in general terms, be comparable. It can be also assumed that the specific sustainability impacts per energy unit supplied are generally applicable for countries with a comparable degree of technological development. However, the insights related to one of the major aims of the study, i.e. the development of an innovative participatory methodology (comprised of a combination of scenario building techniques, multi-criteria analysis and the participatory stakeholder process), are certainly also valid in other sustainability fields which are characterised by a high degree of uncertainty and complexity.

The scenarios presented here are developed in collaboration with scientists and stakeholders and are of an integrative nature with respect to the qualitative story lines and quantified modelling. This is a innovative approach in contrast to the existing scenario studies for Austria (Kratena and Schleicher 2001, Haas et al. 2001, Haberl et al. 2003, Kratena and Wüger 2005, Kalt et al. 2010). The scenarios focus on the future development of the renewable energy sector in Austria. However, large-scale hydropower is not taken into account. The main rationale behind that is the present energy policy in Austria that does not include the construction of new large hydropower plants. Furthermore, the long construction period associated with large dams would probably reach beyond 2020, the time frame of the present study.

The time horizon of the scenarios is 2020. This mid-term time frame allows for the examination of existing technologies only, and is not long enough to account for the emergence of new technologies. The quantitative modelling of the scenarios is not based on an economic model, but on time series regressions and biophysical datasets on upstream resource flows (life-cycle-analysis data inventory). The growth of individual technologies is outlined by linear and exponential extrapolations. The key aspects of the scenarios are: (1) the technology mix, (2) the additionally installed capacity per technology type until 2020, (3) the question of central versus decentralised future energy systems, and (4) a specific bio-energy topic according to primary or secondary biomass utilisation.

Objectives and research questions

The primary objective of this study is to apply a sound theoretical framework to the interactions of society and nature, and to appraise the sustainability of energy scenarios. This will be inspired by the universal-historical examination of the energy transition from the agrarian mode of subsistence to the fossil-fuel-based industrial energy systems. Such a perspective on the past transition of the energy systems demonstrates the essential role of energy systems for the society-nature interactions and the fundamental structural consequences of energy transitions. The study aims to identify structural changes associated with the sustainability energy transitions from a system's perspective, scrutinizing their societal and natural consequences, taking the role of feedback loops explicitly into account. The study elaborates on questions related to the evaluation of future options and to the identification of favourable options with this in regard.

Another objective is to test and explore the practicability of an innovative methodological package that is based on the combination of a scenario analysis with MCA methods within a participatory stakeholder process. For this objective, a single in-depth case study for Austria is employed. The insights gained from the case study are aimed at contributing to the debate on governance (i.e. participation of stakeholders in strategic decision-making) and to exploring the role of science in the context of future energy transitions related to sustainability. The case study is organised along the following milestones:

- Identification of key Austrian energy stakeholders to participate in a stakeholder process
- Development of alternative renewable energy scenarios for Austria until 2020
- Identification of sustainability appraisal criteria
- Development of an impact matrix (environmental, social, economic, and technological dimension) for the energy scenarios
- Exploration of the social preferences of energy stakeholders for future sustainable energy systems
- Calculation of a multi-criteria analysis ranking of alternative renewable energy scenarios
- Test of the robustness of the results in a detailed sensitivity analysis

The DPhil thesis presented here is guided by the following research questions. Some research questions are of a theoretical nature and are employed to create a framework for the empirical parts. The more methodological and empirically-oriented research questions provide a framework to structure the case study and the results.

How can a systemic perspective on sustainable development as society-nature interactions contribute to an enhanced understanding of transitions towards more sustainable energy systems? What, in particular, can be gained by regarding natural systems and their dynamics as endogenous factors?

> How can future options of the energy system be appraised given such complexities and uncertainties? Do the methodological approaches of scenario building and multi-criteria appraisal (MCA) with stakeholder participation provide a 'toolbox' adequate for exploring sustainable development of the energy systems?
>
> Which future energy systems and technologies show up in the Austrian sustainable energy discourse as represented by the stakeholders involved in the study? How do these energy systems and technologies perform according to the multi-dimensional sustainability criteria?

The following sections of this thesis are: (1) a methodological section, (2) an empirical section, (3) a discussion, and (4) conclusions. The theoretical, methodological, and empirical research questions presented above will be the connecting thread leading through the thesis, and will be synthesised in the Conclusion.

In the methodological section, two theoretical chapters will lay out the assumptions underlying and guiding the empirical approach. It will introduce energy as a key sustainability issue and put forward a systems perspective on the dynamic and complex interactions of society and nature as the basis for sustainable development. Current mainstream theories on energy transition such as a universal historic perspective and the orthogenetic evolutionism are presented, and the role of acting and managing such a transition is scrutinised. This section provides the starting point for the empirical section, presenting the rationale and operationalisation of a methodological design based on the combination of participatory research methods, scenario analysis and multi-criteria analysis for sustainability appraisals of energy technologies.

The empirical section consists of two chapters. The first chapter provides the operationalisation of the methodological rationale for the in-depth case study of Austria. The second chapter of the empirical section presents the empirical results and a detailed sensitivity analysis. The challenges and opportunities related to the methodological approach are summarized in the Discussion section. Eventually, the Conclusion section ends the thesis with a reflection on the research questions.

Methodological Section

This DPhil thesis deals with approaches to managing energy systems in order to move towards a more sustainable future. Starting from a general discussion of systems perspective on sustainable development, it applies this perspective to further the understanding of the complexity of energy systems. Particular attention is paid to the dynamic nature of complex systems, i.e. their ability to change and transform, on the basis of analyses of historic transitions of energy systems and of conceptual considerations. Systematic explorations of the characteristics of energy systems and their fundamental role in the interactions of society and nature allow conclusions to be drawn regarding the challenges of how to transform energy systems and so contribute to a transition towards sustainability.

These methodological discussions guide the empirical section of the dissertation, which presents a case study focusing on the management of a transition towards a more sustainable energy system in Austria. In a participatory setting, experts and stakeholders were involved in identifying possible energy futures and their sustainability profile. The following research questions guide the methodological work in this dissertation:

> How can a systemic perspective on sustainable development as society-nature interactions contribute to an enhanced understanding of transitions towards more sustainable energy systems? What, in particular, can be gained by regarding natural systems and their dynamics as endogenous factors?
>
> How can future options of the energy system be appraised given such complexities and uncertainties? Do the methodological approaches of scenario building and multi-criteria appraisal (MCA) with stakeholder participation provide a 'toolbox' adequate for exploring sustainable development of the energy systems?

The main proposition of this DPhil thesis is that the management of transitions towards more sustainable energy futures has to take a systemic understanding on board- in particular of the interrelated nature of the natural and of the socio-economic systems.

In the first chapter of this section, the theoretical foundations of sustainability and energy systems are developed, bringing together concepts from different disciplines. The aim of this section is to form a window, an opening towards an interesting and innovative view that frames the empirical research.

The main theoretical concepts brought forward are the following: sustainable development, concepts of society-nature interactions, complex evolving systems in interaction, and energy systems. The integration of these concepts leads to the systematic exploration of characteristics and dynamics of the energy supply and demand system, probably one of the most important issues of sustainability. An exploration of the interactions of society and nature from a systems perspective aims to add an innovative aspect to the current discussion of the transition and innovation of energy systems. Here, the role of technology is discussed on a very general level, and from this starting point, the potential benefit of a systemic perspective in understanding, describing and eventually managing transitions of the energy systems is explored. The understanding of socio-technological systems will play a central role in this context, whereas the natural systems play a more explicit role.

Based on these theoretical considerations, the next chapter elaborates on notions of system change, focussing on revolutionary and gradual forms of change. Current concepts of energy transitions, such as multi-level concepts are presented. In-depth investigations into historical energy transitions, in particular the transformation from the agrarian mode of subsistence to the fossil fuel-based energy system of industrialised society, applying in a universal historical perspective, allow lessons to be learned from the past regarding the future energy transitions. This historical presentation enables a profound understanding of a complex systems perspective on energy transitions, depicting the interplay of relevant agents and form of negative and positive feedback loops in the course of industrialisation. Finally, this perspective allows generating new insights into the multi level concept of socio-technological transitions.

A final methodological chapter presents and discusses scientific methods that can be applied to appraise energy systems and to identify sustainable options. This chapter elaborates on scenarios, MCA, and, participation research methods, and, their combination in the context of the transition processes. This section concludes with a summary of the key methodological insights.

Conceptual framework for sustainable energy systems

The challenge to accomplish a development of society that "…meets the needs of the present generation without compromising the ability of future generations to meet their own needs" concerns political decision making and science alike. Since its formulation in 1987 by the Brundtland Commission, and the following international, national and regional political commitments, such as the Kyoto protocol, the Post-Kyoto process, national sustainability plans or the Agenda 21 action plan[5], sustainable development became widely accepted as a common political and social goal. Despite the fact that the definition is ambiguous in scientific terms and notwithstanding the ongoing dispute as to whether 'sustainability' can ever be achieved, or if it is rather a 'moving target' (Hjorth and Bagheri 2006), or even just a guidepost vision for actions to be taken, the concept of sustainability has found its way onto policy agendas world-wide. Sustainable development entails policy, action and research that follow long-term and integrated considerations on the intimate interlinkage of socio-economic, and environmental development.

Sustainable Development and Energy

Energy is a key sustainability issue, related to current and future socio-economic as well as environmental problems. In physical terms, energy denotes the ability to perform work, which, in closed systems, cannot be created or destroyed, but can only be changed from one form into another. Energy conversions follow the laws of thermodynamics, which claim that energy can neither be created nor destroyed (law of conservation of energy), and that any energy conversion incurs degradation of energy concentration (law of entropy). Energy is required for every process in the biosphere and for every human action.

Energy is a key currency of ecological systems (Odum 1971) and is thus also central for the biological functioning of society, i.e. the reproduction and operation of human bodies. Solar energy is the main energy source on this planet. The starting point of almost all ecosystem energy flows is the process of photosynthesis (with the exception of chemosynthesis), in which solar energy is converted by primary producers, mostly green plants but also bacteria, to

[5] Agenda 21 emerged as a practical programme for application on the local level from the United Nation Conference on Environment and Development in 1992.

chemically stored energy in carbon compounds, such as biomass. This provision of energy by plants determines the amount of trophic energy available for transfer from plants to other levels in the trophic webs in ecosystems. Many aspects of ecosystem functioning, e.g., nutrient cycling, build-up of organic material in soils or in the aboveground compartment of ecosystems, available biodiversity, but also patterns and processes, vitally depend on this energy flow.

The availability and use of energy are constituent elements in the functioning and organisation of socio-economic systems as well (Haberl 2001, Haberl 2006, Pimentel and Pimentel 1979, Smil 2003, Smil 2008). First of all, humans just like all other heterotrophic organisms depend on a steady energy intake in the form of food (somatic energy). However, humanity's use of energy is not restricted to this basal metabolism. Human society uses a huge variety of energy sources for technical applications, such as the burning of firewood or the burning of gasoline to generate mechanical power (exosomatic energy). Biomass is the most important energy carrier for human society: in its fossilised form for the industrialised world, in its most recent form mainly for the developing, but also for the industrial world. The availability of technical energy, i.e. energy availability and technology to use, is regarded as a major determinant for economic development. (Ayres et al. 2003, Ayres and Warr 2009) The energy consumption of society is found to correlate with economic growth very closely in industrialised societies, withstanding even the recent explicitly policies which explicitly aim at a de-coupling of economic growth and energy consumption. (Ayres et al. 2008, Ockwell 2008) A secure energy supply in the form of sufficient electricity, heat and fuels supply for transportation is regarded as the base of all economic activities across all sectors. Energy policy is one of the highest ranked policy realms of national and international governmental institutions, supported by industry and driven by economic interests. Access to and availability of energy resources are a cause for international tensions and cooperation alike in world-wide markets.

One of the foremost problems jeopardizing sustainability is related to industrial energy utilisation: The combustion of fossil fuels results in considerable greenhouse gas emissions to the atmosphere, far beyond the rate at which carbon is sequestered by natural systems, e.g. by oceans or vegetation growth. This results in an accumulation of greenhouse gases, mostly CO_2, in the atmosphere, which is affecting the global climate system with manifold consequences for human societies and human well-being. (IPPC 2007a)

Thus, energy plays a crucial role in society and in natural processes alike. This over-arching character of energy makes a systemic understanding of energy issues necessary in order to advance towards a more sustainable form of development. A transition towards more sustainable energy provision and use – especially an overall reduction of the total energy consumption in industrialised countries – plays a key role in this regard. However, this path is neither straightforward nor simple: empirical analyses have shown that in the past efforts to reduce energy consumption by technological innovation, i.e. increases in the efficiency of energy input per service unit, have regularly been overcompensated by surges in consumption and thus have remained almost ineffective. (Hertwich 2005, Polimeni et al. 2009) The fostered usage of alternative energy sources substituting for fossil fuels, in particular renewable energy sources, has gained attention in the sustainability debate as an important development path. (Turner 1999, Ragauskas et al. 2006) Nevertheless, the potential of currently available technologies for renewable, more sustainable energy provision is limited in magnitude and will have to be accompanied by simultaneous reductions in overall energy consumption. (OECD/IEA 2008)

Why a wider systemic perspective is required for framing sustainable energy systems

Sustainable development entails the integration of three principal dimensions of development, the social, economic and ecological dimension, on an equal footing. (Hak et al. 2007) This basic understanding of sustainable development represents an advance on the debate on 1980s, which framed environmental problems as mere economic problems of market failure and sought purely economic solution for coping with them. The Brundtland report, commissioned in 1984, has, in a way, put an end to this and similar one-dimensional single perspectives by emphasising the intrinsic interdependencies of social, economic and environmental problems. This report represents a milestone in the popularisation and definition of the concept of sustainable development, arguing for the integration of the three pillars in the light of intra- and intergenerational equity. In 1992, at the United Nations Conference on Environment and Development (UNCED), the so-called Rio Conference, this basic understanding was deepened and became mainstream thinking for political decision making, business and academic communities over succeeding decades.

However, the concept of sustainability as based on the Brundtland definition of sustainable development has attracted criticism: Many of these criticisms are grounded in the fundamental ambiguity of the definition of sustainability, which itself origins from the fact that it is the outcome of a broad political process and not of scientific rigour. The separation into three dimensions proved to be politically powerful, but resulted also in a separation of the three dimensions e.g. into distinct policy fields, such as economic, social and environmental policy, and so neglected more and more the integrated and interdependent nature of the three dimensions. Critiques refer to the consequential reduction of the weight of one of dimensions at the expense of another, e.g. a loss of significance of the social dimension due to the insertion of the environmental dimension (Spehr and Stickler 1998) or the reduced weight of the environmental dimension resulting from the “doubling”of the human sphere into an economic an a social dimension of equal weight. (Bauler et al. 2007)

The independent representation of the three dimensions elated in the pillar metaphor represents a strongly reductionist model for complexity, which, nevertheless, is also grounded in the fact that the three dimensions of sustainability are not necessarily mutually reinforcing but often also mutually contradictory, with a synergistic interplay – “win-win” – being the exception. The unsatisfactorily simplified three pillar representation has been addressed by several authors and alternative presentations have been suggested, such as the ‘prism of sustainability’, which includes a fourth dimension of institutional sustainability, stresses the interactions between the dimensions. (Spangenberg et al. 2002a, Spangenberg 2002b, Young 1999) These and similar attempts acknowledge and stress that no pre-defined absolute optimum between the three pillars exists, and that only procedural compromises between different interest groups who share some of the normative guidelines can be achieved (Kastenhofer and Rammel 2005).

The notion of three integrated, non-separable dimensions of development shifts the focus of research and decision making away from “separationist” perspectives towards an integrated analysis of the interface and interactions of society and the natural environment. Recent international documents, e.g. the 2005 World Summit Outcome Document by the United Nations, refer significantly to such integration by arguing for "interdependent and mutually reinforcing pillars" of sustainable development (UN 2005).

It is now widely acknowledged that the basis of analysis related to sustainable development is the coupled socio-ecological system. (Gallopin 2001, Kates et al. 2001, Turner et al. 2003, Cash et al. 2003) This notion of the interactions of nature, society and technology is not a new one and stems from the social theories of the nineteenth century, eventually feeding into sustainability discourse in the last decade of the twentieth century. (Kates 1988) According to Kates 1988, prominent theoretical authors such as Malthus, Marx, Schumpeter, Rostow, and Freeman explicitly address the interplay of society and technology. Interactions between technology and nature are discussed prominently in Commoner 1996, Schumacher 1973, Lovins 1977, and Sachs Sachs 1988.

> “Within the interactive theories of accounting systems based on energy (Odum 1976), materials (Ayres 1978), or monetary information (Leontief 1977), and system models such as

Living Systems (Miller, 1978), adaptive ecological models (Holling 1973) and global and regional models of doom and hope (Meadows et al. 1972 and Cole et al. 1973)" Kates 1988.

Georgescu-Roegen contributed a systems perspective to economic theory in the form of a "comprehensive theory of economy, society, and biophysical constraints" (Gowdy and Mesner 1998), called 'bioeconomics'. (Georgescu-Roegen 1977) Georgescu-Roegen highlighted potential or actual conflicts between rapid economic growth and future resource availability (Tisdell 1997) and moved beyond the classical economic boundaries by including the dissipation of materials in his theoretical considerations, an approach that later also provoked some criticism. (Ayres 1997) He refers also to the importance of the timescale of sustainability taking into account that most economic models refer to a maximum time horizon of 50 to 60 years and usually much less. Georgescu-Roegen was an important figure in economics integrating systems perspective into economic theory by explicitly addressing the relevance of the entropy law to economic activities, long-term considerations and the interactions between natural and social systems.

In the last decade, in opposition to the growing separation of the three pillars of sustainability in political decision making, a group of scientists programmatically argued the need for "sustainability science" as an separate field of research (Clark and Dickson 2003, Parris and Kates 2003, Kates et al. 2001). Sustainability science puts the study of the interactions between society and nature at the core of its scientific mandate. It explicitly "seeks to understand the fundamental character of interactions between nature and society" (Kates et al. 2001) and "seeks to address the essential complexity of those interactions". (Clark and Dickson 2003) This claim for a systems perspective on sustainable development, which moves beyond the isolated pillar understanding, entails broadening the scope of what is conventionally subsumed under the term of "science" to move towards an integration of knowledge beyond structured academic disciplines and beyond the confines of academia. Inter- and transdisciplinary research is a prerequisite for informing decision making processes and so guiding the sustainability transition in scientific terms. Although progress has been made in these fields since then, in 2006 the Council of the European Union states that "there is still a strong need for further research into the interplay between social, economic and ecological systems […] " (Council of the European Union 2006)

Integrated sustainability requires the adoption of a long term perspective, e.g. by anticipating the needs of future generations, looking beyond short term optimisation of utility and profits and aims at "the reconciliation of society's development goals with the planet's environmental limits over the long term". (Clark and Dickson 2003) Taking this as a starting point, the concept of sustainable development acknowledges the long-term dimension of problems such as resources scarcity, famines, environmental collapse, social inequality, etc, their effects, interactions and in particular the time lags, critical thresholds, and tipping points involved in those interactions. It emphasises the fact that consequences of actions cannot always be observed or experienced by the actors themselves, but that this still does not absolve actors of responsibility for those actions[6].

The following chapter is dedicated to the discussion of a specific theoretical model of society-nature interactions.[7] The aim of this exercise is to deepen a systemic understanding of sustainable development and to conceptualise energy as a key interaction feature between nature and society.

Society – nature interactions model

The theoretical model of socio-ecological systems as developed by the Vienna school of Social Ecology (Fischer-Kowalski 1997, Fischer-Kowalski and Weisz 1999, Fischer-Kowalski and Erb 2006) claims to be accessible from both a social and natural science perspective and to be therefore useful for an interdisciplinary approach to sustainable development.

The core of the theoretical model builds upon the work of three authors: Boyden's 'Human Ecology Model' Boyden 1992}, Godelier's work on society-nature interrelation as a driving force of social change Godelier and finally inputs from Sieferle's work on complex systems and cultural evolution. (Sieferle 1997) Here, only a very condensed form of the theory

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[6] This argument is conducted in economic terms through the discussion of discounting rates, which is strongly criticised in Ecological Economics. "Any individual must certainly discount the future for the indisputable reason that, being mortal, he [she] stands the chance of dying any day. But a nation, let alone the whole of mankind, cannot behave on the idea that it might die tomorrow." (Georgescu-Roegen 1986)

[7] The operationalisation of the theoretical model is the concept of 'societal metabolism', a term originally formulated by Marx and Engels addressing labour-process, here applied as material and energy flow accounting, and the concept of 'colonisation'. (Fischer-Kowalski 1997) "Colonisation of natural processes refers to the deliberate and sustained transformation of natural processes using various forms of intervention such as planting, application of agrochemicals, consolidation of farmland, changes of the water regime, breeding, or genetic engineering." (Fischer-Kowalski and Weisz 1999) The two concepts 'societal metabolism' and 'colonisation' are not applied in this study; nevertheless, it draws from the theoretical conceptions represented in the society-nature interactions model.

formation is presented.[8] Essentially, Boyden's elaborations on the distinction between a material and a symbolic world are enriched with a deeper understanding of self-organising cultural patterns by Godelier and finally advanced by Sieferle through a universal historical view of cultural evolution of society-nature interrelations.

The key feature of the model is to understand human society as a 'hybrid' of the material and the symbolic realms (see Figure 1). From a philosophical point of view it is a realist concept in the sense that it approves the biophysical functions and their existence in independency of the observer or his or her consciousness. Nevertheless, it can be linked as well to the constructivist concept of discourse. . The promising advantage of this interpretation is the integration of the material and energy profile of a society and the acknowledging of the symbolic process in social systems.

As visualised in Figure 1, there are two co-existing worlds: the natural, material world, which follows a biophysical logic, and the social, cultural, symbolic world, which follows discourse logic. Society needs to reproduce itself in both worlds, biophysically and culturally. According to Sieferle, "there can be no contact between culture and nature unless mediated by population." (Sieferle 1997)

[8] Find a detailed elaboration of the theory formation inFischer-Kowalski and Weisz .

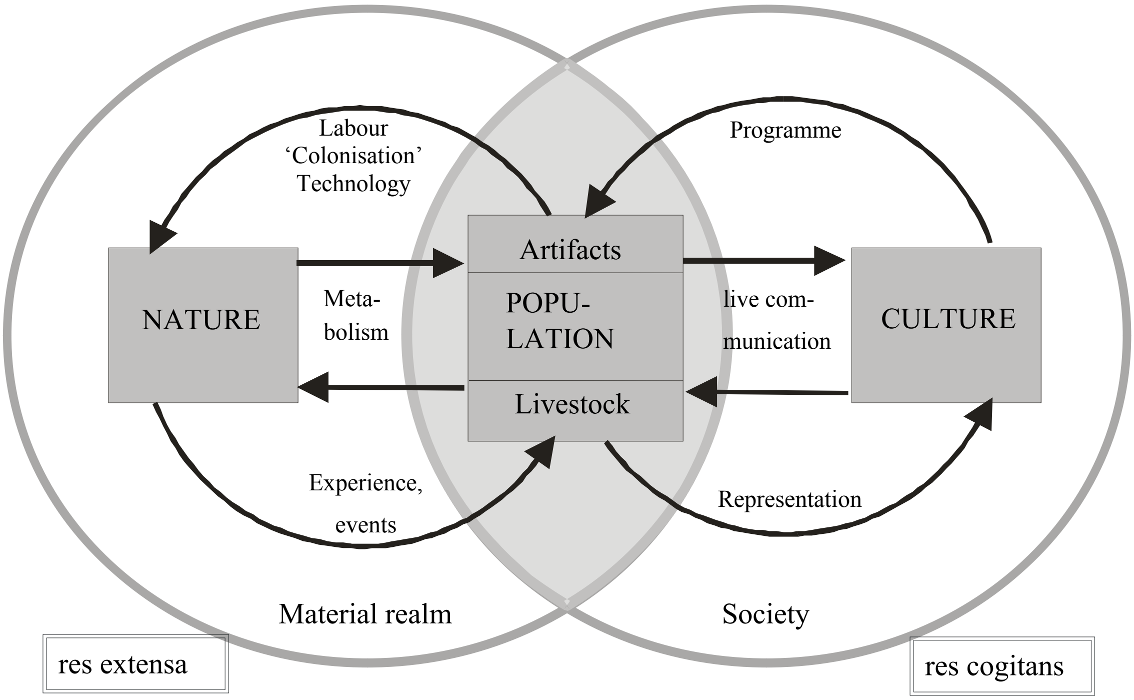

Figure 1. A graphical representation of the theoretical society-nature interactions model by the Vienna school of Social Ecology (Fischer-Kowalski 1997, Fischer-Kowalski and Weisz 1999, Fischer-Kowalski and Erb 2006, Fischer-Kowalski and Haberl 2007).

Fischer-Kowalski and Haberl (2007, p. 12) state: "According to our understanding, society comprises both a cultural system, as a system of recurrent self-referential communication, and material components; in other words, a certain human population as well as physical infrastructure […] and animal livestock, which in their entirety may be defined as 'biophysical structures of society' […] This notion of society allows an epistemological framework for the interactions of social an natural systems to be specified. It comprises a 'natural' or 'biophysical' sphere of causation governed by natural laws, and a 'cultural' or 'symbolic' sphere of causation reproduced by symbolic communication. These two spheres overlap, constituting what are termed the 'biophysical structures of society', According to this concept, the process of interactions between nature and culture can only occur via these societal biophysical structures." Central terms of the society – nature interactions are 'metabolism' and 'colonization'. Fischer-Kowalski and Haberl (1998, p. 573) further: "The concepts of socio-economic metabolism (basically the material input, processing and releases of societies and the corresponding energy turnover) and colonization of nature (activities which deliberately alter natural systems in order to render them more useful for society) […] are attempts to relate the notion of 'sustainable development' to core characteristics of society, in a historical perspective." Still, within the cultural or communicative realm, society depends on nature only indirectly, via its biophysical compartments. Events that happen in the material realm need to be represented culturally as experiences (and how they are represented, depends on the existing culture which then is – however incrementally – transformed by new representations. Which "programme" guides the actions that then have an impact upon the material world is also determined communicatively/culturally. Occasionally the distinction between "hardware" (namely biophysical compartments) and "software" (namely culture/communication) is used to explain the relative functional interdependence, but distinct character nevertheless.

However, it is important that the separate spheres are not understood in the traditional geographical sense. In most conceptualisations, the natural environment has been perceived as everything other than human society- a concept of humankind versus nature.[9] This kind of separation is no longer very useful since the anthropogenic interactions with nature are so advanced and the human impact on nature so wide spread (‘colonisation’ of nature), that it becomes difficult to find ‘pure’ nature in a geographical sense. In the theoretical model at hand, the differentiation between two systems is made on a more abstract level. Influenced by systems theory, the differentiation is made according to the different logics of systems functioning. The discourse logic of the symbolic world, on the one hand, needs communicative reproduction to maintain (see also Luhmann).[10] The material logic of the biophysical world, on the other hand, follows natural laws like gravity and phenomena such as space, mass, temperature, pressure, speed, etc. The biophysical world requires energy for its reproduction. To a large extent, the symbolic world and its communication exist independently of phenomena in the biophysical world, which is also discussed by Hajer in the context of environmental discourse[11]. (Hajer 2003)

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[9] This understanding of nature has been presented in a romantic form, in a threatening form, and in a resource-centred, functional form over time and by different interest groups. (Fischer-Kowalski 1997) In the most common economic concepts the functional understanding of natural systems is dominant and limits natural systems basically to resources on the one hand and on the other hand to waste sinks.

[10] This concept of a symbolic system understands symbolic reality as a social communications process in contrast to a concept in which an interpretation of reality is related to individual mental models of the reality.

[11]It is important to mention here that most communication within the social systems is rather independent from the material world. Biophysical logic is rather distant in many instances. On the individual level, its presence is rather a minor factor, e.g. for people working intellectually in surroundings that do not resemble their natural habitats anymore, living out of fridges, etc.. Nevertheless there are some popular activities ‘feeding’ our biophysical realm, such as literally food, or engagement with the weather (temperature, humidity, wind), or dealing with the coordination of bodily movements in gravity (sports, dance, etc.). Our bodies are the personal biophysical dimension of the ‘hybrids’. Though, they are very often only experienced as troublesome limitation for providing a functioning brain. The symbolic realm is more vivid in daily life when e.g. dealing with concepts, behavioural norms and rules, symbols and language, interaction, relationships and networks, power, money, etc. The point is that most of the time, the activities in social systems are essentially decoupled from the materiality natural realm (which can be called civilisation). So are the bases of our decisions, even if these decisions will affect the material world. Environmental policy and actions are not simply a reaction to irritations from the material world but the output of a long and complex process incorporating several social subsystems where discourse, knowledge, power, and institutions play a role. (Pellizzoni 2001)

In articulate contrast to Luhmann systems theory, this model attributes to society explicit material components (the human population, companion animals, and cultural artefacts). Society is therefore bound to biophysical logic (beyond structural coupling[12]). The individual human but also human societies are seen as a 'hybrid' of the biophysical system and the symbolic, cultural system. A similar differentiation in information technology would be that between the software and hardware components of computers.

Focusing on the interactions of the two realms, the symbolic and the material, it is important to understand that the symbolic world only has a physical imprint via action. This could be understood in Marxian terms as 'labour' or as 'colonisation' in Fischer-Kowalski's interpretation. (Fischer-Kowalski and Erb 2006) In the context of this DPhil thesis, though, technology is put into focus as the 'extended arm' of society. [13] This model enables us to conceptualise technology as (part of) the interactions of society and natural systems. It is therefore an umbrella model embracing (1) the dynamics within society leading to a certain development in technology and (2) that technology's effects upon natural systems. In the specific context of this DPhil thesis and generally speaking for sustainability policy issues it is necessary that both arenas and their interactions are accessible in a theoretical model.

The main troubling materialised effects of the industrialisation in general and the energy policy of the last decades in specific is the intensive use of fossil fuels and the resulting CO_2 emissions. The theoretical concept of discourse is helpful in this context to address the appraisal and decision mechanisms concerning more sustainable energy technologies in the symbolic realm of society. Using the concept of discourse ,'the interactions between the social processes through which actors are mobilized around certain issues, with specific ideas and concepts that create common understanding of given problems' can be analysed. (Hajer 1995) It therefore allows the manifold perspectives and interests in society and their interactions leading to e.g. new policies and funding schemes to be addressed, which consequently entail actions such as enlarging wind power capacity, which in turn leave a biophysical imprint on nature. Certain discourses arise in a certain time and context and will be irrelevant or replaced by a new discourse over time, in

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[12] Culture has to be responsive to natural systems in a sense that the material conditions of the communicating agents are sustained ('strukturelle Koppelung' translated as "structural coupling", see: http://www.libfl.ru/Luhmann/Luhmann4.html).

[13] In a personal interview with Helga Weisz in Oct 2006, the role of technology in the theoretical model is discussed. She uses the definition of technology as the ratio between inputs and intended and unintended outputs. (Weisz 2006)

some cases strategically to avoid even more pressing but less politically or economically promising issues. [14]

The sociological constructivist concept of discourse [15] used here is building on Foucault's understanding of discourse, defined by Hall as "a group of statements which provide a language for talking about- a way of representing the knowledge about- a particular topic at a particular historical moment". (Hall 2001) According to Hajer, who works with Foucault's concept of discourse and who has undertaken influential work on environmental discourse, "[d]iscourse is defined [here] as an ensemble of ideas, concepts, and categories through which meaning is given to social and physical phenomena, and which is produced and reproduced through an identifiable set of practices." (Hajer and Versteeg 2005) The understanding of different representations/interpretation of reality enables us to anticipate the conflicts and the actions taken in a more effective way. According to Hajer, to have the same 'story lines', a coherent interpretation of reality, binds us into 'discourse coalitions'. In other words "[E] each discourse rests on assumptions, judgment, and contentions that provide the basic terms for analysis, debates, agreements, and disagreements." (Dryzek 1997)

The main mechanism referred to here is that discourses, which achieve power in society, can mobilise resources and consequently leave their imprint on the material realm. The leading question in respect to managing a transition towards more sustainable energy systems is: what mechanisms exist that can ensure that available information and discourses are taken up from less powerful niche agents in the technology decision processes? This is important in order to widen the parameters of the debate and consequently to arrive at innovative, new solutions. Opening up the discussion and appraisal process allows us to end up with something that is "more coherent and normatively more consistent with the prevailing institutions and procedures

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[14] From an evolutionary economics point of view, the resilience of socio-economic systems explains the unwillingness to take up information (appraisal) and to react to information (choice). Resilience is primarily relevant in reacting to information. It is a critical mechanism, essentially a self-critical mechanism, that is appraises (1) whether the information is read correctly and (2) whether information is interpreted correctly.

[15] The structuralist and post-structuralist movements in France in the 50s have been historically influential for the increasing and manifold use of this concept. (Keller 2004) A profound bifurcation took place when, one the one hand, Foucault and, on the other hand, Habermas worked with the concept in completely different ways in the last century. The latter, coming from critical theory, formulates a normative model of free speech and communicative competence in a power-free space for discourse ('herrschaftsfreier Diskurs'). This work is therefore also referred to as 'discourse ethics' Foucault by contrast is also interested in the interaction of power and knowledge but in an analytical, not a normative way.

of representative democracy." (Stirling 2005) In an appraisal / decision-making situation, discourses are screened and certain discourses used whereas others are ignored. The question here is which discourses have the power to be heard (selection, inclusion or deliberation in decision-making, policymaking) and what are mechanisms to ensure inclusion? This question will be addressed in detail in the chapter The choice of methods of this thesis discussing a particular set of participatory technology appraisal methods.

As shortcomings of this theoretical model the missing differentiation within the social system should be pointed out. Because of this, equity issues and all distributional problems cannot be addressed adequately. The other shortcoming, relevant in this context, is that no time horizon is directly incorporated and consequently it provides no explicit clue about the nature of transitions in society-nature interaction.

For the task of reflecting on an integrated and deliberative appraisal of more sustainable technology options, this theoretical model offers the right system boundaries and accessibility. Further specific conceptual challenges of society-nature interactions shall be illuminated with systems theory to provide a more profound understanding of the issues.

Complex systems theory on society-nature interactions

The natural and social systems are complex evolving systems. The fact that a reductionist, mechanistic understanding has proven to be only helpful to a very limited extent in addressing environmental and societal questions regarding sustainable development has put greater emphasis on a system perspective. The notion of systems and complex systems originated historically within natural science, where it is fairly well established in the understanding of ecosystems. Thereafter, systems understanding spread to the social science realm. [16] Gunderson and Holling focus on an integrative theory 'to rationalize the interplay between change and persistence' for human and natural systems. (Gunderson and Holling 2002) [17]

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16 The work of theoretical biologist Ludwig Bertalanffy, and biologist Humberto Maturana has been substantive for systems understanding in social science. Also the entropy law played a catalyst role in respect of general systems theory.

17 The general relevance of mechanisms constituting both types of complex systems is stressed in Gunderson and Holling's Panarchy theory. The adaptive cycle stands in contrast to hierarchical understanding representing a cycle of change whereas variety is a changing variable. (Gunderson and Holling 2002)

The overall rational of the present argumentation is to argue that a lack of systems perspective explains at least partially why certain attempts to move towards more sustainable energy systems have not been successful.

The systems theory of Niklas Luhmann provides key contributions to the understanding of systems in the field of sociology and beyond. According to the author, the overall core functional mechanism of systems is 'Autopoiesis'[18], which is characterised by the self-referential sustaining mechanisms of systems. As a thoroughgoing constructivist, Luhmann understands the object solely in terms of its interactions/ communication[19] and 'objects' per se are not relevant in systems theory.

Even though Luhmann's system theory is very abstract there are lessons to learn from him regarding a general understanding of systems. He explicitly addresses societal handling of environmental problems from a systems perspective in his book 'Ökologische Kommunikation' (Luhmann 1986). In an earlier book, he states the generally valid fact that, for systems, the environment (in this sense environment is understood simply as that which surrounds the system) is always more complex than the system itself. Luhmann 1984 This means that autopoietic systems cannot build up as much of their own complexity to fully meet or control the complexity of their environment. For this reason 'each system has to reduce the complexity of the environment, mainly by restricted and categorical perception of the environment', to be capable to deal with it (this author's translation of "*Jedes System muss Umweltkomplexität reduzieren- vor allem dadurch, dass es die Umwelt selbst nur beschränkt und kategorial vorformiert wahrnimmt*"; Luhmann 1986).

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18 The term 'autopoiesis' was originally coined by the Chilean biologist Humberto Maturana when trying to formulate a principle for the organisation of living beings. According to Maturana, a living system is characterised by the ability to produce the constituent elements itself and to reproduce and therefore define its entity. Niklas Luhmann expands this term to other systems, namely social and psychological systems. Autopoietic systems are characterised by having a specific mode of operation that doesn't exist elsewhere. Communication is the mode of operation in social systems. Systems characteristic and requirement for existence is an operative separation. Operative closure ('operative Schließung') means that in autopoietic systems operations depend on and derive from former operations of the system, which means they are self referential. This separation is the base of the autonomy and therefore existence by contrasting against the system's environment. (Baraldi et al. 1997)

19 "No data per se plays a role in social systems but merely communicated data that has communication effects" (loose translation from "Tatsachen an sich sind nichts, nur Feststellung von einer Tatsache hat Kommunikationswirkung"; Luhmann 1986).

However, it is understood that the autopoietic social system is in a loose way dependent upon and adaptive to its environment, an aspect that is addressed with the term ‘structural coupling’ (‘strukturelle Koppelung’). Despite the fact of operative closure (‘operative Schließung’), which makes it impossible for the environment to directly influence the system, there is a reference between the systems, e.g. the materiality continuum (‘Materialitätskontinuum’), which is necessary to sustain the communicating agents in social systems. It seems that Luhmann’s systems perspective is not only a clue that enables us to better understanding systems but also to understand the challenges of societal attempts to move towards sustainable development, when sustainable development is understood as the “fundamental character of interactions between nature and society”. (Kates et al. 2001)

The complexity of two interacting, complex, evolving systems, namely nature and society, is what we are dealing with when managing a transition towards more sustainable energy systems. “Environmental problems by definition are found at the intersection of ecosystems and human social systems, so one should expect them to be doubly complex”. (Dryzek 1997)[20] Luhmann makes a plausible argument from a systems perspective for why social systems have structural limitations when it comes to reacting to environmental problems (irritations), even if their very basis for existence is under threat (see below for further detail on Luhmann’s position). (Luhmann 1986)

If one function of culture is the emancipation of society from nature, consequently sustaining a social system within the environment, it becomes obvious that, in a counter-intuitive sense, social systems have learned not to react to their environment[21] but rather, on the contrary, to become independent to a certain degree. In this sense are self-harming activities of social systems by all means a possible part of the evolution. From the autopoetic systems rational immediate actions are more important than the long term future considerations, since the future might not be reached, if the Autopoesis can not be continued successfully.

> “Die ökologische Selbstgefährdung liegt also durchaus im Rahmen der Möglichkeiten von Evolution….Die primäre Zielsetzung autopoetischer Systeme ist immer die Fortsetzung der

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[20] The model of ‘co-evolution’ is widely applied to conceptualise the interactions and interdependence of two or more agents.

[21] this is a loose translation from “Und evolutionstheoretisch gesehen wird man sogar sagen können, dass die sozio-kulturelle Evolution darauf beruht, dass die Gesellschaft nicht auf ihre Umwelt reagieren muss.” (Luhmann 1986)

> Autopoesis ohne Rücksicht auf die Umwelt, und dabei wird der nächste Schritt typisch wichtiger sein als die Rücksicht auf Zukunft, die ja gar nicht erreichbar ist, wenn die Autopoesie nicht fortgesetzt wird." (Luhmann 1986)

The other important limiting factor is that, in cases where social systems do read and react to irritations from the environment, they only do so in a way that makes sense[22] to them. Sense is generally created through differential technique, which means always in contrast to what is usually defined as expectations. As a consequence, all information produced in social systems refers purely to internal system logic (is self-referential; Luhmann 1986) and brings with it significant blind spots.

This leaves a rather bleak picture of the possibilities for coordinating social system needs and ecological system needs. It does point out the theoretical challenges of problem definition and explains in a way the limited success experienced in moving towards more sustainable energy systems in practise today.

The theoretical model on society and nature interaction, though going along with Luhmann's system theory, adds one very important factor: society is a hybrid of the symbolic realm and the material dimension. This brings out even more clearly the fact that society depends upon or actually participates in the fate of the natural environment and can not abstract itself from the natural environment.[23] Society needs to reproduce itself biophysically and communicatively. Acknowledging the hybrid character of society means that the optimisation of technological development in the energy sector has to anticipate and reflect on the effects on the natural environment and the impact on society entailed by achieving more sustainable development.

Sustainable energy systems

In order to achieve a change in the energy sector, more than new technology is required. An understanding of 'energy systems' has proven to be helpful in addressing the complexity and

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[22] "Sense is a representation of the world's complexity, which is compatible in the respective moment". (loose translation from Luhmann 1986)

[23] The classic tool for attempting to emancipate society from the natural environment is technology. Since the handling of fire (some 100,000 years ago), the emancipation of human societies from natural cycles and rhythms has been attributable to the use of technology.

the profoundly interactive character of the organisation of society's energy supply and demand. The general attributes of complex systems, such as being self-organising, emerging properties, evolving, feedback loops, non-linearity and uncertainty, which are discussed in sustainability science are largely applicable to energy systems. (Dincer and Rosen 1999, Kates et al. 2001, Clark and Dickson 2003, Foxon and Pearson 2008)[24]

That technology is more than the machinery itself is argued in the broader sociological discourse on technology, which understands technology as "configurations of technological and non-technological components" (Fleck 1993), "configurations that work" Rip and Kemp 1998, or "socio-technical ensembles" (Bijker 1993). Already very early on, technology is understood as the artefacts ('applications') and the management that is necessary: "Technology denotes the broad area of purposeful application of the contents of the physical, life, and behavioural sciences. It comprises the entire notion of technics as well as the medical, agricultural, management and other fields with their total hardware and software contents" (Jantsch 1967 p.15)

A recent German term from Majer 2005 is "eingebettete Technik", which is understood as integrated coherent technological development and its implementation towards sustainable development. (translated from Sothoude 2006). The role of technology in society is widely discussed and one common discourse concerns the way in which the causality works: i.e. whether society is influencing technology or the other way around. This discussion could be summarised as social construction versus technological determinism. (Grübler 1998) In this DPhil thesis, the view taken is that both directions are meaningful: socio-technical systems are at the same time socially constructed and society-shaping (Hughes 1987, Joerges 1988). 'Technology is social structure' and 'not only affects but constitutes societies'. (Sclove 1995 p11 and p17) Wynne argues further that technology also influences values in society: 'technological decisions, which we usually suppose to be subject to a coherent and independently formulated frame of social values, actually influence the shape of dominant social values themselves'. (Wynne 1980)

An additional important point this thesis wishes to make, though, is that technology is not only diffused and integrated into society (Grundwald 2000) and constituting society but that,

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[24] In the context of technology, for example, a self-organising character is described in the literature as technology having a ' life of their own', 'autonomy', and 'development momentum', 'technological drift' and 'path dependency'.

moreover, technology is the interaction of the social and natural systems. Based on the theoretical model of society-nature interactions discussed earlier, technology itself is a hybrid of the biophysical and symbolic realm and is a constituting part of the interaction of society and nature.

The broader literature on innovation and innovation systems (Lundval 2010) concerns another common theoretical approach for analysing energy systems as a specific case of technological systems. These generally comprise of actors (and their competencies), networks, and, institutions. (Jacobsson and Lauber 2006) The market formation and competition of emerging technologies are the focus of this approach, whereas the interactions with the natural environment are characteristically not present.

A more recent systems understanding of technology is expressed in theoretical concepts as socio technical regimes (Berkhout 2002, Smith 2007), socio-technical systems (Geels 2004b), and large technical systems. (Hughes 1987) Yet, the systemic character of technology and consequently of energy systems are built merely on the complex interactions within the social system (e.g. markets, industry, consumers, policy makers). But also here the natural system is not explicitly present in the concept of either socio-technical systems or regimes. Winner puts a definition forward according to which ‘technologies [are understood] as structures whose conditions of operation demand the restructuring of their environment’. (Winner, 1978) The environment refers exclusively to the social environment. Few recent studies address the relation of technology and ecosystems, and theoretically founded considerations of this interrelation are rare (see, for example, Berkhout 2003, Berkhout et al. 2003). In contrast, the Resilience Alliance regards technology as an external factor to socio-ecological systems. (Smith and Stirling 2008)

Energy systems are unique in the sense that energy is a key limiting driver in both social and natural systems and are consequently directly communicating agents. Energy systems demonstrate in an exceeding way the relevance of reflexivity between socio-technical systems and the natural systems. In this context, sustainable energy systems are conceptualised as the sustainable interactions of social and natural systems. [25]

Another advantage of this systemic view is that it enables a procedural understanding of long-term sustainable change. This cannot be delivered by a simple definition of technology as being the input-output factor between resources and wanted or unwanted goods. When technology is reduced to a kind of conversion method between inputs and outcomes, it gives no handle to understand the mechanisms and obstacles of technological change.

Recent theoretical and practical approaches, such as transition management (Kemp 1994, Rotmans and Loorbach 2008) and reflexive governance (Voß et al. 2006), share a systemic understanding of socio-technical change. The following section discusses the profound relevance of the interactions of society with nature for a transition towards more sustainable energy systems.

How changes of, or transitions between energy systems can be brought about

There is an immanent need for a structural change of the present energy supply and demand patterns, therefore the nature of an energy transition and the possibilities for managing an energy transition towards more sustainable energy systems are key challenges for science, policy, and industry. Concepts such as transition management (Kemp 1994 Kemp and Rotmans 2004), strategic niche management and reflexive governance (Voß et al. 2006, Smith et al. 2005, Berkhout et al. 2004) and the multi level concept of socio-technical change (Rip and Kemp 1998, Kemp et al. 2001, Geels 2002) lead operational discussions on how sustainable transitions can be governed.

[25] The concept of ‘viability’ of technology by Georgescu-Roegen captures part of this attempt: A technology is not viable unless it can support itself without drawing down irreplaceable stocks, and is also not viable if it impairs the ability of the fund factors to maintain the economic process. According to Georgescu-Roegen, “Fund elements are those productive agents unchanged in the process, that is, inputs that enter and exit in a form that is economically the same (e.g. labour)”. (Gowdy and Mesner 1998)

Especially for large technical systems sizeable investments are usually associated with a structural change, long-term infrastructural decisions are required and several contradictory interests, manifested in institutions and power, are involved. It will be argued in the following section that apart from the economic, infrastructural dimensions the structural change of the energy system has vast implications for the practises within society (housing, communication, life style, etc.) and also for the interactions between society and nature. The challenges of managing interacting systems from a systems theory perspective have been discussed earlier. Two main arguments are stressed at this point again, because they are relevant for the governance debate: (1) the self-referential character of the social system and the subsequent problems of reading other forms of systems logic and anticipating it within the decisions and actions taken; (2) the absence of an overall coordinated action of the social systems, 'Total operation', due to the existence of subsystems.

Direct steering towards a more sustainable energy system is not possible. (Polatidis et al. 2003) Anticipating the wide range of future consequences of a structural change of the energy system, e.g. towards renewable energy systems, proves extremely difficult. Due to the numerous interactions, delayed reactions, frequent indirect or unintended impacts, which are all characteristic for complex systems the degree of uncertainty when appraising energy systems of the future is very high (even without anticipating structural change) and to some extent irreducible. The diversity of actors and interests is another important social dimension of this complexity. The current energy resource problem, combined with the anthropogenic climate change, therefore qualify as so-called 'persistent' problems, characterised by high uncertainty, a multitude of actors and diverse interests, and by being difficult to structure. Whereas "persistent problems require transitions: fundamental changes in structure, culture, and practises of societal systems." (Rotmans and Loorbach 2008)

Nevertheless, theories and models of change do try to anticipate general processes of change, e.g. technological change, modernisation, evolution, competition and co-evolution, etc. and work on, for example, identifying main drivers and obstacles. General models of change are developed to anticipate what the future holds for specific cases. In many respects it is asserted today that the primary driver of societal change is associated with technological advancement. Technology is often dealt with as a 'joker' whereas without it the Malthusian dilemma of resource scarcity and population growth is inevitable. The extent and speed of technological innovation in industrialised countries cannot be denied. Profound studies have proven, though, that in many cases the efficiency gains due to better technology are more than compensated by behavioural adaptations, known as the 'rebound effect'. (Polimeni et al. 2009) Therefore the social, behavioural and institutional changes (accompanied by technological innovations) do gain considerable importance as key factors of technological change.

Having elaborated in the last section on energy systems as a key factor in the interactions between social and natural systems, it is claimed here that consequently the transition of the present energy systems towards more sustainable energy systems has to take into account the interactions of societal and natural systems. Hence, the following section addresses the absence of the interaction between social and natural systems from the current understanding of technological change and transition.

In the following section, general notions of systemic change are introduced, which are relevant when differentiating between different theoretical perspectives. According to the authors Polatidis, Haralambopoulos, Kemp, and Rothman three types of technological change of the energy regime can be categorised: (1) the optimization, which involves incremental change in e.g. energy efficiency or end-of-pipe technologies, (2) the partial system redesign which includes e.g. extended renewables, and, finally (3) the system innovation. Systems innovations means a change in the system architecture e.g. decentralised electricity generation and use. (Polatidis et al. 2003)

The specific transition theory known as 'the multi-level concept' (Geels 2002) is elaborated here, informed by the analysis of a universal historical perspective on the transition to fossil fuel-based energy systems. This perspective is introduced here in order to present a convincing implementation of the theoretical understanding of society-nature interactions in respect of energy transitions. The specific role of feedback loops as stabilising and enhancing mechanisms of energy regimes is discussed. The overall aim is to stress the necessity of explicitly anticipating interactions between social and natural systems in technological change towards more sustainable development and to inform present understandings of energy transition.

Change in energy systems

Understanding energy systems as socio-technical systems, change is more than solely technological change. Practices, institutions, infrastructure, etc. are incorporated in the socio-technical system and are part of the change process. It becomes apparent that according to this conceptualisation, change goes far beyond replacing old machinery with new machinery and that technical innovation has to be accompanied by a social innovation and infrastructural innovations[26]. Stirling summarizes: (Stirling 2005)

> "Earlier deterministic, linear notions of 'progress' have given way to a picture of contingency (David, 1985), social-shaping (Bijker, 1995), momentum (Hughes, 1983), lock-in (Arthur, 1989), autonomy (Winner, 1978) and 'entrapment'. (Walker, 2000) The form and direction taken by our science and technology is no longer seen as inevitable and monolithic, awaiting 'discovery' in Nature. Instead it is increasingly recognized as being open to shaping by individual creativity, collective ingenuity, cultural priorities, institutional interests, stakeholder negotiation and the exercise of power." (for quotations, see Stirling 2005)

The recognition of the central role of technology for development is deeply founded, however. Several models of technological change have been developed and key factors for innovation identified. Authors such as Kondratief, Schumpeter, Marx, Freeman, Dosi and Podobnik have contributed to an understanding of technological change and innovation as prominently as e.g. the s-wave. The focus of these models is mostly upon the economic and technical drivers (Grübler 1998, Freeman 1994a) and the relation between innovation and capital is a widely discussed key element in this respect. Yet, certain historical analyses of the industrial transformation show that the vast innovations that took place at that time cannot be sufficiently explained by the presence or absence of capital. (Sieferle 2003)

Regarding the ultimate objective of managing a transition towards a more sustainable future, the interactions between natural and societal systems have to be taken into account. The representation of the natural system is necessary to monitor technological change and furthermore energy transition in a reflexive way, in terms of the impact on the environment and therefore upon long-term sustainability.

The changing socio-technical system is described in the multi-level concept, extending the definition of change to include more than technical change. The multi level concept is an evolutionary model differentiating three levels, which are essential for the understanding of transitions: the niche level, the regime level and the landscape level. (see Figure 2). The fundamental mechanism is the eventual inclusion of niche elements, e.g. grass root developments as self engineered solar heating units for households, into the regime that change

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[26] This systemic view on energy transition contains the phenomena of 'path dependency' and 'technological lock-in'.

or add to the established practises and technologies. The internal niche processes have been analysed in the concept of strategic niche management. (Kemp et al. 1998 Smith 2007) The landscape level comprises overall norms and values and the natural (material) environment. Changes in the landscape level may put pressure on the regime and opens a window of opportunity for niche technologies.

> “The meso level of the ST-regimes [socio-technical regimes] accounts for stability of existing technological development and occurrences of trajectories. The macro level of landscape consists of slow changing external factors, providing gradients for the trajectories. The micro-level of niches accounts for the generation and development of radical innovations.” (Geels 2002)

The strength of this concept is that it presents a simple structure based on co-evolution, explicitly accommodating the notion of socio-technical systems.

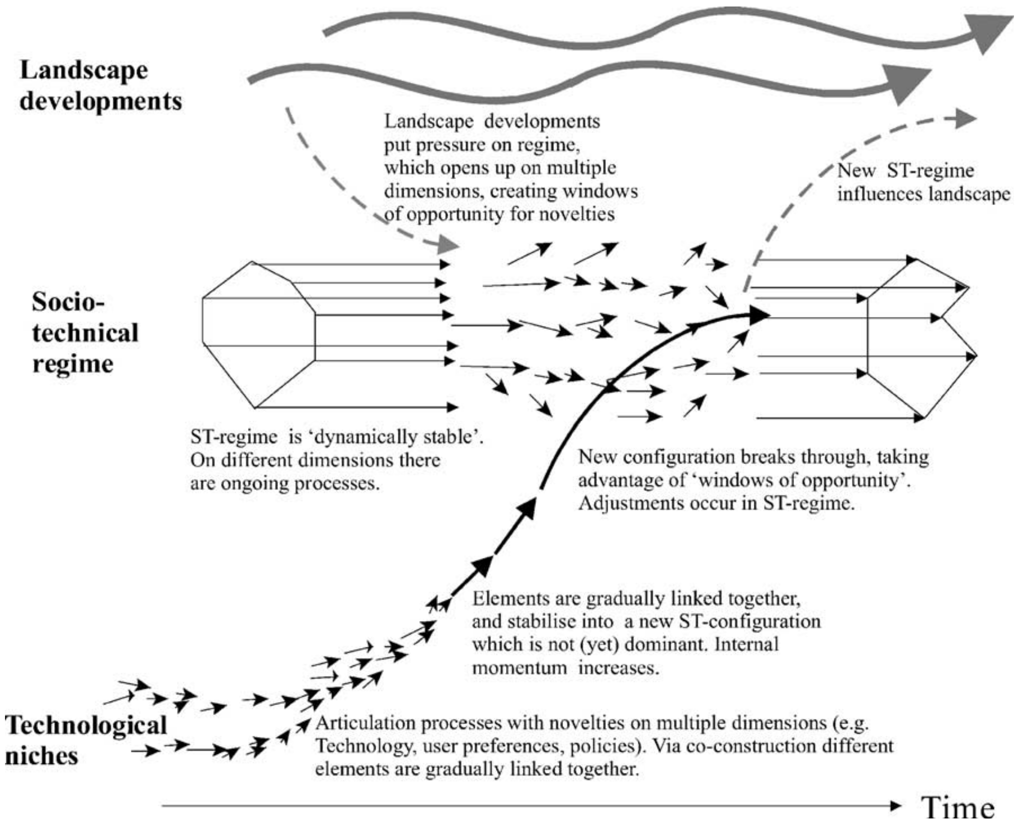

Figure 2. A dynamic multi-level perspective on system innovations. (Source: Geels 2002, p. 110).

One important weakness of the multi-level concept, which will be further elaborated on here, is the undifferentiated conglomerate described as landscape with no explicit understanding of systemic boundary with the natural environment[27]. “The transition management approach is more focused on social, economic, and cultural changes, changes that may imply a change in environmental impacts.” (Fischer-Kowalski and Rotmans 2009)

A specific perspective on the historical energy transition of the industrial transformation, which explicitly takes into account natural systems and the interactions of social and natural systems, is presented here to demonstrate an application of the theoretical society-nature interactions model. Before this, general notions of changing energy systems are discussed here, providing a deeper understanding of interactions between natural and societal systems and feedback loops, as constituent elements of systems.

Technological innovation is often in a rather undifferentiated manner associated or even equated with progress and advancement per se. Modernisation theories in the social sciences in general imply that change is always for the better, towards the more advanced and civilised. “This dynamic expresses itself in many respects, as technological progress, as increased knowledge, as economic growth, as a process of “civilisation” or “modernisation” of the world.” (Sieferle 2003)

Contrary to this are theories of change, such as socio-metabolic theory, which do not understand change as in principle an ascent towards the ‘better’ but instead see several possible equivalent states of a social systems with certain interaction intensity and patterns with the natural systems. These non-modernisation theories do not corporate a value judgment per se, nor do they credit technological advancement per se as an improvement. The focus is upon whether or not societal interactions (labour, technology colonisation, etc.) with nature are sustainable in the long run.

[27] Other criticism or suggested potential for improvement, which can not be addressed in this thesis, points in the direction that the multi-level concept implies a one-way direction, failing to consider in which sense the regime does influence niche activities, and niches each other, etc. (Smith 2007) Furthermore, the empirical evidence for this type of transition is only based on historical data and not many present-day case studies have yet been analysed using this concept. (Genus and Coles 2008)

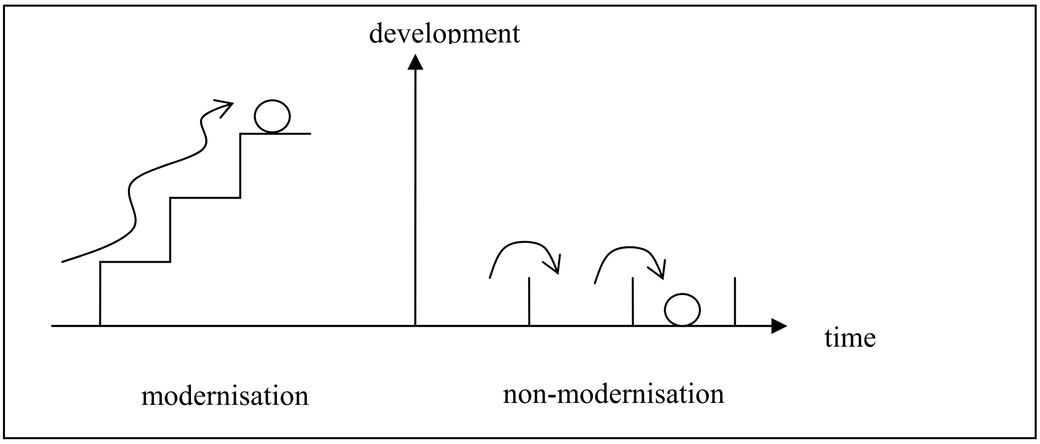

Figure 3. Graphical representation of modernisation theories, implying a change towards the better over time, versus non-modernisation theories assuming several egalitarian states of the social system.

Common to both approaches, however, is the existence of a certain inertia to change resulting from the resilience of the system[28], which is to be overcome. There are two complementary concepts of how to surmount the power of established mechanisms either by revolutionary turnabouts or by small gradual steps. The key difference between these is whether the format of the system after change (transition, transformation) is determined by the system's initial preconditions. This involves differentiating between cases in which the transformed system has already "slumbered" in the former system or those in which the new system is in a completely new format. A revolutionary turnabout leads to a new format, while small gradual steps of change happen within the old format. This differentiation is discussed in the literature as two opposing theories of change - orthogenetic evolutionism and contingency theory (Sieferle 2003, or in other words rationality versus contingency (Staudenmaier 1994) or radical versus incremental change. (Freeman 1994)

The basic element of orthogenetic evolutionism (rationality, incremental change) is gradualism, meaning that there are no breaks or leaps in historical terms.

[28] The general inertia of systems towards change is, expressed in a positive connotation, the resilience of the system, which is understood as a quality of systems. (Gunderson and Holling 2002)

> “No separate societal formations, but an open and continuous progressive flow leading towards the future…. [T]hat can be understood as a unified progressive and teleological process of humanity towards insight, control and wealth”[29] (Sieferle 2003)

That is also referred to as the “Western technological master narrative of progress”. (Staudenmaier 1994) This is clearly the case in the example that Macfarlane presents, referring to the authors Stubbs and Maitland, whose analysis concludes that nineteenth-century England has its roots even in Anglo-Saxon England. Maitland refers in this context to his ‘organic-growth model’. (Macfarlane 1986)

Contingency theory (radical change) is based on improbable revolutionary breakthroughs.

> ”The major revolutions in world history like the transition to agricultural societies or the start of industrialisation are in this perspective not determined by their initial preconditions. They are unexpected events emerging fortuitously in social areas that were not necessarily unstable or prone to self-transformation.” (Sieferle 2003)[30]

Following contingency theory, change is in principal “totally unpredictable and surprising”. (Macfarlane, 2000 in Sieferle 2003) [31]

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[29] This idea could be allied to biological theories of evolution until neo-Darwinism shook off all remains of teleology. “As a consequence, the orthogenetic stance could no longer be based on a general theory of evolution, including biological, cultural and social dimensions.” (Sieferle 2003)

Orthogenetic evolutionism is therefore almost equivalent to evolutionary feedback in Lamarckism, where evolution is understood as a learning process. “When nature has unambiguous qualities, the positively feedback process of acquiring knowledge about these qualities must lead to permanent and continuous improvement in adaptation, and the logical end of this process is optimal adaptation.” (Gallopin et al. 2001)

[30] To give a classical example: Max Weber’s construction of a causal relationship between Protestant ethics and the ignition of capitalist accumulation. In 1500 Christian reforming movements took place and led in Geneva to Calvinism. This was exported to England and could there, under social and political conditions in which where puritan sects could flourish, initiate a process of capitalist innovation. This example makes clear how improbable this process was and “under many circumstances it might have failed before it became self-sustained.” (Sieferle 2003)

[31] Regarding the change of scientific paradigms or ‘episteme’, a similar theory of change has been promoted by Kuhn in his work ‘The Structure of Scientific Revolutions’ (Kuhn 1962) and by Foucault in ‘The Order of Things’ (Foucault 1989)

The difference between radical and incremental change could be a mere scale issue or political motivation though[32]. Nevertheless from a systemic perspective the differentiation becomes certain significance that shall be elucidated at this point.

The main driving mechanisms of systems, or in other words, the constituent functions of a system are feedback loops, both negative and positive ones. (Maturana and Varela 1987) Generally speaking, feedback loops process some proportion of the output signal of a system and pass it back to the input. This mechanism stabilises or enhances the dynamic behaviour of the system. A changing system will therefore necessitate a change of feedback loops. New feedback loops can be understood as new functions accentuating new or even introducing new drivers (parameters) into the system. Feedback loops as the functional constitution displace each other or make each other obsolete (not gradually or 'just a little bit'). Using the example of the industrial transformation, from the moment the limiting factor of energy source became obsolete, the negative feedback was displaced by a positive feedback loop between energy consumption, technological progress (innovation) and economic growth (see Figure 4 and 5)for a simplified graphical representation of feedback loops)

An example shall demonstrate this kind of 'translation' of a society-nature interactions system in its feedback loops, anticipating the universal-historical analysis of the industrial transformation in more detail in the following section:

A window of opportunity opened in the seventeenth century in England, where under very specific circumstances the inertia of agricultural societies that had existed for almost 10,000 years was overcome by a new self-enhancing feedback of growth.

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[32] A relativisation of the strict ontological taxonomy of change is however necessary from a constructivist perspective. Above all, the patterns of change finally observed do depend on the time-scale the observer chooses. (Giampietro 2002, Giampietro 2004) Selecting a very small time-scale means that even revolutionary change may seem like a step-by-step, gradual process.

Furthermore, as MacFarlane states clearly, "if we are dedicated to hunt for dissimilarities [between past and present] then 'revolutions' before which things were very different are what we shall hope to find …"(p 162). Interpretations of the past using alternative theories of change are helpful in different respects. This is also true with regard to conceptualising future change. "..[I]f all that exists now can be shown to be the result of a recent 'revolution', then it is easier to consider changing present institutions. …The premise of continuity can conversely be attractive to those who wish to stress enduring values, who dislike profound change." (Macfarlane 1986, p164)

Historical energy transition taking into account society-nature interactions

A perspective on the industrial revolution concerning the transition towards fossil fuel energy systems is chosen demonstrating the power of an interpretation that takes the interactions between society and nature into account.

This perspective on energy transitions offers two added values for the research questions we are dealing with and informs the general discussion on the upcoming energy transitions by:
1) Recognising the society-nature interactions and the role of energy in this interactions
2) Demonstrating the role of feedback loops and structural change of feedback loops in energy transitions

In Rolf Peter Sieferle's work, energy technology is plausibly described as a key interface of natural and social systems and as a major driver for the types of interactions between society and nature. From a universal historical perspective, he characterised three types of energy regimes in human history: the hunter-gatherer societies based on solar energy use, the agrarian societies with a managed solar energy system, and the industrialised societies founded on fossil fuel-based energy systems. (Sieferle 1997 Sieferle 2001) In this terms the universal historical perspective allows a completely different narrative compared to the majority of literature on historical transitions as e.g. Parker 1986, Macfarlane 1986, Rostow 1960, Grübler 1998, Common and Stagl 2005.

The energy regimes of each of theses societies are characterized by the following annual energy flow per capita. (Sieferle 2003)[33]:

Hunter gatherers	10-20 GJ and 2-3t
Agrarian societies	60-80 GJ and 4-5t
Industrial transformation	250 GJ and 20-22t

In one of Sieferle's recent publications, he addresses the pertinent questions of how industrialisation started and why it did so in Europe.[34]

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[33] The form of material interactions between societies and their physical environment can be referred to as 'social metabolism' (Fischer-Kowalski 1997) This metabolism, in other words the whole area of production, consumption, technology, and population, is ultimately determined by the availability of energy.

> "How can it be explained that one particular region in the world left the several thousand year-old pattern of agrarian civilisation with the consequence that all other civilisations had to follow this path willy-nilly?" (Sieferle 2003 p7)

To outline the basic features of agrarian societies, the main production mode involves controlling and managing solar energy flows, essentially on the basis of biotechnology. Common and Stagl 2005 A key feature is that all societal specifications, such as e.g. cities, specialists and their institutions, have to be sustained by the agricultural harvest. "The socio-economic basis of the agrarian society was the tributary appropriation of surplus". [35]. p14 Sieferle 2003 Generally speaking, agrarian societies are energetically sustainable in the sense that they live from flows and not stocks. These flows, however, are so small that energy is fundamentally scarce. As a social consequence, the majority of people live at subsistence level and famines do occur on a regular basis.

From a systems perspective, the key explanation for the consistency of agrarian societies over such a long period lies with the negative feedback loops systematically regulating population and economic growth and consequently preventing structural changes. In agrarian societies, "each step into the direction of physical growth destroys the potential of further growth, so that the agrarian economy necessarily approaches a natural limit sooner or later." (Sieferle 2003, p13)

In an agrarian society, which are based on solar energy systems, energy converters, nutrients, tools, means of transportation, and building materials are appropriated from natural materials.[36]

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[34] This particular publication focused on a comparison with China. Putting into question why industrialisation happened in Europe, in the UK, even though generally speaking, many key historical technological developments have happened first in China. In his 1620 publication 'Novum Organum', Francis Bacon mentions three inventions with high significance: the printing press, gunpowder, and the compass, whereas in fact all three innovations had their origin in China.

[35] The basis of agrarian society is the peasant society, which is also the level to which it returns when high culture collapses. A return to hunter gatherer societies can only be observed under very rare circumstances. Significant features of agrarian society include cities, trade and industry, writing, metallurgy, social stratification, religious institutions, government administration and large empires. "However, these features are based on the agricultural foundation, which defines the scope that other areas of life possess ranging from the economy to politics and the military to everyday life." p10

[36] "As an effect of this strategy more and more areas of the natural environment are transformed into an 'artificial' condition which makes them more fit for specific human needs. This colonising, however, does not

Even though the agrarian mode of production provides the basic structure, specific environmental conditions have a stronger impact on the particularities of agrarian societies than in the case of industrialised societies. Essentially, "they [agrarian societies] are less able to substitute lacking conditions and to modify or even create a favourable environment than industrialised societies can do". (Sieferle 2003, p10) Regional isolation ("regional limited recursive communication"), in addition to the afore-mentioned constraints on adaptation, causes several functionally equivalent (technical) solutions. This isolated characteristic of agrarian societies is partly due to the very limited extent of affordable transportation. (Boserup 1981) When utilising solar radiation, which reaches earth distributed over a very large area, as the basic energy source, the key challenge is to concentrate energy. In principle, the energy harvest must be positive including transportation expenditure, which means that distances should not be too long. As a consequence, agrarian societies are always scattered over a large area. (Boserup 1981)

Sieferle summarises three key factors for a perpetuating negative feedback loop in agrarian societies as follows: (Sieferle 2003)

(1) people are at the mercy of natural fluctuations,
(2) high population density leads to the spread of parasitic micro-organisms
(3) warfare is a regular occurrence

The diminishing marginal returns in agricultural production (despite technological advances[37]) and the lack of power to modify or even create favourable environments mean society is directly affected by natural fluctuations. As a consequence, famines occur regularly. From the perspective of population dynamics, increased nutrient supply in agrarian societies leads to population growth. This means that per capita wealth fails to improve. In cases where the population density increases too much, disease or even epidemic plague regulates population growth by forcing it downwards. Regular warfare is caused by the expansion tendencies of agrarian empires. Warfare activities are mainly motivated by a wish to gain (or not lose) areal territory as the key source of wealth. "A rich and dynamic agrarian society was finally either conquered by booty-seeking predators or it took the path of conquest itself until its forces were

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only require initial work, but a permanent effort is necessary to keep up artificial conditions in view of spontaneous tendencies of nature to regain the colonised zones." p14 (Sieferle 2003)

[37] "In general, the spread of technical and economic innovation, which did take place sporadically, was hindered by the inherent shortage of energy and material." (Sieferle 2003 p14)

exhausted.” (Sieferle 2003, p 15) Warfare works as a factor in the negative feedback loop in the sense that the disruption of production by predation increases in the same measure as wealth grows.

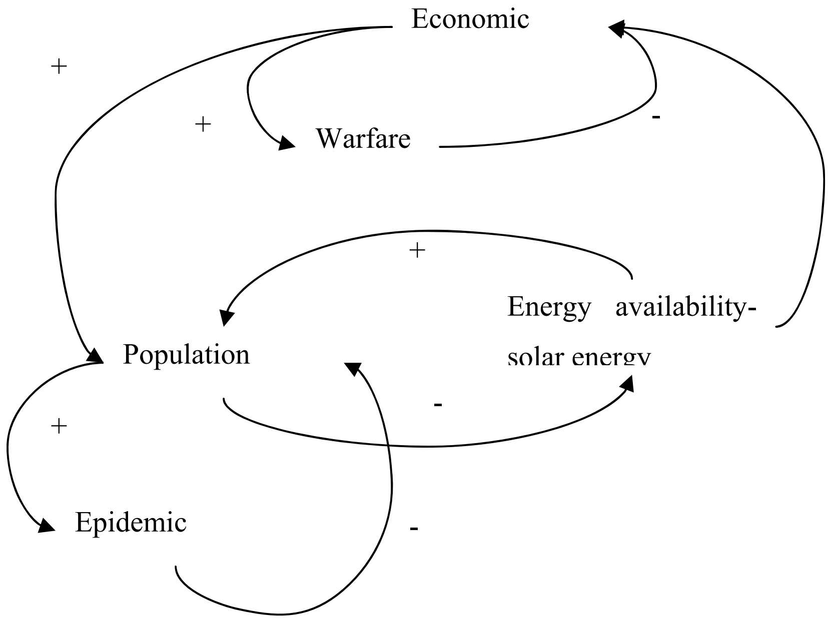

Figure 4. An exemplary representation of the stabilizing feedback loops in agricultural societies between economic growth, warfare, population growth, epidemic plagues and energy availability (the graph does not claim comprehensiveness).

Consequently “[A] agrarian societies are caught in a trap from which they normally cannot escape. From this perspective industrialisation was a highly improbable singularity, blasting a pattern that worked for almost 10,000 years.” (Sieferle 2003 p15) [38]

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[38] A consideration of solar-based energy systems is especially relevant today since renewable energy systems are essentially solar-based energy systems. Modern renewable energy systems can be expected to be different from agrarian energy systems due to the different starting position concerning the equipment, practices and institutions e.g. technology, information technology, global markets, etc. But nevertheless, an understanding of society-nature interactions in solar energy systems and their basic constraints can be informative regarding future prospects for renewable energy systems in industrialised societies. Concrete conclusions from the historical analysis will be presented in the final part of this section.

The industrial transformation

The industrial transformation or 'industrial revolution' in England in the seventeenth century is discussed in great detail in existing literature. (Macfarlane 1986) For Parker the "fair and correct way to look at …(industrial revolution) revolutions in a few industries, though small in themselves when happened, were mighty in effect." (Parker 1986, p177) Sieferle would not agree with this rather technocratic point of view and would, on the contrary, stress that from the systemic perspective of society-nature interactions, the industrial transformation is a key transition in the universal historical time-scale.

For the purpose of this DPhil thesis, only a concise question relating to the industrial transformation is addressed with the specific intention of deepening a systemic understanding of energy transitions: How could agrarian societies break away from the negative feedback loops that were preventing agrarian societies from making a major transition for a very long period? The answer to that question promises to provide insights for today's discussion on transitions and managing transitions.

In a simplistic understanding, the enhancing combination of the factors energy consumption and innovation forms the basis for the economic growth of industrialised countries over the last 200 years. (see Figure 5) "..a positive feedback loop between consumption (of stocks) and innovation emerges" (Sieferle 2003) starting out from a pioneer situation when the large stock of fossil fuels was discovered and appropriate technology was available[39].

[39] In metabolic terms, industrialisation is based on the transition to a fossil fuel-based energy regime that allows its resource base to switch from "organic" to "mineral" material. Other than in most 'modernisation' theories, the industrial transformation is interpreted here as a change of the social-metabolic regime, which is not at a higher level of development. The physical dimension of this change from organic to mineral material can be empirically demonstrated in energetic and material terms. (Krausmann 2001, Schandl and Schulz 2002, Sieferle 2001)

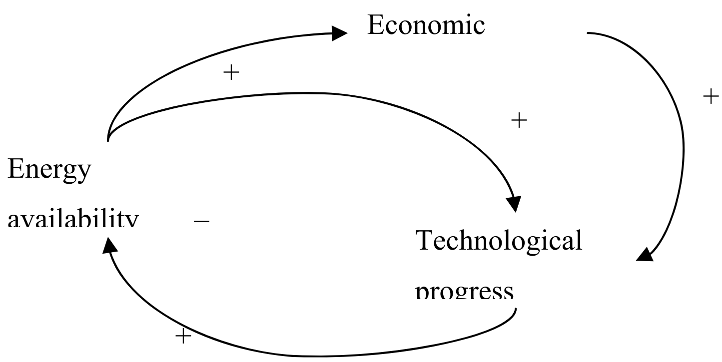

Figure 5. An exemplary representation of the enhancing feedback loops in industrial societies between economic growth, energy availability, technological progress and population growth (the graph does not claim comprehensiveness)

A precondition for the transformation was the extensive development of fossil energy. The transformation was not so much a matter of coal use as such[40] but more the simultaneous appearances of several technical processes allowing for a fossil fuel-based energy system: (Sieferle 2001)

- Developing steam pumps for use in coal mining enabled the supply of fossil energy sources to grow and stabilise
- Melting and freshing of iron with coke
- Building of steam railways and steam boats to emancipate transportation from the restrictions of bio-converters

With these simultaneous developments, the former restrictions related to solar energy resources became obsolete and a positive dynamic of growth started. Before the industrial transformation, qualitative growth, understood as an increase in per capita consumption of energy and materials, had existed only for limited periods.

Following Sieferle's argumentation, this was possible in agrarian societies under two conditions:

[40] Coal was used in Europe from Roman times and coal mining was an important feature in the Chinese economy. But "sporadic use of coal is not identical with the emergence of a fossil energy regime." (Sieferle 2003)

- Super-abundance of resources due to a pioneer or frontier situation[41]
- Technological progress offers the opportunity not just to consume stocks more rapidly but to tap into inexhaustible flows with a higher efficiency

"A sustained economic growth would depend on a dynamic, in which (cost neutral) technological efficiency can be increased faster than the marginal returns decrease", which would be a theoretical escape from the agricultural trap of stagnation. According to Sieferle, there is no historical case in which this strategy has succeeded for a longer period. (Sieferle 2003 p 18)[42]

Besides technological and economic macro-inventions, several psychological and socio-political preconditions exist for the industrial transformation to take place, from Sieferle's perspective[43]. By overcoming hindering factors, such as the predatory pattern and the scattered innovation system, through socio-political innovations such as the commercial society, the negative feedback loops became obsolete and could be replaced.

Because of the psychological and socio-political similarities between the European countries, the industrial transformation could be taken up much more easily than had it originated e.g. from China.[44]

Nothing indicates that the window of opportunity was opening anywhere else than in England to overcome the feedback loops of the social-metabolic regime of agricultural societies. Despite this, current research provides the impression that the level of European civilisation was about

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[41] The classical historic example for this special situation is the arrival of the Maoris in New Zealand and finding an over-abundant meat resources (Sieferle 2003)

[42] However, for shorter periods of some decades or even two or three generations, such growth regimes supported by innovation was viable even in the agricultural past. (Sieferle 2003, p18)

[43] "In respect to the mental preconditions a scientific world view and an experimental style connected with modern natural philosophy shifted innovation from tinkering to methodological inventions.

In a socio-political respect, the predatory pattern dissolved with the transition to a "commercial society". The main features of this were the transformation of the state into a service institution for civil society, providing property rights and the rule of law, the consequence of which was the dominance of individual achievement (instead of status), functional differentiation of society and social mobility." (Sieferle 2003)

[44] Empirical analyses from Krausmann et al. show, for example, that in the middle of the nineteenth century there was a large gap between the material conditions in Austria and in England. Austria might still have been metabolically closer to Chinese conditions than to those prevailing in Britain. During the next 150 years this gap closed with remarkable rapidity. (Krausmann 2001, Krausmann et al. 2003)

equal to that in e.g. China in the eighteenth century[45]. The industrial transformation is not per se a logical sequel or an extrapolation of agricultural societies in the sense of continuous progress. The ignition of this transformation was an extremely improbable occurrence that could only have taken place under very specific and unpredictable circumstances which presumably only existed in England. Since other European societies shared so many conditions with England, they could switch to these trajectories with some delay but without severe problems. This, however, was not the case in China nor in the Ottoman Empire.

To summarise, the economic growth of industrialised societies is an indisputable fact. This is and was made possible by establishing a positive feedback between innovation and economic growth in a situation of over abundance and therefore breaking out from the negative feedback loops of agrarian societies. But "the question remains that if these are properties of a system in balance or if we are still in the midst of a transition which lasts far longer than theorists like Marx could imagine." (Sieferle 2003) Physical economic growth at a considerable rate is not possible over longer periods. (Daly 1992) From an universal historical perspective, this indicates that we presently are in a unique situation the end of which may lie in a not too distant future. But even though "[T] the heritage of the fossil age is not just empty deposits, but also a large amount of know-how that might not have been acquired without this historical detour of squandering resources[46]." (Sieferle 2003)

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[45] This holds for material standards of living, for civil administration and for transportation, while agrarian productivity might even have been higher in China at that time due to the multi-cropping system favoured by climatic conditions. (Sieferle 2003)

[46] Most technological inventions that may lead to high energy efficiency in the future would have been impossible under the conditions of severe energy scarcity inherent in the agricultural mode of production.

Summary of key theoretical insights

This section aims to summarise and close the theoretical considerations by highlighting the key insights that frame the empirical research section.

After discussing the fundamental role played by energy in socio-economic as well as natural systems, it becomes evident that technical energy use is a key parameter in the context of sustainability. Energy technologies relate directly to the interactions of natural and social systems. Studying historical trajectories of energy use from a socio-ecological systems perspective enables insights to be generated into the complex interlinkages, feedbacks and interdependencies and into the fundamental (radical) structural changes that are associated with an energy transition. The challenges and obstacles of such structural changes go far beyond gradual changes such as the development of new machineries or technical equipment. The social reflexivity of society-nature interactions, although challenging, is a prerequisite for society to develop more sustainable strategies in coping with the natural systems.

A sustainable energy transition is driven by diverse and contradicting perspectives and interests and has far-reaching structural consequences for society. Top-down approaches to steering such a transition are thus very much prone to failure; bottom-up deliberative approaches can be seen as much more favourable; as they explicitly aim at reconciling different perspectives via negotiation processes.

From the discussion of these theoretical traits, the following three insights shape the design and framework of the empirical research presented in this thesis.

(1) Socio-technological change in the face of society-nature interactions

One of the overall messages of the theoretical chapters is that a systemic perspective on sustainability has to focus on the interactions of society and nature. Technological innovation per se is not enough to achieve more sustainable energy systems. Technology has to be understood as part of the interaction between nature and society. The concept of socio-technical systems concentrates on the wider societal process of technical change but fails to address natural systems. Natural systems, on the one hand, provide the ultimate source of energy for society, and it matters, in what form: whether spatially dispersed and with a low energy density, or locally concentrated with high density, whether as radiation, solid matter or liquid. The amount of supply, and the conditions of supply, ultimately is determined by natural parameters.

On the other hand, in order to access energy sources, societies need to intervene into natural systems and restructure them for the purpose of energy extraction. This may be the large-scale deforestation of land area for agricultural use, infrastructure modifying aquatic systems for electricity generation, or intrusion in geological deposits. In all cases, this involves a complex interaction in which social systems are forced to change in order to incapacitate them for such interventions, and in which natural systems change – not only in the way intended, but also entailing a number of unintended consequences (such as soil changes, changes in atmospheric and water cycles, geological depletion and various accidents) that in turn societies need to cope with. An analysis of sustainable energy systems and innovative technologies needs to take the dynamics of society and their interactions with natural systems into account.

(2) Sustainability relates to the interactions of two complex, adaptive systems – and this has implications for the research methodology

Sustainability cannot be defined for a single system. Rather, sustainability refers to the interactions of systems, an interaction that is not detrimental for either one of the systems involved in the long run. In the case of sustainable energy systems, it refers to the interaction of two systems, the social system and the natural system. Both are characterised by their own system logics, causal relationships and endogenous feedback loops. Both systems are complex and cannot be understood by the description of their parts alone. Instead, they are characterised by emergent properties. In consequence, the interactions of society and nature are not straight forward but involve feedback loops across scales, time lags, irreducible uncertainties, and non-linearity. Science is far from being able to fully capture these complex interactions. Moreover, it is a matter of variable preferences and risk assessments within society which decisions on alternative futures to take. Thus, within the realm of social systems, the complexity of this interactions reflects itself in a multidimensionality of preferences, and in a spectre of social discourses perceiving and weighing realities differently. Therefore, the complexity of alternative future options has to be taken into account, in research and in methodological design for decision making. Scenario building is a technique allowing to reflect a certain complexity of possible future developments, more than just distinguishing between single technology options, and to learn about trade-offs and synergies from and among relevant stakeholders.

(3) Multiplicity of perspectives and interests in energy transitions

Within society, direct steering towards a more sustainable energy system is beyond the range of options. There are several legitimate and often ambiguous problem definitions and perspectives related to the particular background and interests actors are associated with. In the face of the far reaching consequences a change in energy systems has upon social life, and in the face of the lack of predictability of such a change, problem-focused, adaptive, and reflexive governance processes are required. An appraisal of alternatives has to involve different interest groups, not only to incorporate the multiplicity of legitimate perspectives in a negotiation process, but also to capture those interests upon which a sustainable alternative may build. A multi-stakeholder multi-criteria analysis of future scenarios seems an appropriate tool to identify the policy options towards a more sustainable energy future. In the next section its methodological prerequisites from a research perspective will be further elaborated, the methods inventory presented and discussed in greater detail.

The choice of methods

Having discussed theoretical challenges of an energy transition towards more sustainable energy systems, the methodological needs for operationalisation from a research perspective will be the focus at this point. Therefore an innovative package of participatory research methods is introduced, combining a participatory scenario-building technique and participatory multi-criteria analysis. The aim of this section is to discuss the combined use of scenario-building and participatory multi-criteria analysis (MCA) in the context of renewable energy use and the conclusions drawn from the theoretical section. The empirical research section presents an in-depth case study which applies this methodology package and analyses the details of the methodology used.

Scenarios have been applied increasingly in decision-making about long-term consequences and involve projecting different possible pathways into the future. Scenario analysis takes account of a higher degree of complexity inherent in systems than the study of individual projects or technologies. MCA is a widely used appraisal method, for capturing the state of a societal discourse and assessing options on the basis of a multi-dimensional criteria framework and calculates rankings for different options. The aim here is to systematically analyse the potential and limitations of the methodology (1) for identifying the complexity of decision-making about the long-term consequences of changes in socio-economic and biophysical systems; and (2) for appraising energy futures.

One fundamental assumption in this work is that there is no 'right' technological solution, which can be identified merely by scientific practices, but that it any such solution will be subject to a high degree of uncertainty and ambiguity. (Stirling 2001, Stirling and Mayer 2001, Foxon et al. 2008)[47]. A discussion process in wider society is needed to define what the problems are and what the adequate and favourable technological solutions are[48]. In particular,

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[47] 'This, of course, is the social construction critique of the claimed objectivity of scientific knowledge extended to technology.' (Bijker 1987)

[48] "Underlying much of the energy debate is a tacit, implicit divergence on what the energy problem 'really' is. Public discourse suffers because our society has mechanisms only to resolving conflicting interests, not conflicting views of reality, so we seldom notice that these perceptions differ markedly (Lovins 1977)" (Schwarz and Thompson 1990)

the processes by which innovation in terms of technical applications occurs often seem to be merely moving in the direction of business as usual and the opinion of wider society is usually excluded. A wider consideration of which specific innovations are favourable and helpful in a sustainable sense and for whom they are helpful is usually neglected. (Stirling 2005)

This starting assumption concurs with a broad existing body of literature. This is, on the one hand, generally the discussion of the need for a more integrated assessment of technology. (Giampietro 2002, Giampietro 2004, Giampietro et al. 2006, Weaver and Rotmans 2006), and the key aspect of integrated analysis is to consider multi-dimensional and multi-scale information. (Rotmans 2002)

On the other hand, a more deliberative approach towards technological development is claimed in several publications. (Bijker 1987, Illich 1998, Schwarz, 1990, Sclove 1995, Stirling 2005) As Bijker claims 'technology is never just a neutral tool. Technology is social relation.' (Bijker 1987) Arguing that technology and the risks associated with technologies have an influence on everybody's lives, a participatory decision-making mode for technological change is put forward in Sclove's Democracy and Technology. (Sclove 1995) Reflexive modernisation Beck et al. 1994 suggests the anticipation of future consequences in modernisation and technological change.

A transition to more sustainable energy system is a stepwise process (even if in the end it may lead to be a radical change). Participatory multi-criteria methods do not – as the niche-regime-model- refer to and rely upon evolutionary outcomes of competitions, but rather reflect a broader public discourse, in which different experiences and interests reflect themselves. Thus these methods are highly adequate focusing on the (in the original model often neglected) cultural realm, the existing social consciousness, and, current contradictory interests possible transitions towards new energy systems will have to deal with as a point of departure.

Recent assessment approaches combine explicitly integrated and deliberative research methods, such as the Integrated Sustainability Assessment (ISA) that generally addresses sustainability problems. ISA can be understood as "a cyclical, participatory process of scoping, envisioning, experimenting, and learning through which a shared interpretation of sustainability for a specific context is developed and applied in an integrated manner in order to explore solutions to persistent problems of unsustainable development" (Weaver and Rotmans 2006). Moving towards more sustainable development, methodological assets have to be taken on board to address the general features of complex systems in change, such as multiplicity of legitimate perspectives, non-linearity[49], emergence[50], self-organisation, multiplicity scales[51] and irreducible uncertainty.(Funtowicz and Ravetz 1997, Gallopin 2001, Gallopin et al. 2001, Kates et al. 2001, Folke et al. 2002, Pahl-Wostl 2004, Fiksel 2006)

Other, more specialised appraisal practises for sustainable technologies working according to these premises are already established and discussed in the literature, e.g. constructive technological assessment (CTA). (Schot and Rip 1997) This approach emphasises the early involvement of a broad array of actors to facilitate social learning about technology and potential impacts and "conceives technology assessment potentially to be a constructively democratic, reflective and discursive process". (Genus 2006) To improve energy planning and more specifically to find a transition towards more environmentally friendly and sustainable energy systems, authors have put forward a method combining integrated assessment, transition management, and multi-criteria analysis. (Polatidis et al. 2003)

Multi-criteria analysis has proven to be a useful tool for carrying out integrated and deliberative technology appraisal and has been applied in several case studies. (Stagl 2003, Kowalski et al. 2009) The method offers a transparent structure for revealing the underlying decision-making

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[49] Non-linearity in complex systems represents a significant challenge to linear causal thinking, which is the "basis of our knowledge about nature and our major scientific laws, [and] assumes that certain causes are acting together linearly to result an event. The outcome of the event is assumed not to affect the input." (Hjorth and Bagheri 2006, Pahl-Wostl 2004) On the contrary, circular causations, where a variable is both cause and effect, are very common in problems nowadays as the result of interactions between society and nature. For example: the societal concept of nature influences what is perceived and measured from nature while the reverse is also true.

[50] A key feature of complex systems is that their characteristics cannot be wholly explained by the characteristics of their constituent parts, but that complex systems produce so-called emerging properties: This feature is memorably presented by the metaphorical inequation '$1+1 \neq 2$'. The underlying theoretical assumptions of complex systems understanding go beyond the analytical paradigm, which puts forward the perception that analysing small pieces eventually creates an understanding of the whole. So, essentially from a systems perspective, the focus of the analysis switches from single parts, as in analytical reductionism, to the study of the connections and interactions of the parts within a context.

[51] It is widely acknowledged that differing observations of the same phenomenon can be made on different scales. Complex systems are often nested hierarchical systems. So, consequently, the multiplicity of scales has to be addressed by, e.g., working on different institutional scales, the international, the national, and the regional, simultaneously or combining results from different levels. (Schneider et al. 1998, Rotmans 2002 Giampietro 2002, Jaeger and Tol 2002, Giampietro 2004)

criteria and their importance. This enables reflexivity and social learning in a deliberative context. (Stagl 2006) Multi-criteria mapping is an innovative MCA method with an especially compelling focus on deliberation. (Stirling and Mayer 2001, Burgess et al. 2007)

The use of scenarios developed jointly with stakeholders and external experts allows for the integration of multiple interests and perspectives and conflicting objectives. Scenarios provide alternative representations of uncertain future states. One of the first empirical investigations of citizens' preferences regarding energy scenarios was undertaken in Germany. Participatory planning cells were organized to evaluate four energy scenarios and to formulate recommendations for the policy maker (Renn et al. 1984).

The combination of participatory approaches with, on the one hand, multi-criteria evaluation methods, and on the other hand, scenario building has proven promising for sustainable energy planning in a number of case studies such as Konrad et al. 2004b, MacDowall and Eames 2006, Anderson et al. 2006, Ornetzeder and Rohracher 2006, Gamboa and Munda 2007 (for a more detailed literature review see Kowalski et al. 2009).

As practise clearly shows, in energy planning there is no action as a system entity ("Totaloperation"). Luhmann's systemic understanding of society makes clear that ambitious actions of social systems are undertaken by several differentiated subsystems with separate functional logic and communication codes[52]. A chorus of different voices reacts towards an environmental irritation (e.g. climate change) or certain aspects of it (e.g. the costs of climate change, the risk of flooded areas and migration issues, the resulting change and loss of biodiversity, technological innovations etc). And in addition, since these social subsystems observe each other, there is a continuous parallel observation of the respective subsystems' operations, creating effects that may go quite against the original intention. Luhmann 1986 This phenomenon is also discussed in another context as a source of uncertainty in social systems. "In those systems [complex 'reflexive' systems], another source of uncertainty arises: a sort of 'Heisenberg effect', where the acts of observation and analysis become part of the activity of the system under study, and so influence in various ways." (Gallopin et al. 2001)

[52] In Luhmann's work the subsystems of social systems are: the educational and research system, the political system, and the juridical system.

A possible way to address the limited ability of a societal entity to react as a whole to the environment is represented by forms of reflexive governance, (Voß 2004) which means reflecting on the impacts of certain actions and on the different interests involved.
In Luhmann's words:

> "To the extent that technical interventions change nature and consequently create problems for the society itself, more intervention competences have to be developed, which have to be practised under the criteria of self-reflection." (Luhmann 1986)

Scientific methods to identify and appraise future energy systems

The role of science to interpret phenomenon and generate knowledge (sometimes falsify knowledge) using transparent methodologies and concepts, and to systematise knowledge clearly has importance in attempts to move towards more sustainable energy systems. Societal self-reflection is certainly perceived as a rather new role for science to play. [53]

Many authors question the ability and problem-solving potential of disciplinary science and simple optimisation of factors when it comes to sustainability issues. A new understanding of science is represented in, e.g., mode-2 science (Gibbons et al. 1995, Nowotny et al. 2001, Nowotny et al. 2003) co-production of knowledge (Jasanoff 2004), post-normal science (Funtowicz and Ravetz 1993 Funtowicz and Ravetz 1994), sustainability science (Kates et al. 2001), sustainability governance (Gallopin et al. 2001), social learning for sustainability (Luks and Siebenhuner 2007) or reflexive governance (Voß 2004). What these all have in common is the notion of greater interaction between academic disciplines (interdisciplinary approach) and with actors outside academia (transdisciplinarity). Therefore the work of scientists becomes also a negotiation process arguing on which concepts are particularly helpful for certain problems. Problem-oriented research across disciplines is one key attribute in sustainability science. (Kates et al. 2001)

> "Hence, it (sustainability science) often leads to blurring boundaries between scientific objectives of knowledge production, verification and accumulation, and the societal objectives of dealing with urgent problems, normative issues (see also Luks and Siebenhuner 2007) and

[53] Following the differential techniques we can only understand something in contrast to our expectations. So the question of in which differentiation scheme are facts acquired or should they be acquired points to the important role of science. (Luhmann 1986)

opposed interests groups, as well as between scientific quest for truth and the societal quest for justice." (Kastenhofer and Rammel 2005)

In addition, due to the different kind of problems, different working approaches in science are necessary. These include inter- and transdisciplinary research methods and consequently new skills for scientists that go beyond traditional fragmented and mechanistic science based on rational choice. (Polatidis et al. 2003, Hjorth and Bagheri 2006) From a science perspective, this is an interesting yet also threatening challenge, since "such indistinct boundaries present a certain threat to the autonomy and integrity of the (sub)-systems" (Kastenhofer and Rammel 2005) as in the case for academia and its organisation in distinct disciplines. Ockham's Razor, representing a nominalist and reductionism point of view, '*entia non sunt multiplicanda praeter necessitatem*' translated by Gallopin as "One should not increase, beyond what is necessary, the number of entities required to explain anything"; is valid for systemic research too but 'what is necessary' may need to be adapted. (Gallopin 2001)

The authoritarian attitude of science, with scientists as the exclusively privileged holders of knowledge, cannot be maintained in the light of high and irreducible uncertainty (Funtowicz and Ravetz 1993, Meijer et al. 2005), non-linearity and different legitimate perspectives have proven that science may gain incorrect results (e.g. in the case of CFCs and the resulting ozone hole) or in not being able to give satisfying answers in many cases. Thus there is a legitimisation and trust issue between society and science and also within science that might be a prerequisite and also a symptom of challenging the role of science and therefore widening the methods scheme. A sustainable adaptation of science has to reflect on the present role of science in society. (Wynne 1993)[54]

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[54] Paradigms and practises in science have been constantly evolving (see a broad summary of the development of science in Gallopin et al. 2001) and the standing of science has changed over time with a key historically shift during the Age of Enlightenment in the eighteenth century, when the influence of science increased significantly (in the western hemisphere) and in a stepwise fashion replaced religion as the single instance to attain truth. Therefore attaining the truth was no longer inevitably bound to religious content and religious interests. An alternative knowledge concept was established that was mainly based on rationality, the exercise of reason and conducting experiments. This development took place in parallel with the process of separating the state and religion. This can be seen as a historical emancipation process. But further changes of the role of science seem necessary whereas now the emancipation is from an authoritarian academia, an expert society. (Illich 1998)

The role of scientists is to generate and manage knowledge and data and furthermore provide information to support decision-making by e.g. politicians. Nevertheless, it is widely recognised that experts do this with certain subjective interests in mind due to, e.g., their conceptual background, funding and publishing issues, personal interests, etc. The “privilege” of objective truth is not any longer believed to exist and is not accepted as an attribute of scientists per se. Rather than revealing “what is right”, the negotiation process is “right under which circumstances and right for whom”? The same is true for applied science and technological development. “The traditional view is that decisions regarding technical issues should be left in the hands of experts and scientists” but “counterarguments point out that there are frequently limitations in the knowledge of experts, who often disagree among themselves.” (Rowe and Frewer 2000, p5)

> “What is considered a technical fact, and what is seen as belonging to the realm of social values, needs to be treated as part of the empirical dispute over definitional boundaries that is integral to technological decision controversies.” Schwarz and Thompson 1990 p22-23

This specific discourse over the role of science in transdisciplinary research, whether values and facts differ in an ontological way, (Gallopin 2001) raises questions as to whether scientists really have the ability to produce facts in a privileged sense. Even given a more moderate rating of the ability of science to produce facts, the equating of values and facts does not seem a helpful assumption. The epistemological difference is that the bench mark of truth is recognisability and inter-subjective reproducibility and the criterion for values, in contrast, is approval and not truth. Therefore facts can be false while norms and values cannot be false. In the context of individual freedom, such as freedom of religion, this seems a very important civil right. A consequence of breaking down the difference between values and facts would be to diminish the difference between ideology and truth. There are simply different arguments regarding facts or values: on one hand, claiming transparent rules for scientific work, binding scientists into a strict corset of legitimate ways to argue to ensure quality management in sustainability science, and on the other hand arguing in favour of the freedom of diverse values.

Acknowledging that reality is experienced in a mix of values and facts and scientists and others lack the means to distinguish them clearly, there is an urgent need to deal with this and incorporate both facts and values in analysis by making use of transdisciplinary research.

> “In short, what is required is not just to acknowledge that facts are value-laden but to adopt an analytical approach that can come to terms with the interaction between factual and value dimensions in a single conceptual frame.” (Schwarz and Thompson 1990, p23)

Participatory research methods represent a possible strategy for acknowledging the mix of values and facts. And particularly participatory multi-criteria decision analysis allows explicit integration of values into the analysis. Whereas MCA generally follows the idea that facts and values can be separated and are to be differentiated, facts are located in the impact matrix and values are expressed within the selection of criteria and in the form of weights. MCA offers a framework taking values and facts arising from a participatory process into further analysis, which is particularly helpful for aiding decisions. Scenario building, too, can integrate values and facts in a profound way. It allows, on the one hand, for a discussion as to what favourable futures are and for lessons to be learned about sustainable visions and, on the other hand, for coherent future profiles to be modelled. The specificities of participatory research methods, MCA and scenario building and their combined use for managing a transition towards more sustainable energy systems are discussed in further detail in the following section.

Participatory research approaches

Since the adoption of participation in Principle 10 of the 1992 UN Rio Declaration, there has been explicit international acknowledgment of this new practice in sustainability science. (Nations 1992) In 1998, the European Commission brought forward the Aarhus Convention on Access to Information, Public Participation in Decision Making and Access to Justice in Environmental Matters. (European Commission 1998) Since 2001, the European Union recognises participation as a main element for the orientation of general governance as stated in the White Paper on European Governance. Participation is quoted as one of the five “principles of good governance” along with openness, accountability, effectiveness, and coherence. (Commission of the European Communities 2001) In a specific environmental context, participatory governance is explicitly addressed in the Sixth Environment Action Programme of the Community 2002-2012 and also in legal instruments such as the Water Framework Directive (European Parliament and Council of the European Union 2000).

Participatory processes can be seen in very general terms as “institutional settings where stakeholders of different types are brought together to participate more or less directly, and more or less formally, in some stage of the decision-making process”. (van den Hove 2003) Under the particular conditions of representative democracy, participation is an additional means for citizens and organisations to influence the political process of decision making on diverse levels. (Bloomfield et al. 2001, Kohout 2002) Market dynamics work well for the optimisation of systems whereas other agents are essential to ensure that a long-term perspective and long-term costs are considered. (Polatidis et al. 2003)

Among new challenges for science are transdisciplinary work, active policy integration and continual learning under the conditions of evolving systems. (Luks and Siebenhuner 2007) The heterogeneous influence of industry, government, non-governmental organisations, citizen engagement and non-university research units indicates an institutional diversification process in the sustainability discourse arena, where academia has to adapt in order to deal with the multiple border-line situations. “The combination of professional expertise, scientific methods and well-defined targets can no longer, on their own, ensure an efficient and effective planning process [towards more sustainable energy systems].” (Polatidis et al. 2003) Participatory research methods claim to meet the challenges of uncertainty, scale, and multiplicity of legitimate perspectives and to enable scientists to interact with wider society to define and find solutions to problems related to the move towards more sustainable development.[55] (Stagl 2003)

Participatory approaches to environmental policy-making provide a means to address the four major characteristics: complexity, uncertainty, large temporal and spatial scales, and irreversibility. These characteristics have consequences for “what we call the social characteristics of environmental issues” and include the need for participatory processes. (van den Hove 2000; see Table 1) The interactions of natural and social systems needs to be substantiated by new sorts of democratic institutions and “institutional arrangements to address the theoretical and practical challenges of environmental management” (Spash 2001) and more specifically to address the continuous change, uncertainty and multiple legitimate perspectives of systems. (Stagl 2003)

[55] An alternative approach to steering complex evolving systems towards more sustainable development, which is put forward in wholly economic discussions, is the internalisation of externalities and the use of market forces to regulate environmental and social problems. One of the key problems of this approach, from an ecological economist perspective, concerns the incommensurability and the weak comparability of different forms of capital, in the sense of a strong sustainability concept. Sound attempts at participatory cost benefit analysis do exist: for more details see Niemeyer and Spash 2001.

Environmental issue characteristics	Consequent problem-solving requirements
Complexity	Innovative answers
Conflicts of interest	Conflict resolution processes
Dynamic aspects	Dynamic processes
Uncertainty	Flexible and adjustable answers
Reducible uncertainty	Progressive integration of information
Irreducible uncertainty	Integration of different value judgements and logics
Diffused responsibilities and impacts	Involvement of the many different actors
No clear division between micro and macro levels	Involvement of actors from different levels
Long time span, immediate costs and long-term benefits	Involvement of concerned actors
Long time span and large space scale	Depart from traditional short-sighted politics while remaining democratic
Irreversibility	Proactive approaches
Transversality	Allow for coordination across policy areas integration into multiple sectors

Table 1: Environmental issue characteristics and consequent problem-solving requirements (source: van den Hove 2000).
In the literature, up to three major types of arguments are brought forward that provide general support for participatory research approaches. (Rowe and Frewer 2000, O'Neill 2001 Stirling 2005 Blackstock et al. 2007) "Under a normative view, participation is just the right thing to do. From an instrumental perspective, it is a better way to achieve particular ends. In substantive terms, it leads to better ends." (Stirling 2005 p68)

The latter motivation, to substantively gain 'better' results in terms of robustness and quality from participatory research, seems to be a reaction to unsatisfying results from traditional methodological approaches, for example, questioning the possibility of designing top down what might better work from bottom up. (Smith and Stacey 1997) When working with complex problems of interactive systems, the high degree of uncertainty in particular has to be explicitly addressed by research in order to increase the quality of results. (Dryzek 1990, Wynne 1992) Post normal science in that respect takes the position that in research matters with high levels of uncertainty and high stakes such as climate change, GMO, sustainable energy transition etc., new methodology is necessary to meet the challenges explicitly favouring participatory research methods. (Funtowicz and Ravetz 1992, Funtowicz and Ravetz 1993, Funtowicz and Ravetz 1994)

Another important argumentation concerns the achievement of 'social learning' in addition to generally better results. (Renn et al. 1995b, Stagl 2006, Luks and Siebenhuner 2007) Studies review (Bloomfield et al. 2001) whether deliberative and inclusive processes lead to 'better' decisions and come to the conclusion that there is a lack of empirical analysis and evaluation of participative processes but nonetheless that important benefits can be drawn from the process itself, pointing out specifically the building of trust in existing political institutions. Social learning is an output different to merely the research results. As such it is a quality that is useful beyond the direct purpose of a single project; it can be more extensively seen as an investment in social capabilities to deal with problems that have no single optimisation character. “Social learning refers to the process by which changes in the social condition occur, particularly changes in popular awareness and changes in how individuals see their private interests linked with the shared interests of their fellow citizens” (Webler et al. 1995b, p 445). A study shows furthermore that people gain well-being from political participation: “People gain procedural utility[56] from participation in the political decision-making process itself, irrespective of the outcome.” (Frey and Stutzer 2001)

Some authors question “the myth of the best argument”, and are pointing to the role of power even behind substantive argumentations. (Pellizzoni 2001, Stirling 2005)[57] . The potential of failure and manipulation in participatory processes needs to be taken into account, in order to maintain the interest and commitment of the civil society. (Spash 2001)

The motivation to legitimise decisions is an instrumental aim in participatory approaches. The performing of ‘alibi’ participatory processes is a common accusation and also a real issue in cases where the policy uptake of alternatives is not regarded as a possibility from the beginning on. (Renn et al. 1995a, Rowe and Frewer 2000) To avoid public rejection and escalation such as the erecting of physical blockades, problematic issues can be anticipated with participatory methods in advance. The importance of building of trust should not be underestimated in decision-making and participatory processes may be installed as a means to restore trust. “Trust

[56] In an empirical analysis looking at Swiss citizens and foreigners living in Switzerland, the authors found that the difference in their well-being was significant and was strongly connected to procedural utility derived from being able to participate and/ or to already participate actively in policy decision-making processes. Utility is measured by individuals’ reported subjective well-being or happiness but is considered as a quite different source of well-being than hedonic outcomes or instrumental outputs, as they are used in traditional utility functions. The study shows that “procedural utility accounts for larger differences in subjective well-being than the full range of individual income.” (Frey and Stutzer 2001)

[57] Pellizzoni differentiates between internal and external power. Whereas external power is due to the institutional power or status enabling somebody else to be included or excluded from communication, internal power is “the ability of an argument to assert itself by virtue of its greater forcefulness”. His claim is, though, that internal power is “nothing but an insidious form of external power”. (Pellizzoni 2001 p 62) This refers to the discussion mentioned previously regarding the difference between facts and values.

is crucial to agreeing on workable outcomes under conditions of disagreement" (Bloomfield et al. 2001)

The third and relatively less recent aim, following a normative argument, generally promotes the strengthening of democratic features in decision-making processes as already encountered in Habermas' 'discourse ethics'. (Renn 1992, Webler 1995a)[58] The 'empowerment' argument, the deliberation of those with marginal or excluded interests rather than dominant institutions or elite social groups, (Stirling 2005, Stagl 2006) assumes that "involvement is an end in itself, rather than a means to an end." (Rowe and Frewer 2000) The normative discussion, once strongly present in the 1960s, is active in respect to the process of achieving more sustainable development again represented by the discussion of the shift from 'government' to 'governance'. The general claim is that those who are affected by a decision (who have stakes in the outcome) should be included in decision-making. (Laws 1996) One of the main underlying assumptions and a major challenge for participatory decisions is the legitimacy of different interests and preferences or "plurality of standpoints and inevitable coexistence" (van den Hove 2003). New governance institutions are necessary to accommodate different interests. (Spash 2001) Participatory research is located along a gradient of being rather research driven (i.e. the main aim is to advance research objectives) or development driven (focused on empowerment objectives). (Martin and Sherington 1997)

Along this line is the acknowledgment of the importance of 'local knowledge' leading to a reciprocal understanding that invokes all forms of rationality, not just objective scientific approaches. (Davies and Burgess 2004, Webler et al. 1995b) When citizen are involved in decisions which affect their community, local empowerment encourages them to behave like more mature and responsible democratic citizens. (Barber, 1984) This phenomenon on a societal level is also referred to as 'social learning' (Webler et al. 1995b)

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[58] The authors see communicative competence in their theory as different from Habermas'. "In summary, Renn and Webler see competence as a feature of the process, whereas for Habermas competence is a quality of the individual." (Webler and Tuler 2000, p568)

Degree and Representation in participation

For participatory and analytical approaches alike it is true that the framing[59] of the research influences the outcome. So, consequently a key question for both approaches is 'Who is involved in setting the framing?' Questioning the 'opening up' and 'closing down' timing in research is a key issue, whereas a participatory approach is in that sense equally sensitive to the implications of that practised power. (Stirling 2005)

There is no general rule concerning the extent of deliberation in participatory process. It depends very much on the specific situation as, e.g., the type of problem, aim, time and resource constraints, etc. Whereas some generalisations are made in the literature according to which "more knowledge based decisions (e.g. technical risk assessment) will require lower levels of involvement than more value-based decisions." (Rowe and Frewer 2000) Differentiations according to the specific aim do affect the degree of participation, e.g., participatory decisions versus discussion processes, social appraisal versus social choice (Stirling 2005), and value articulation versus decision recommending (Jacobs 1997).

A general difference from representative democracy is that no democratic legitimisation (majority) is necessary to achieve influence. (Kohout 2002)[60] The 'ladder of participation' is a visualisation of the possible degrees of participation from the 1960s, extending from citizen information through citizen consultation mechanisms to direct public involvement in decision making. (Arnstein 1969) Biggs differentiates between four modes of participation: contractual, consultative, collaborative, and collegiate. (Biggs 1989, in Blackstock et al. 2007) A more recent guidance in Arnstein's tradition on choosing different levels of public involvement is published by the OECD, essentially differentiating between informing, consulting, co-deciding, delegating parts of the decision and supporting institutions engaged in more or less autonomous decision making. (OECD 2004)

Representation in participatory processes is one of the turning points and a key evaluation criteria, (Rowe and Frewer 2000) since a necessarily selective inclusion of perspectives has a strong framing effect on the problem definition, alternatives, criteria and consequently on the outcome. (Laws 1996, Banville et al. 1998, O'Neill 2001, Stagl 2003, Omann 2004) This can be

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[59] The framing of research is comprised of e.g. research question, problem definition, choice of methodology, inclusion of disciplines, characterising of alternatives, interpretations of uncertainties etc. (Stirling 2005)

[60] Whereas the organisation of quasi-democratic groups such as associations improves the legitimacy of participation. (Kohout 2002)

overcome by choosing a large sample or even a random stratified sample of citizens to meet statistical requirements for representativeness. An alternative strategy is to select a restricted number of representatives for certain interests and arrive at a comparatively smaller number of participants, each representing a certain perspective, e.g., the environmental perspective, the industry perspective, etc. This approach is usually referred to as stakeholder participation but is also employed, e.g., for citizen focus groups. Questions that arise in relation to this concern are whether it is a legitimate assumption that such representatives of interests exist and what kind of selection procedure ensures a broad and fair arena of perspectives. It is apparent that a vast range of criticism exists in political science questioning the concept of a politics of interest. Schwarz and Thompson 1990 p 39 In favour of the representation of interest in participatory processes is the argumentation that there are several interests that cannot be directly put forward as the environmental interests and the interests of future generations. (O'Neill 2001)

The basic assumption behind all participatory processes is that people in general consciously know what they want and why they want it. But expressing latent needs in apparent declarations is very challenging, however, and may already be the result of a social learning process. [61] A concern regarding a lack of information is often raised in the context of active citizen participation. Although there is a necessary asymmetry of information in complex societies, "there is no need for trade-off between democratic deliberation and expert effectiveness." (Bohmann 1999, p592) In participatory processes, participants need to value and respect the positions of others. It is helpful if positions are explicitly argued out since in heterogeneous groups, not much is taken for granted. Trust is therefore a key issue: "Trust is crucial to agreeing on workable outcomes under conditions of disagreement." (Bloomfield et al. 2001) When working with stakeholder participation, transparent stakeholder analysis is necessary, revealing the criteria for inclusion. (Banville et al. 1998)

Quality of participatory research

The need to formulate quality criteria for participatory research methods is widely recognised. (Bloomfield et al. 2001, Rowe and Frewer 2000) Addressing the issue of quality with a procedural rationale, inherent in participatory research methods, presents a different challenge in contrast to traditional analytical methods. Ensuring quality management, guaranteeing the

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[61] The contrary view would be the generalised assumption that people don't know what they want or can't express it: a broad dispossession of autonomy. Nevertheless, this viewpoint ought to create an awareness of the demanding nature of deliberation and that knowing about one's own needs and preferences also across spatial and temporal scales is not a matter of course neither for lay person and nor for experts.

comparability of participatory methods and furthermore enabling the standardisation of methods are to a certain extent important steps towards participatory research that qualifies as a legitimate and practicable research method. Missing empirical comparisons "reflect the difficulties in implementing controlled experimental studies in this domain".[62] (Rowe and Frewer 2000, p 11) A universal dichotomy found in the literature is the differentiation between procedural and substantive categories in quality assessment. (Rowe and Frewer 2000, Stagl 2003)

Webler, Kastenholz & Renn define 'fairness' and 'competence' as the key categories for evaluating 'cooperative discourse' introducing the notion of 'social learning'. (Webler 1995a) An evaluation framework using social goals is put forward in the work of Beierle where the respective goals are educating the public, incorporating public values and knowledge into decision-making, building trust, reducing conflict, and ensuring cost-effective decision making. (Beierle 1998) Rowe and Frewer suggest two main categories of criteria: acceptance criteria (representativeness, independence, early involvement, influence, transparency) and process criteria (resource accessibility, task definition, structured decision making, cost-effectiveness). (Rowe and Frewer 2000) A recent publication summarises quality criteria in a literature review and produces an extensive list of criteria in three categories which are process-related (champion/leadership, communication, conflict resolution, influence on the process, representation), context-related (political, social, historical, environmental context in which the process/project occurs) and outcome-related (accountability, capacity building, emergent knowledge, recognised impacts, social learning, transparency). (Blackstock et al. 2007)

The particular effectiveness of different participation methods is not well conceptualised. The work of Rowe suggests looking at two types of evaluation criteria for public participation methods: acceptance criteria and process criteria[63]. (Rowe and Frewer 2000) (See Table 2)

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[62] Difficulties arise among other things from the great numbers of variables to control, from the variety of ways the same method can be applied and from the lack of standardised measurement instruments. (Rowe and Frewer 2000)

[63] The direct use of appraisal criteria for stakeholder participation methods is to be discussed further.

Acceptance criteria	Process criteria
Criterion of Representativeness	Criterion of Resource Accessibility
Criterion of Independence	Criterion of Task Definition
Criterion of Early Involvement	Criterion of Structured Decision-Making
Criterion of Influence	Criterion of Cost- Effectiveness
Criterion of Transparency	

Table 2: Evaluation Criteria for Methods of Public Participation (Rowe and Frewer 2000)

To warrant a transparent and structured discussion and decision-making process, especially when dealing with the exceedingly complex issues of future sustainable energy systems, accompanying methods are necessary and scenarios can play a key role here.

Scenario Analysis

Scenario building is a technique allowing the integration of diverse possible future developments into analysis, taking more complexity into account than single technology options do, and learning about trade-offs and synergies. What kinds of energy futures are favourable and how decisions taken today may lead to these favourable futures are key questions and there is no simple answer, given the high degree of uncertainty and diverse interests involved.

> "No amount of sophistication is going to allay the fact that all your knowledge is about the past and all our decisions are about the future." (Wilson 1975)

Over the last two decades, the application of scenarios as a 'judgemental forecasting' tool has gained much popularity for strategic analysis and longer-term planning (Bunn and Salo 1993). In scientific assessments, scenarios are usually based on an internally consistent and reproducible set of assumptions or theories about the key relationships and driving forces of change, which are derived from an understanding of both history and the current situation. Often scenarios are formulated with the help of formal numerical or analytical models. Scenarios are representations of alternative futures that help to explore possible futures. Each scenario is an alternative representation of how the future might unfold. Using scenarios assists in the understanding of possible future developments of complex systems.

The construction of scenarios for exploring alternative future developments under a set of assumed conditions has a long tradition in strategic decision-making (WBCSD 1997, Shell

2008), and especially in decision-making in an energy context (e.g. Ito et al. 1997, Haldi 2000, Nakicenovic 2000, Oniszk-Poplawska et al. 2003, IEA 2003, Nitsch et al. 2004, Ghanadan and Koombey 2005. Environmental and energy scenarios have been developed for different temporal and spatial scales, from global and (inter)national long-term scenarios (IPCC 2004, Nakicenovic 1998, Raskin et al. 1998, Eames 2002) to local mid-term scenarios (Georgopoulou et al. 1997). Among the non-energy scenarios, climate change and land-use change scenarios are most prominent (IPCC 2004, 1992, Nakicenovic, 1998b, Nakicenovic Nakicenovic 2000). Scenario building has become one of the main methods used for addressing the complexity and uncertainty inherent in long-term challenges, such as sustainable development.

Considering that social-ecological systems act as strongly coupled, complex and evolving systems, integrated assessment means have to be developed. The concept of resilience[64] helps us to understand "how to sustain and enhance adaptive capacity in a complex world of rapid transformation." The authors consider two useful tools for resilience-building in social-ecological systems, which are structured scenarios for envisioning alternative futures and active adaptive management (Folke et al. 2002).

The literature distinguishes different types of scenarios (EEA 2001, IPPC 2001, Berkhout et al. 2002), which include:[65] (1) extrapolatory approaches (forecasting), which assumes that the future is essentially defined as a continuum of the past; (2) normative scenarios (back casting), which are orientated towards certain milestones and where the actions are enumerated on the assumption that the future can be created; and (3) exploratory scenarios. Exploratory scenarios differ from the former two insofar as they do not claim to predict the future but endeavour to describe a 'possibility space'. Implicit in forecasting is a rather mechanistic view of systems, implying the general supposition that simplified quantitative models can portray the future. Extrapolation, though, produces quantitative parameters that can be compared, etc. Smil claims "a manifest record of failure" in energy forecasting history of the last one hundred years but on the other hand criticizes the fact that the use of exploratory means can be "too broad to serve as useful guides of effective action" (Smil 2003). In exploratory scenarios, the future is a social construction about which legitimately diverse opinions exist. Typically they include a narrative element – a 'storyline' – and some quantitative indicators (Berkhout et al. 2002). Further

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[64] Resilience is the capacity to buffer change, to learn and develop. (Folke et al. 2002)

[65] This is not an exclusive list of types of scenarios, other typologies exist. For instance Bunn and Salo 1993, referring to Ducot and Lubben (1980), distinguishes between exploratory and anticipatory scenarios on the one hand, and descriptive vs. normative scenarios as well as trend vs. peripheral scenarios on the other hand.

distinguishing factors among the range of scenario-building techniques are, firstly, the process of development and as such the degree of stakeholder or public participation, and secondly, the issue of whether scenarios consist of descriptive, narrative parts and/or a quantitative, modelled parts.

Even thorough data collection and good modelling would not enable us to understand systems fully and to determine possible future system states. Moreover, some physical and socio-economic systems are poorly understood and the level of uncertainty is very high. Scenarios, as a collection of futures, are intended to establish the boundaries of uncertainty and the limits to plausible futures (Wilson 1975). Scenarios are artefacts of the complex reality of environmental and socio-economic systems and their interactions that bring to the fore certain relevant aspects and a number of plausible variations. Defining two relevant parameters a compact 2-by-2 matrix can be established for locating the scenarios. A innovative way of providing such a framework for scenarios is carried out in the UK Environmental Future Scenarios (see Eames 2002, Berkhout and Hertin 2002, Berkhout et al. 2002): four exploratory scenarios are defined in the four quadrants of a two-dimensional matrix where the axes represent the central dimensions of change: the social values (horizontal axis) and the governance systems (vertical axis; see Figure 6).

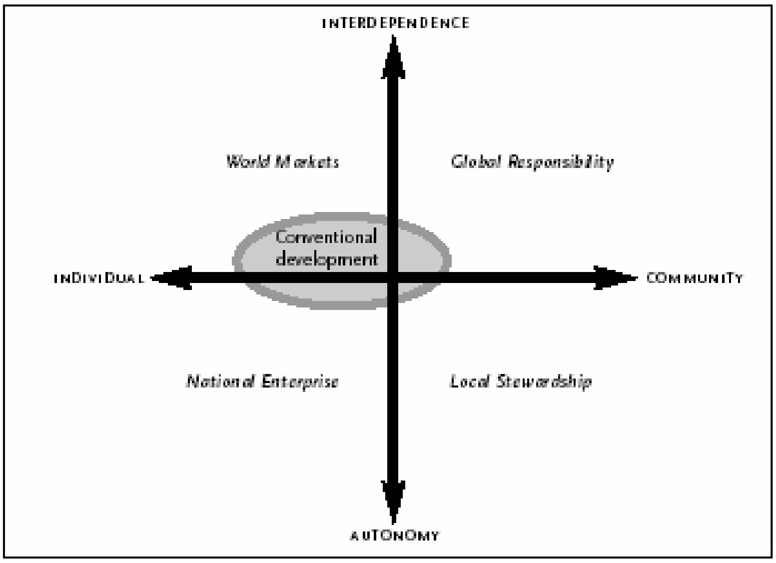

Figure 6. Framework for scenarios developed and applied in the UK Environmental Future Scenarios (Source: Eames, 2002)

"A scenario is an image of the future, arising from interpretations of the present and an internally consistent story about the path into that future" (Darton 2003) (see Figure 7). Communication using images and stories is a very important feature of scenarios for developing, better understanding, and communicating pathways toward a more sustainable future. The narrative character of scenarios enables value issues that are usually more implicit in the technology discussion to be addressed explicitly.

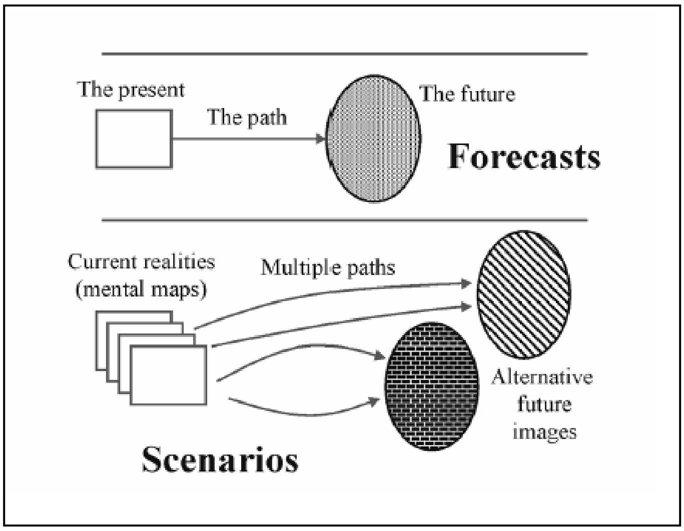

Figure 7. Forecasting contrasted with scenario planning (Source: Darton 2003)

Therefore, scenarios are useful tools for scientific assessments, for learning about complex systems and the visions and goals according more sustainable energy systems and consequently for informing policy-makers (Jefferson 1983, Davis 1999). The result is a multi-dimensional representation of futures, which is demanding to compare and evaluate without further systematic and computational tools. To evaluate the effects of certain decisions and actions in the scenarios, Darton suggests a coherent set of "sustainability metrics" or indicators, which are modelled in an exemplary way. (Darton 2003)

MCA complements scenario development in a good way by offering an algorithm to systematically aggregate multi-dimensional information, and therefore reduce the scenario (information) complexity in a transparent way. Scenarios can be assessed according to sustainability dimensions with different forms of data and information, conflicting objectives are transparently structured and accounted for, and therefore decision-makers can be effectively supported.

Multicriteria Analysis (MCA)

Multi-criteria analysis (MCA) is widely applied to aid decision making in the context of energy management and energy policy, e.g. Stewart and Horowitz 1991, Mirasgedis and Diakoulaki 1997, Dodgson et al. 2000. Most applications in energy planning focus however on technical planning (e.g. as described in Hobbs and Meier 2000), and typically do not include either society-nature interactions or stakeholders in a systematic and participatory way. However, as in other research areas, a trend towards an increased involvement by stakeholders can be observed in energy research. In several case studies, MCA has been combined with participatory processes. It is considered to be particularly well suited for the participatory design of new strategies addressing environmental and sustainable development issues. (De Marchi et al. 2000) A participatory MCA approach for renewable energy planning was applied in Georgopoulou's case on a Greek island in the 1990s. Renewable energy options were evaluated using the MCA approach- ELECTRE III[66]- embedded in a participatory process. Eight renewable energy strategies were formulated and evaluated by stakeholders using 15 sustainability criteria. (for further detail see Georgopoulou et al. 1997); further examples are Haralambopoulos and Polatidis 2003, Polatidis et al. 2003, Greening and Bernow 2004, Madlener and Stagl 2005, and Stagl 2006, Gamboa et al. 2008. Multi-criteria mapping, a

[66] ELECTRE III is based on pair-wise comparison as is PROMETHEE.

specific participatory MCA tool, works with data intervals and therefore addresses the issue of uncertainty within the evaluation data in a very thoughtful way (Stirling and Mayer 2001, Burgess et al. 2007), whereas the applied aggregation mode, the weighted sum method, is rather simple and has certain limitations when using for multi-dimensional problems. (Pohekar and Ramachandran 2004)

A general overview of the application of different MCAs to sustainable energy planning indicates a paradigm shift in energy planning approaches. Analytical Hierarchy Processes and outranking techniques like PROMETHEE and ELECTRE are the most popular methods in use at the current time. (Pohekar and Ramachandran 2004)

The theoretical foundation of MCA is built on the concepts of weak comparability and incommensurability. (Martinez-Alier et al. 1998) They describe in practical terms the way in which different units of measurement need to be accounted for, avoiding the immense information loss of solitary accounting systems as in economic accounting (in monetary units) or physical accounting (in physical units e.g. t or J). Weak comparability, hitherto, implies that these different dimensions cannot be traded against each other fully, in the sense of the strong sustainability concept.

In the method strand of social multi-criteria evaluation incommensurability is further sub-divided into the concepts of social incommensurability and technical incommensurability. (Munda 2004) Social incommensurability refers to the existence of a multiplicity of legitimate interests and values in society, whereas technical incommensurability refers to the issue of representation of multiple identities in descriptive models.

The application of MCA allows one to integrate or even "overcome conflicts between long-term ambitions and short term concerns" (Polatidis et al. 2003). In the context of energy transition management, the authors suggest the weighting of the criteria to make sure the long-term consequences are adequately addressed. An increased weight on environmental criteria is thus helpful in the pre-development phase of transitions (to "include externalities"). Whereas, for the acceleration phase, a high weight on energy resource criteria is suggested in this framework. And finally, high weight on socio and economic criteria in the stabilisation phase. (Polatidis et al. 2003)

In MCAs there are generally six elements to be defined. In participatory MCAs, an agreement according these six elements has to be found. They are, either to a certain extent or comprehensively negotiated with the stakeholders:

– the set of alternative options
– the set of criteria
– the scores attributed to each of these criteria for each of these options
– the weight to apply to criteria
– the ranking method to be used to compare options
– the role to be given to the MCA in the (participatory) decision process at hand van den Hove 2003

Therefore “MCA establishes the basis for decomposing and structuring the decision exercise on which different actors with various criteria bring their particular interests.” (Polatidis et al. 2003)

PROMETHEE is one of the most widely-used outranking methods based on pair-wise comparison, which allows input data according to the alternative options, the criteria, the weights on the criteria, and the preference functions. (Brans and Mareschal 1990, Geldermann and Zhang 2001) The specificity of the information requirements, e.g. the specific form of input data defining the social preferences, is determined by the model assumptions of PROMETHEE. (De Keyser and Peeters 1996) In a Swiss case study nine different electricity scenarios have been evaluated according to sustainability indicators[67] with PROMETHEE. A group of ten stakeholder representatives focused on the technological options of future electricity generation. (Haldi 2000)

The PROMETHEE multi-criteria evaluation will be applied to assess the identified performances of renewable energy scenarios along sustainability indicators in a transparent way in a so-called impact matrix. Weights can be given to the criteria expressing the preference of certain interest groups and, therefore, different rankings of the scenarios are accomplished through the accumulation of the data.

Embedding scenario development and MCA in a participatory stakeholder process enables the multiplicity of legitimate perspectives to be taken on board. Furthermore, such a process allows

[67] Eleven sustainability criteria were selected with 28 indicators from the economic dimension (8), environmental dimension (16) and social dimension (5).

room (1) to learn more about the ambiguous arguments formed by different interest groups (social learning) and (2) to have the consequences reflected in the evaluation and consequently the ranking of the scenarios.

When evaluating the multi-dimensional sustainability performance of future energy options, a certain set of sustainability criteria is usually applied.

Sustainable development is based on the three pillars and so are usually the indicator frameworks: the social, the economic, and the environmental indicators. The institutional dimension of sustainability is regularly added as a fourth dimension. (UNCSD 1996) To measure the sustainable performance, criteria and indicators have been developed. The political process itself in moving towards sustainability is considered to be subject to social and institutional sustainability issues, e.g., opportunities for participation. (Spangenberg et al. 2002a, Spangenberg 2002b) The work on economic and environmental sustainability criteria and indicators is far more developed than that carried out on the social and institutional indicators. In particular, the relevant topics for social indicators differ greatly according to the context, e.g., whether developing countries or industrialised countries. The key issues of paid work and gender are specifically pointed out by some social sustainability studies. (Littig and Griessler 2005)

Despite a general attempt to agree on a common set of sustainability criteria to allow comparability, the contexts of specific cases seem to address sustainability issues in different ways and the set of indicators varies with that. A further question to be addressed, concerns whether the eliciting of indicators should be a part of the participatory process. (Fraser et al. 2006) In the specific context of energy planning, a set of official indicators for energy related evaluations is called for. (Vera and Langlois 2007) Practice shows, however, that these vary despite certain constant indicators.

The UK Sustainable Development Strategy published in 1999 says “at the heart of sustainable development is the simple idea of ensuring better quality of life for everyone, now and for generations to come” and presents four main objectives and an extensive list of indicators (UK Government, 1999):

- social progress which recognises the needs of everyone
- effective protection of the environment
- prudent use of natural resources; and
- maintenance of high and stable levels of economic growth and employment

These objectives indicate that some of these different interests will be contradictory at some point. "The political challenge is then to integrate the dimensional objectives and policy goals into a joint perspective of sustainable development, avoiding or at least minimizing trade-offs between different objectives". (Spangenberg 2002b)

Summary of methodological insights

The bottom line is that innovative methodology is needed to embrace the challenges of managing the transition towards a more sustainable energy system. Revisiting the earlier theoretical discussion, a methodology is required that can explicitly address the complexity of the social and natural systems in their mutual interactions since the energy system and its transition exists at interface between the two.

To have a methodological grasp of the issues and consequently to increase the quality of research results and managing attempts towards more sustainable energy systems, the general features of complex adaptive systems, e.g., high levels of uncertainty, conflicting objectives, different forms of data and information, multiple interests and perspectives and accounting for complex and evolving biophysical and socio-economic systems, all have to be addressed. The methodology design of the present case study attempts to do so and thus to gain insights for further applications. The combined use of scenario analysis and participatory MCA promises to take account of the complexities of the relevant socio-economic and biophysical systems and the uncertainties of long-term impacts. Multi-dimensional data and information is structured according to key sustainability dimensions and aggregated in order to aid decision making. The methodology package belongs therefore to the family of integrated sustainability assessments (ISA) [68] and is valuable in the context of transition management.

The aim of the applied methodology is to identify different possible and more sustainable energy futures and their functioning dynamics with a certain degree of complexity and then to

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[68] The EU project MATISSE (6th Framework Programme, www.matisse-project.net) developed the following definition: "ISA is a cyclical, participatory process of scoping, envisioning, experimenting, and learning through which a shared interpretation of sustainability for a specific context is developed and applied in an integrated manner in order to explore solutions to persistent problems of unsustainable development" (Weaver and Rotmans 2006, p.12).

compare and appraise them according to sustainability criteria. To integrate multiple perspectives and conflicting objectives, a concise set of future energy scenarios developed with stakeholders is effective. On the one hand, scenario development enables stakeholders to be visionary and to build possible[69] futures containing their ideas, experiences, and perspectives. On the other hand, scenarios can be effective tools for communicating with other stakeholders. Scenario narratives have a high potential as they are generally easier for stakeholders to deal and 'work' with future developments than to operate with purely quantitative information alone. One of the resulting challenges, however, will be to convey the complexities behind the narratives and than to develop quantitative and qualitative assessment tools. Moreover, this requires an organised and systematic development procedure that can achieve credible scenarios in terms of comprehensiveness, consistency, and coherence. (Bunn and Salo 1993)

MCA complements scenario development by offering an algorithm to systematically aggregate the multi-dimensional information, and therefore reduce the scenario (information) complexity in a transparent way. The information from the impact matrix and criteria weights is used to calculate a ranking of the scenarios. The methodology presented allows, furthermore, for stakeholders to be given the opportunity to explore the role of the impact matrix and their weights further and make reasoned changes if they wish. This enables reflective learning about problem definition, future consequences and one's own and others' preferences.

The main motivation for the participatory stakeholder process in the present case study was to achieve a normatively and a substantively[70] better discussion and decision making process regarding more sustainable energy futures in Austria. The most important topics were (1) dealing with the high degree of uncertainty and ambiguity of favourable renewable future energy systems and (2) allowing the inclusion of less powerful niche perspectives on energy transitions. Decentralised or distributed energy generation in the sense of 'soft energy pathways' (Lovins 1977) and 'energy citizenship' (Devine-Wright 2007) are examples of concrete niche energy discourses at hand.

The aim is to provide an opportunity that enables learning and discussion in the context of mutual respect between the stakeholders. The setting is very important for the kind of encounter

[69] Note: scenario analysis encourages stakeholders to explore possible futures, not only futures that are currently perceived as probable.

[70] The instrumental perspective is less relevant in the present context since the performed participatory process was not part of an official policy process.

and communication. “Attention must be paid to the way in which institutional opportunities shape participants’ understanding of their position and role” (Laws 1996). Usually the participants, especially when working with professional representatives, have a common history of meetings, disputes, and also argumentation. A transparent schedule and an inspiring new approach handled by a neutral facilitator may put what is already a well-known topic and well-rehearsed argument in a different light. The idea of “cooperative discourse” (Webler et al. 1995b) is to achieve consensus that draws the focus away from the pure egoistic approach of rational choice theories “and puts emphasis on understanding the values, beliefs, and intentions of oneself and others”. (Webler et al. 1995b) Consensus between stakeholders can be found on several levels (see for more detail Dryzek and Niemeyer 2006). Therefore consensus and a legitimate pluralism can accompany each other. (Dryzek and Niemeyer 2006) Van den Hove sees “participatory approaches to be thought on a continuum between consensus-orientated processes in the pursuit of a common interest and compromise-orientated negotiation process aiming at the adjustment of particular interests.” (van den Hove 2003) Nevertheless, even providing an enabling opportunity, constructive interaction between participants is fairly unlikely to happen spontaneously in the midst of conflict and uncertainty. Another challenge within stakeholder participation is that non-participation and dropout rates among stakeholders during the process is not something research can control, but is still a factor that might have severe effects on the research outcome. (Renn 2003)

To meet the above described requirements for a solid methodological design renders a single case study approach the most promising research method. A single case study that aims at exploring in depth the practicability and feasibility of innovative methods will enable a thorough analysis of the process as well as of the results. Consequently, it will allow systematically reflecting on shortcomings, challenges and details of the methodological design by not just developing it on the ‘theoretical sketch board’ but via learning-by-doing. This is well in line with (Yin 2003), who states that “An exploratory case study (whether based on single or multiple cases) is aimed at …determining the feasibility of the desired research procedure.”

In consequence, however, it should be noted that this basic approach, does not allow for straightforward comparisons of the case study results with the outcomes of other, similar case studies. The advantage of a single, in-depth exploratory case study is that it allows for intensive methodological explorations and discussions in order to gain detailed insights in the methodological opportunities and challenges. Ensuing, these insights are indeed transferable to other contexts and can be used to draw generalized conclusions and so contribute to knowledge and theory building (Yin 2003a) what is exactly the aim of this study.

Empirical Section

The in-depth case study on renewable energy futures in Austria aims to gain methodological insights into the innovative methodology combination of participatory MCA and scenario building, and to give details regarding amore sustainable future for Austrian energy.

Austria is a central European, landlocked country in the temperate vegetation zone, with a temperate and alpine climate. It has approximately 8.3 million inhabitants; 1.6 million live in the capital Vienna which is located in the East. Since 1995, Austria is a member of the European Union. Austria has a long history as an influential monarchy and is traditionally in cultural and economic co-operation with Eastern European countries. Austria is a republic with a parliamentary representative democracy (since 1920) comprised of nine federal states called ‘Bundesländer’. It has a long tradition of social partnership.

The Austrian landscape is dominated by mountains: the Alpine Arch covers an area of app.70%. Another large fraction is covered by forest (47%). The Alps (Central Eastern Alps, Northern Limestone Alps, and Southern Limestone Alps) are dominant in the west, and the foothills of the Alps (with a climatic influence of the Hungarian plain) are dominant in the East. The South of Austria is influenced by the Mediterranean climate and has the most sunlight hours. Average sunlight hours throughout Austria range from five to eight hours in summer to two hours in winter. The summers are reasonably hot with summer temperatures between 20-35 °C, whereas the winters are cold, with temperatures between -10-0°C, with snow cover and ice. The largest river in Austria is the Danube.

Owing to the topography, a fraction (20%) of Austria's total area is unusable, bearing rocks and glaciers (see Figure 8). The remaining areas are used for farming, forestry and settlement infrastructure. Roughly half of that area is covered by forests. The agricultural sector is mostly structured into small units producing mainly cereals and maize (corn and green maize for silage), potato, rape, sunflowers, sugar beets, vegetables, fruits and wine. The percentage of organic farming is high in comparison to other European countries, amounting to approximately 2.5% of the total farming area in 2000. Owing to the large forest cover, forestry in Austria is an important economic sector, with an extensive wood industry which includes sawn wood and wood based panels as well as wood by-products used for paper production.

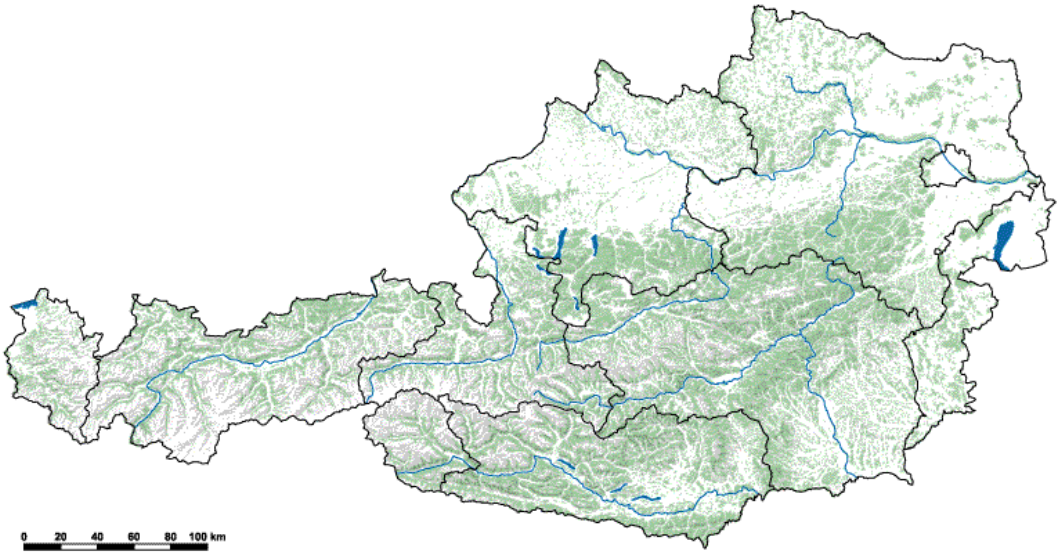

Figure 8. Map of Austria showing major rivers, lakes, political boundaries (provinces, black lines) and the complex topography owing to the Alpine arch.

Austria, a member of the European Union since 1995, is characterized by a well-developed market economy and a high standard of living. Its average per-capita GDP amounts to 39 200 $(PPP)/cap/a, and the unemployment rate is at approximately 5%. Besides the highly developed agricultural sector, which contributes less then 2% to the total GDP, its economy features a large service sector (~69% of GDP) and a sound industrial sector (~30% of GDP). The Austrian economy has benefited greatly in the past from strong commercial relations, especially in the banking and insurance sectors in central, eastern, and south-eastern Europe. Austria's largest trading partner is Germany, its northern neighbouring country, and its economy is strongly export oriented.

Austria is a country with a long history of renewable energy use, namely burning of wood chips and use of hydro power for heating and traffic. The total energy use per year was 302,372 GWh in 2008, whereas households use 25%, traffic 33.7%, and industries & services & agricultural sector use 41.3%. (Biermayr 2009) The electricity demand is rather high within the European context. The county's largest oil refinery is in Schwechat near Vienna, and is operated by ÖMV. It refines all the petroleum produced in Austria, as well as the crude petroleum imported via a pipeline from Trieste, Italy. There is no nuclear power in Austria. In 1978, a public referendum voted against nuclear power. There are large hydro power plants in Austria. In particular, storage power stations create a high economic profit: while off-peak nuclear power is imported, peak renewable electricity is exported to e.g. Germany. The export of environmental technology and in particular renewable energy technology (solar thermal panels, biomass technologies) and renewable energy components are highly profitable for the Austrian production sector.

There is a remarkable amount of renewable energy potential in the forest and the widespread river systems. There is some wind potential mainly in the East, and a high-risk wind potential in mountainous areas. The share of renewable energy is 28.1% of the total energy use in the year 2008. 72.1% of the total electricity demand is from renewables, stemming mainly from large hydro power and 34% of the heat demand, stemming mainly from solid biomass. (Biermayr 2009)

The main renewable energy support schemes are feed-in tariffs (following the Germany model). There are additional subsidiary schemes to encourage installation of photovoltaics, solar thermal plates, household pellet furnaces, and thermal insulation. The tradable CO_2 permits are an incentive for the industry to improve energy efficiency. Energy matters belong generally to the competence of the Federal Ministry of Economy, Family, and Youth. Climate change targets and implementation of water policies (EU Water framework directive) are issues tended by the Federal Ministry of Agriculture, Forestry, Environment, and Water Management. This division creates certain institutional barriers to an effective energy policy towards a more sustainable energy system.

Even though Austria has a proven history of renewable energy use and a somewhat deep awareness of environmental problems, the present political commitment to a modern sustainable energy system with a drastic increase of the share of renewables and reduction of the overall energy demand is absent.

Methods

The aim of the applied methods package (scenario development, MCA embedded in a participatory stakeholder process) is to envision scenario alternatives which would be favourable and ultimately lead to more sustainable energy futures for Austria. Furthermore, the aim is to compare and appraise these futures in a transparent way according to multi-dimensional sustainability criteria.

To integrate multiple perspectives and conflicting objectives inherent in energy discourses, a concise set of future renewable energy scenarios are developed jointly with stakeholders and external experts. They provide alternative representations of uncertain future states (narrative storylines, qualitative descriptions), as well as detailed modelling of different technology mixes which take natural and technical potentials into account. In this case, it is best to have a two-stage scenario development process: starting off with exploratory scenarios (opening up phase) and then realising the favourable scenarios in modelled forecasting scenarios (closing down phase). (Stirling 2005)

In this case study, MCA compliments scenario development by offering an algorithm to systematically aggregate multi-dimensional information, and therefore simplifying the scenario (information) complexity in a transparent way. The scenarios can then be assessed according to the sustainability dimensions with different forms of data and information. This way the diversity of the often conflicting objectives of the stakeholders regarding sustainable energy systems are transparently structured and accounted for. Decision makers can be effectively supported.

The initial scoping phase of the case study started in 2003[71] and involved a detailed literature research, exploratory interviews, and the process of stakeholder identification. (see Figure 9 for an overview of the phases of the case study) The four exploratory interviews delivered information about the main drivers and topics that might be interesting for the scenarios, gave insight to the key energy stakeholders in Austria, and allowed an overview of the present renewable energy discourse in Austria. Additionally an external expert discussion was held specifically on the social and institutional dimension of the sustainability evaluation in the energy context.

The stakeholder identification was performed with the help of a matrix structure based on the stakeholders with power to influence energy decision (importance) and stakeholders who are

[71] The case study has contributed to the research project ARTEMIS: "Assessment of renewable energy technologies on multiple scales -- a participatory multi-criteria approach." funded by the Austrian Science Foundation (June 2003 - May 2006). The project comprised two parallel case studies in Austria, one focussing on the national level, the other one on the local level. I have been responsible for the design, coordination and realization of the national case study. The empirical material collected in this project context significantly contributed to the empirical section of my DPhil thesis. The project team discussions and efforts provided a structural and intellectual support for the case study design. In particular Reinhard Madlener has greatly contributed to the development of the forecasting energy scenarios. Sigrid Stagl and Ines Omann have contributed their expertise and provided space for broad discussions and reflections related to the application of the MCA and the criteria and indicator framework.

strongly affected by energy decisions (influence). Stakeholders from government, industry, academia, and civil society were identified and invited.

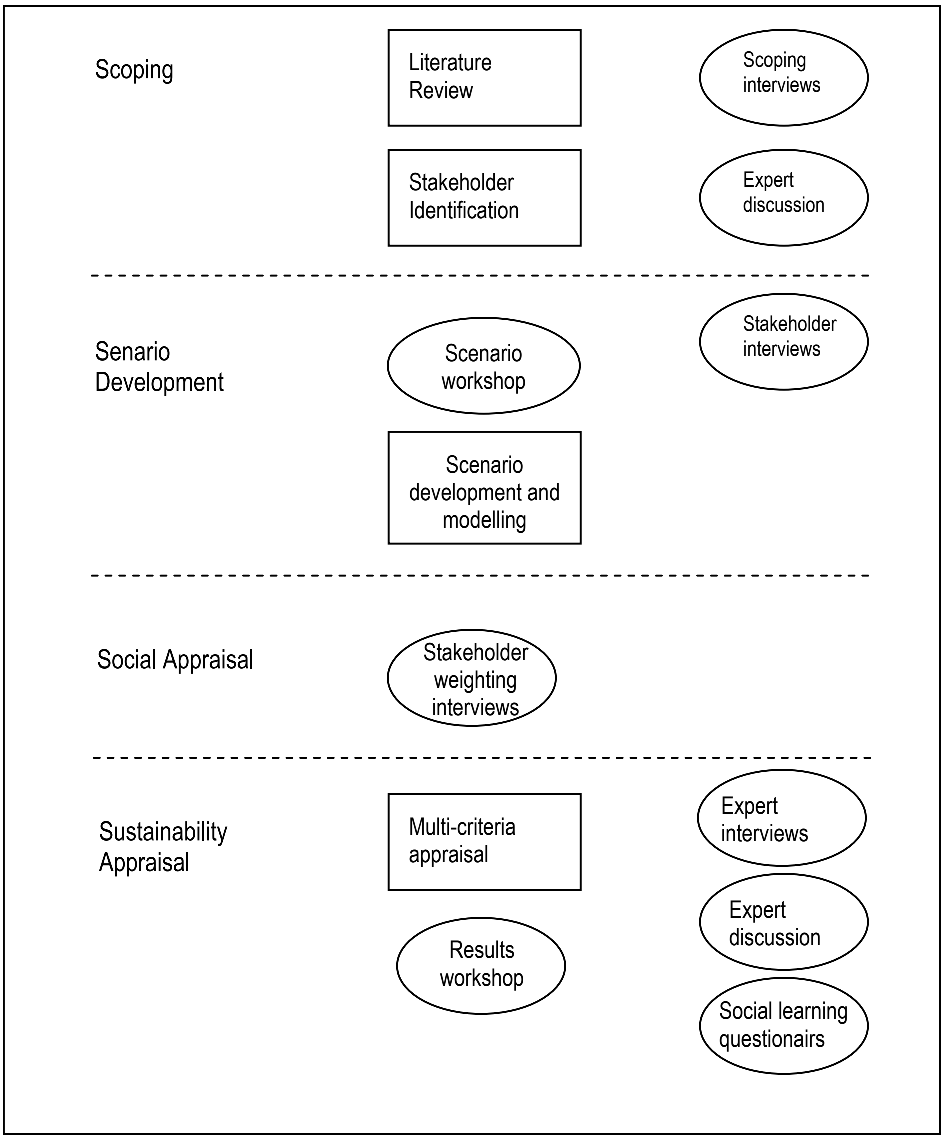

Figure 9. Overview of the case study phases; elements in oval boxes involved the participation of stakeholders

Prior to the first stakeholder workshop in May 2005, the stakeholders were (in telephone interviews) introduced to and questioned about a proposition for the main scenario drivers, a set of scenario storylines, and a set of possible sustainability evaluation criteria. The aim of the workshop was then to develop and agree on a concise number of renewable energy scenarios with their main characteristics and technology profile, and to reach agreement on a set of evaluation criteria. With the comprehensive workshop input the scenarios were adapted, finalised, and modelled with life-cycle data. The social appraisal phase began right after the first workshop in which the set of sustainability criteria had already been decided. In 16 personal interviews, the individual stakeholders ranked the sustainability criteria according to their personal preferences regarding the importance of a more sustainable future energy system.

In the sustainable appraisal phase the impact matrix was completed and the stakeholder rankings of the sustainability criteria were transformed into weights and integrated. The preference functions were developed in a small expert workshop on 20 October 2005 and were included in the MCA. The appraisal was performed producing several rankings of the renewable energy scenarios. To present and discuss the results and allow for further manipulation of the parameters, the second stakeholder workshop took place on 8 November 2005.

In the following section, the details of the participatory stakeholder process, the scenario development process, and the details of the multi-criteria appraisal are presented.

Participatory stakeholder process

The participatory process is comprised of different elements of participation playing a key role to bring insights that are usually not included in a traditional technology assessment. Personal interviews and facilitated group discussions including the experience, the knowledge, the diverse perspectives and value systems of Austrian key energy stakeholders, consequently led to a complete picture which appraised the various favourable renewable energy futures of Austria. Over the period of one year, two workshops were held and 25 interviews with energy experts and stakeholders were conducted. The participatory appraisal process does not directly feed into official policy making, but aims at informing policy makers and broadening the discussion. This is the reason why the process is addressed as a stakeholder discussion process.

Both experts and stakeholders were involved in the participatory process. The distinction between experts and stakeholders was drawn in such a way that experts were addressed when background information and a more detailed understanding was needed. Whereas stakeholders were involved when interests, values, preferences, and experiences were necessary for the designing and evaluating process. However, practical experience showed that the distinction wasn’t very clear at all. In some cases experts and stakeholders were the same person, and experts usually had specific interests as well since they were often , for instance, convinced of a specific technology or had invested a lot of time and money to elaborate on the technology. Certainly, experts have a specific socialisation in their academic discipline and institution that include value systems.

The overall cooperation with the stakeholder process was rather structured regarding the way that proposals and drafts were discussed. New suggestions and additions by the stakeholders were discussed and included to the maximum possible extent. This approach was chosen to allow for complete integration and detailed discussion in a considerably limited time frame. The stakeholders invested two hours in interviews and two half-day workshops to design the scenarios, the evaluation parameter, define the weights on the criteria, and discuss the scenario performance. This process of opening up (exploration of scenarios, discussion of criteria, and review of impact data) was followed by a process of closing down (calculation of the rankings, reviewing, and learning) which aids decision-making.

Efforts were made to create a discussion climate where the participants felt their issues were respected and their perspective was validated, while at the same time providing the opportunity to learn about other perspectives and gain new information. Specific insights concerning to the social learning of the stakeholder process are discussed by Garmendia and Stagl who conducted a parallel study focusing on social learning (see Garmendia and Stagl 2010). It was assumed that some of the stakeholders had a history of meetings, discussions, and quarrels, and that tensions and prejudices would be part of the process. Efforts were also made to create a climate conducive to discussion with equally legitimate opinions and perspectives, despite their varying arguments and concerns outside the workshops[72], and equal treatment of the participants enabled social learning. (Berkhout and Hertin 2002)

Scoping phase

The initial four semi-structured scoping interviews with Austrian energy experts[73] from different disciplines were intended to deepen the understanding of recent trends in Austria and discuss scenario parameters and to gain insight into the key energy stakeholders in Austria.

Based on the scoping interview results, a transparent stakeholder analysis was performed to systematically list the relevant stakeholders. Attention was focused on representation of the main areas of the energy system: generation, distribution, and end-use as well as representatives

[72] Independent of their distinct power differences in the “outside world”, the workshops are intended to provide a room for equally legitimate opinions.

[73] Prof. Helmut Haberl, IFF social ecology (Ecologist); Prof. Kurt Kratena, WIFO (Environmental Economist); Dr. Heidi Adensam, Ökologie Institut (Economist); Dr. Beate Littig, IHS (Sociologist)

of the governmental bodies and NGOs. To reflect on the potential power of stakeholders and how much the individual stakeholder groups are actually affected by changes in the energy systems, they were allocated in a 2-by-2 matrix. In that way, four groups of stakeholders were identified:

Group 1 with power and being highly affected
Group 2 with power but not being much affected themselves
Group 3 without power but also being not much affected themselves
Group 4 without power but being highly affected

This exercise helped to closely examine the present stakeholder groups. Following the normative motivation for the application of a participatory method (see subchapter Participatory Research Approach), those groups who are highly affected but have comparably little power on the decisions (group 4) were fix starters in the participatory process. Also, group 1, being affected and having the power to have an impact in the political decision process, was identified as key stakeholder for a participatory process. Groups 2 and 3, neither being much affected themselves, had lower priority for the participatory process. (see Figure 10 for concrete allocation)

The matrix proved helpful to learn about the stakeholders beforehand, yet it proved difficult in the sense that various stakeholders are affected by decisions in varying ways. For instance, the reaction of a Minister of Agriculture, when confronted with budget cuts or political failure, is very different from that of a farmer when confronted with a decrease in profit or even the loss of a farm. So the matrix shall simply be treated as a rough ordering that encourages learning and thinking about the power and stakes the stakeholders have.

Finally 31 stakeholder institutions were identified and invited to take part in the participatory process. A comprehensive list of invited institutions can be found in the Appendix Table A.1.

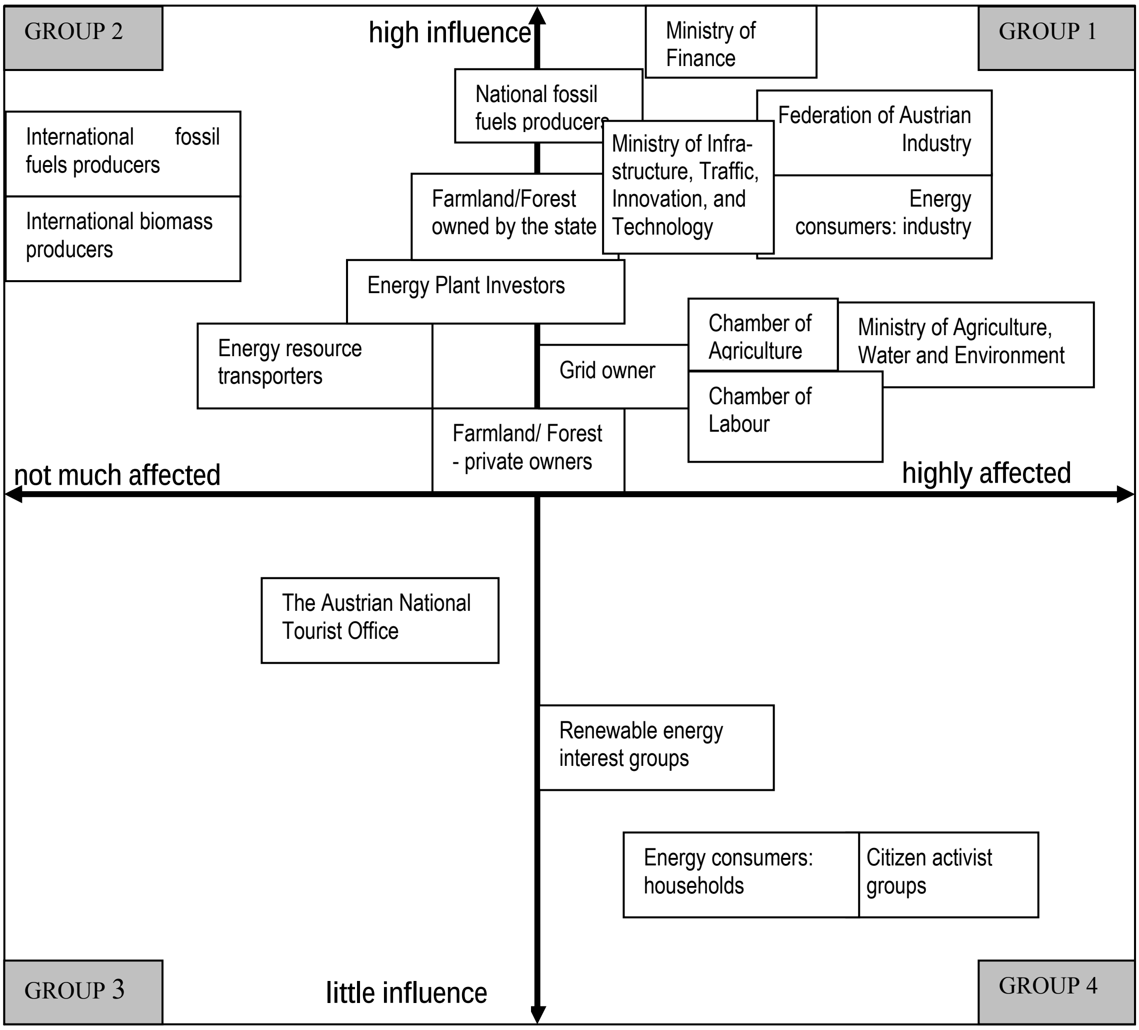

Figure 10. Stakeholder analysis: the x-axis represents how strongly stakeholder groups are affected by changes of the energy system, and, the y-axis represents how much influence (power) stakeholder groups have on the direction of change of the energy systems.

Scenario development phase

In the invitation, the stakeholders were informed of the aim and programme of the process s well as the necessary particular inputs and the expected outputs. As learned from other stakeholder processes, (Webler 1995a) clearly communicating the aims and products of the process to avoid unnecessary frustration and disappointment of the participants is essential for a successful deliberative process. Twelve confirmed they would take part in the process. The drafted criteria list and the outlined scenario storylines were sent to the stakeholders before the workshop so that they could become familiar with the basis of the upcoming discussion. In 12 separate telephone interviews, which took place before the first workshop, the material was individually discussed. This was an opportunity for the participants to make additions and claim changes to the drafted criteria list and the outlined scenario storylines. All additions and changes were noted and incorporated as best as possible.

The first workshop in May 2005, focused on discussing the draft scenarios, selecting the scenarios which are considered to be particularly relevant and/or interesting, and on gathering suggestions for the further development. Several scenarios would be further elaborated to address the different perspectives and visions with respect to Austria's renewable energy futures. It also served as a test for the suggested set of sustainability criteria, which is important for the sustainability appraisal phase. It was an attempt to account for the diverse perspectives and preferences of the stakeholders to the greatest extent possible. Eight participants took part in the workshop alongside the ARTEMIS project team members: Ministry of Traffic, Innovation and Technology, Chamber of Agriculture, WWF, AEA, Chamber of Industries, representative of small hydro power, Eurosolar, and the Centre for Social Innovation. The workshop was professionally facilitated and scheduled for a whole day.

The aim of the workshop was (1) to select and finalise a concise number of storylines for the renewable energy scenarios, (2) to discuss and agree on the set of sustainability criteria, and (3) to obtain a group weighting of the criteria.

The most important results from the first workshop were related to the scenario design and content. New parameters were introduced and draft scenario parameters were removed. The scenario story lines were jointly developed and key technologies were defined. The participants agreed on five scenarios to be worked out in detail, and finally modelled and evaluated. Overall, the involvement of the workshop participants had a great impact on the further development of the scenarios (find more details in the scenario development presentation later). The set of criteria did not produce a great deal of discussion; the list had been already enlarged during the interviews and was accepted in that form (please see below for more details on the presentation of criteria development). Due to the intensive scenario building effort, the original schedule had to be changed and the group weighting exercise could not be performed.

With the inputs of the stakeholder workshop, five renewable energy forecasting scenarios until 2020 for Austria were thoroughly treated and modelled.

Social appraisal phase

The social preferences of the stakeholders were revealed and integrated by (1) defining the set of evaluation criteria in stakeholder telephone interviews and the stakeholder workshop; and then by (2) ranking the criteria in individual stakeholder interviews expressing the regarded importance in respect to a more sustainable future energy system. Due to an unforeseeable and necessary change in the workshop schedule, only individual stakeholder preferences were collected in individual interviews.

The interviews were organised so that that the sustainability criteria were ranked from the least important to the most important by the stakeholders. For that, the criteria were printed out on cards which could be assembled to form a ranking. The ranking method allowed for equal importance and also allowed for the introduction of gaps. These gaps were achieved by means of blank cards between preference levels, enabling stakeholders to put more weight on the criteria above the blank card and less weight on those below. Finally, the stakeholder had to give an estimate of how much more important the first rank is compared to the last.

This rank method worked well for most stakeholders. One of the rankings could not be completed because the stakeholder indicated that he was unable to compare the diverse criteria with each other. He interpreted some criteria in terms of importance but was unable to find them comparable. This is quite a reasonable argument, but nevertheless this single stakeholder ranking could not be integrated in the evaluation. Several stakeholders had difficulties estimating how much more important the first rank is compared to the last. At this point, it was important for the interviewee to give examples and deepen explanations.

One caveat has to be warranted at this instance: it can be assumed that the fact that the individual criteria were described with one term and a short (one sentence) explanation does not necessarily mean that each criterion is comprehended identically by the individual stakeholders. Stakeholders are characterized by their individual contexts and perspectives, and in a narrative setting it is almost impossible to create an unambiguously shared understanding of each criterion. However, this limitation would become effective only in cases where the flexibility of interpretation would result in a different ranking. In order to minimize such effects, particular attention and time was paid to discussing and critically scrutinize the ranking results with the interview partners.

The stakeholder rankings from the interviews were transformed into weights by a method called SIMOS (Maystre et al. 1994b), which could be integrated in the MCA.

Sustainability appraisal phase

For the integrated sustainability appraisal the MCA provides a transparent structure and sophisticated outranking mechanism for the diverse appraisal input information, which includes (1) the sustainability criteria and the energy scenarios which build the multi-dimensional impact matrix based on qualitative and quantitative indicators and(2), the weights which show social preferences and define the impact that each single indicator has on the results ; and finally (3), the preference functions for each criterion, transforming the impact matrix to a preference matrix. The preference functions describe e.g. whether the preference is increasing in linear fashion or whether the preference has a certain indifference threshold.

The sustainability appraisal phase involved the modelling work of the quantitative indicators in the impact matrix. The modelling is based on a life-cycle data base for conversion technologies[74]. For the appraisal of the qualitative impact matrix indicators, two expert interviews were performed. Dr. Beate Littig and Prof. Reinhard Madlener appraised the social and technological dimensions such as social cohesion, security of supply, etc. and the qualitative economic criteria. A qualitative five-step scale was applied (see below for further detail on the presentation of MCA details).

The preference functions were discussed in a small interdisciplinary expert workshop. Dr. Karlheinz Erb (Ecologist), Mag. Andrea Stocker (Economist), and Franz Meister (Engineer) were invited to discuss and give advice concerning which preference functions and particular thresholds to use for the individual sustainability criteria. While explaining the specific purpose of preference functions within the MCA method PROMETHEE, a very fruitful discussion developed on whether preference functions could be used to address the different degree of data uncertainty. The expert group finally concluded that the indifference thresholds of the preference functions are basically an equivalent to the resolution of meaningful data. Where there is high uncertainty, only large data difference are meaningful (small differences are most probable data artefacts), whereas in contrast low data uncertainty allows for a higher resolution since small data differences are already meaningful and must be taken into account. After

[74] An extensive database for the environmental criteria is available from the Austrian Environment Agency (UBA): Global Emission-Model Integrated Systems (GEMIS) developed by the German Ökologie Institut. A specific Austrian data set is available for a large number of energy technologies since 2000. All data is based on life-cycle analysis (LCA).

scrutinising the single criteria and the data bases, respective uncertainty levels were assigned to the quantitative criteria and were adopted in the MCA.

The aim of the final stakeholder workshop in Nov 2005 was to discuss and sum up the results and elaborate on the political implications. The main goal of the second workshop was to present the outcomes of the integrated appraisal (MCA) and to discuss the political leeway for the realisation of the most preferred scenario/s with a group of seven stakeholders[75].

With the help of the preferences of the stakeholders revealed in individual interviews (individual weighting) and the evaluation matrix[76], the rankings of the alternative scenarios were prepared by the researcher. Hence the robustness of the results despite the different weighting constellations is of great interest and relevance. The results were subsequently discussed with the stakeholders. The aim was to come up with policy suggestions based on the main conflicting areas, and to analyse and identify specific obstacles to decision-making with regard to more sustainable energy systems.

The presented products were:

- alternative rankings of the energy scenarios calculated with PROMETHEE
- sensitivity analysis on the stability of the results, offering additional information about the sensitivity of the single criteria.
- identification of possible synergies and the main areas of conflict with respect to the sustainability criteria

In the second workshop the stakeholders articulated a strong desire to discuss the quantitative basis of the scenario modelling. After discussing the data base and modelling assumptions and the detailed feedback of the stakeholders, the identification of the stakeholders with the scenarios could be considerably improved and important amendments collected. Nevertheless, these extensive discussions had implications on the original workshop agenda; due to time constraints a detailed discussion of the challenges of the political implementation of certain scenarios had to be cancelled.

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[75] Note that due to time constraints of the stakeholders, different stakeholders participated in the second workshop.

[76] The impact matrix characterises the social, environmental, economic, and technological consequences of the various energy scenarios.

One possible reason for strong questioning of the underlying scenario modelling assumptions might be that the participants of the second workshops were different from those of the first workshop and therefore not as familiar with the scenario parameters, which have been the product of the first workshop. Another reason, though, might well be that the stakeholders were fully aware of the general importance and contestability of the scoring of scenarios and urged to open up the black box of modelling and questioned the researcher's assumptions critically. . In this workshop the presence of the institutional background and particular interests of the stakeholders, for e.g. the performance of certain technologies, was strongest within the whole participatory process.

Interestingly, some of the stakeholders, expressed their interest for a user-friendly scenario-modelling tool for their own purpose, e.g. to use it in their own institutions. They wished to define technology combinations at the individual level that are particularly interesting and to arrive to the subsequent impacts and scenario ranking by this tool.

The second workshop provided important insights regarding the modelling assumptions of the scenarios..

Another challenge is the stakeholder participation. Renn (Renn 2003), for example, reports that in their study, basic assessment criteria for energy systems were developed in eight meetings, but that not all stakeholder groups were able to participate in the entire assessment and weighting procedure. Ultimately, only two stakeholder groups – representatives of engineers and power plant operators and of the churches – participated in the entire participatory process (i.e. establishment of criteria, assessment and evaluation by means of criteria, weighting and sensitivity analysis), thus invalidating the results as the representative outcome of a process involving all relevant stakeholders.

It is notable that the Federal Ministry of Economics which is in charge of energy-making declined to participate. Another observation was made that niche representatives often struggle more often than regime representatives with financial and human resources, causing obstacles to participation in such a process.

In this case study and the parallel ARTEMIS case study, non-participation on the local level and dropouts of stakeholders was an issue; in most cases it was not clear why participation fluctuated as it did. (Kowalski et al. 2006, Bohunovsky et al. 2007) However, the feedback of the participating stakeholders was positive, and most participants found the methodology helpful for problem structuring and appraisal. The rich representation of possible futures with a limited number of scenarios and the transparent presentation of the data in the multi-criteria framework enabled stakeholders to explore the options in a comprehensive but at the same time structured and focused way. Different types of learning were also reported – cognitive learning,

learning from others and learning about the decision-process methods (for more details see Garmendia and Stagl 2010).

Development of the renewable energy scenarios

Having discussed the overall participatory stakeholder process, this chapter focuses on the specific scenario development process and the evolution of the final renewable energy scenarios. The final energy scenarios are comprised of narrative storylines and qualitative descriptions, as well as detailed modelling of different technology mixes, taking into account natural and technical potentials and the present energy discourses in Austria. For the modelling, a forecasting approach was envisaged to gain insight on the plausibility of capacity increases in the alternative scenario. In the EU climate and energy package of 2008, Austria has a concrete renewables policy aiming at an increase to 34% by 2020. This policy goal did not constitute the scenario building process taking place in 2005. Therefore some scenarios might not reach that goal, and this possibility will be presented in the results and covered in great detail in the discussion.

The role of the scenarios is to provide a structural framework for the discussions on how to determine and restrict the optional space for the development of renewable energy use in Austria. It is important to note, however, that the pre-selection of scenarios undertaken by no means claims to be a comprehensive description of the optional space. Rather, the goal is to provide a vehicle for discussing a certain range of relevant aspects and topics with stakeholders and experts. To achieve this goal, it is important that the scenarios are exemplary in nature; it is of lesser importance that the scenarios are very accurate and detailed. The scenarios are considered useful for dealing with uncertainty of future developments in a visionary and creative manner. Nonetheless, the connection to the real political situation, the natural resource potentials, and the actual market diffusion of renewable energy technologies in Austria within an international context has to be established in order to provide a substantial contribution to the energy debate with the chosen approach. Hence the scenarios are located somewhere between "business-as-usual" and a vision.

The process of scenario development is essentially divided into firstly, the building of exploratory scenarios, secondly, concentrating on a selection of scenarios and lastly, transforming these into forecasting scenarios. The scenario development process started with a scoping process which includes expert interviews and literature review. From that, a discussion proposal for the stakeholder process was formulated including (a) a suggestion of scenario parameters and (b) using the systematic combination of the bifurcal structure of parameters arriving at 16 possible combinations and respective scenarios , and (c) a pre-selection of six differing yet relevant scenarios.

These six scenarios were the basis for the first stakeholder involvement in April, 2005, by means of telephone interviews. The first stakeholder workshop followed in May, 2005. The main input given in the stakeholder telephone interviews and stakeholder workshop was that (a) the scenario parameters were changed and (b) the storylines of the original six scenarios were accepted without significant changes. In that sense, it can be argued that the suggestion of the scenario narratives captured the relevant present discourses quite well. Stakeholders agreed that the storylines are interesting to discuss and make more detailed in a sustainability appraisal. At this point it should be mentioned that exploratory scenario work could have involved stakeholders from the very beginning, starting with e.g. a brainstorming activity. In that way the scenarios would capture the stakeholders' immediate associations and ideas which would have provided valuable input. However, experience showed that the preparation and pre-selection in the discussion proposals generally did not discourage the stakeholders from giving their input. Indeed, to the contrary, as the scenario parameters were changed very drastically.

With the consensus to model five renewable energy scenarios at the stakeholder workshop on 18 May 2005, the forecasting scenario work began. Existing Austrian renewable energy studies were used as a basis for estimations of natural potentials and respective growth rates. (Neubarth and Kaltschmitt 2000, Haas et al. 2001, Kratena and Schleicher 2001, Haberl et al. 2003) A set of technologies was formed that ought to be addressed in the scenarios representing an exemplary technology park in Austria. The equivalent data was located. The data base GEMIS is the main source of quantitative data and their assortment of technologies and data was studied.

In the next stakeholder workshop, five matured and modelled scenarios were presented to the stakeholders. Furthermore, a preliminary ranking of the scenarios by the multi-criteria analysis was discussed. The final aim of the last workshop was to define policy suggestions for the highest ranked scenarios. After the stakeholder participation process, the scenarios were presented at a bi-annual energy conference in Austria and the received feedback incorporated. Since the energy scenarios were also used as the working basis of another Austrian energy modelling project, additional expert feedback on modelling details was made available from an expert workshop and was feed into the scenario details.

Next, the whole scenario development process will be discussed in chronological order and the preliminary scenario products presented. In that way the final product, a collaboration of scientist and stakeholders, can be understood as the output of an integrated process. The contributions to the scenarios from the different actors are addressed in a transparent way. The final five scenarios will be discussed in greater detail in the Results chapter.

Exploratory scenarios

In the exploratory scoping phase of the scenario building, a literature research of existing scenario work (Haas et al. 2001, Kratena and Schleicher 2001, Haberl et al. 2003) was performed and an overview of the present energy policy gained. Four expert interviews were undertaken to gain insight into the present energy discourses and learn about potential scenario storylines and parameters. The interviews were performed with Dr. Kurt Kratena (energy economist and environmental economist; author of two key Austrian energy studies), Mag. Heidi Adensam (economist, working on employment effects of renewables), Dr. Helmut Haberl (ecologist, working on energy policy, biomass technologies, and land use change), and finally, Dr. Beate Littig (sociologist, working on social sustainability and regional energy projects).

The main insights from the expert scoping interviews and the literature research were:

- Traffic and stationary energy supply are dealt with in completely different regulations and concern mostly differing stakeholders
- Stationary power and heat generation are often dealt with together or are the same process as in cogeneration processes
- A wide range of renewable technologies are in use already and more are about to become established (e.g. biogas capacity building) in Austria
- Biomass plays an immediate role in Austria because of the forest abundance and the history of biomass use for energy supply, and is associated with a powerful lobby
- Biomass for heat and electricity generation is an important land-use issue. The area demand is competing with area demand of bio fuels, agricultural production, natural conservation areas, and, recreational areas.
- Biomass residues potential is almost completely used by the Austrian paper and pulp industry. Shifting biomass residues (e.g. biomass waste from the wood industry) to heat and electricity production will only shift the problem of energy resource.
- Decentralised energy systems already play an important role in Austria on the household level (e.g. solar thermal heating, automatic pellet heating systems) but

especially on the level of communities and multi-family houses (e.g. cogeneration power plants running on wood chips)

- There are several scenario studies available for the potential developments of the energy sector and more specifically of renewable energy in the near future.

Building on these insights, the scenarios focus on Austrian electricity and heat generation from renewable energy sources until 2020. In this context, scenarios are considered descriptions of the situation in 2020. Within this time scale it is assumed that there will be opportunity for some change in the feasibility of projects and in the market situation, but it does not include the development of new technologies[77].

The aim of the exploratory scenarios was to facilitate a stakeholder discussion regarding the development of the renewable energy sector in Austria over the next 17 years. They are designed to address concise questions of this future development and are not intended to give a complete picture of future possibilities.

The main questions at this point were:

- What is the main CO_2 reduction strategy for Austria: renewable energy or energy efficiency means?
- How much renewable technology can be installed by 2020?
- Which energy sector plays the paramount role in renewable capacity building - heat or electricity generating technologies?
- Will the development of renewable energy systems foster decentralised or centralised energy systems?

The rationale of questions one and three is that there is only a limited amount of governmental subsidies available and that core areas of energy policy and CO_2 reduction strategies will have to be defined. For that reason, the first question addresses the total energy demand. The two related strategies are either increasing efficiency or decreasing the overall energy demand, or, that an increase of renewable energy capacities should be the main strategy and the overall energy demand is not necessarily decreasing but is shifting to a carbon neutral, renewable energy supply. This parameter takes energy conservation and energy efficiency matters into

[77] For example, hydrogen technologies are not addressed in the scenarios

account. The third question addresses whether the focus lies on renewable heat or electricity generation[78].

Question two reflects the overall political will concerning renewables, and consequently the support for renewable energy capacity building. Furthermore, it addresses the market success of renewables.

The issue of decentralised versus centralised energy systems, which is addressed in question 4., touches on several issues such as (a) the level of implementation of renewables and consequently the individual technology capacity, (b) the ownership structure, and (c) the decision-making structure. The definition of central and decentralised energy systems is ambiguous. In the present energy scenarios the definition attends, on the one hand, to the matter of technology size, which was an important feature concerning the modelling. On the other hand, the definition subsumes the social dimension of decentralised energy systems as regional independency, local revenue, etc. This information has been essential for appraising the social sustainability criteria.

From these four questions, four key scenario parameters were defined: (1) total energy demand, (2) total renewable energy amount, (3) technology mix: power versus heat technologies, and, (4) centralised versus decentralised energy systems.

Scenario-driving forces	Measurement unit & division line regarding decentralised energy supply	Major questions to be addressed
Total energy demand	MWh	Varying the total energy demand allows for consideration of *energy conservation* and *energy efficiency*.
Total renewable energy amount	Installed renewable energy capacity	Variations in (additional) renewable energy capacity (relative to 2002) reflect the overall *political and financial support* of renewable energy sources and their *market success*.
Mix of technologies	% of total renewable energy	Varying the mix of technologies acknowledges

[78] An argument in favour of increasing renewable heating capacities suggests that substitution of inefficient oil heating systems and more efficient gas heating systems would create a remarkable CO_2 reduction. Substituting electricity generation, of which up to ~70% is generated by large hydro power anyways, doesn't bring as much reduction. On the other hand, the electricity demand is steadily increasing and therefore the electricity capacities should be of greater importance for future energy systems.

	share various renewable energy technologies are taking in	the *different technological options* for achieving a certain share of renewable energy supply.
Central (large scale) / decentralised (small scale) renewable energy conversion plants	≤ 100 kW energy plant is considered small scale and above that as large scale	This variation invites the discussion of *planning issues* and *institutional structure* of the electricity and heat production and allocation.

Table 3. Driving forces of the energy scenarios, units of measurement, and major questions to be addressed by them

According to a systematic combination of the four parameters, 16 scenarios were derived. Among those 16, not all of the parameter combinations are possible or plausible. Six preliminary scenarios were elicited as the basis for the participatory scenario development process. For the selection towards a concise number, the following criteria were applied: The final scenarios aim to be

- exemplary but in a feasible range
- coherent and dissimilar enough
- to cover enough options but are of confined number

The scenarios 2, 5, 7, 12, 13, and, 16, were elicited for further relevance (see appendix for a scenario parameter description).

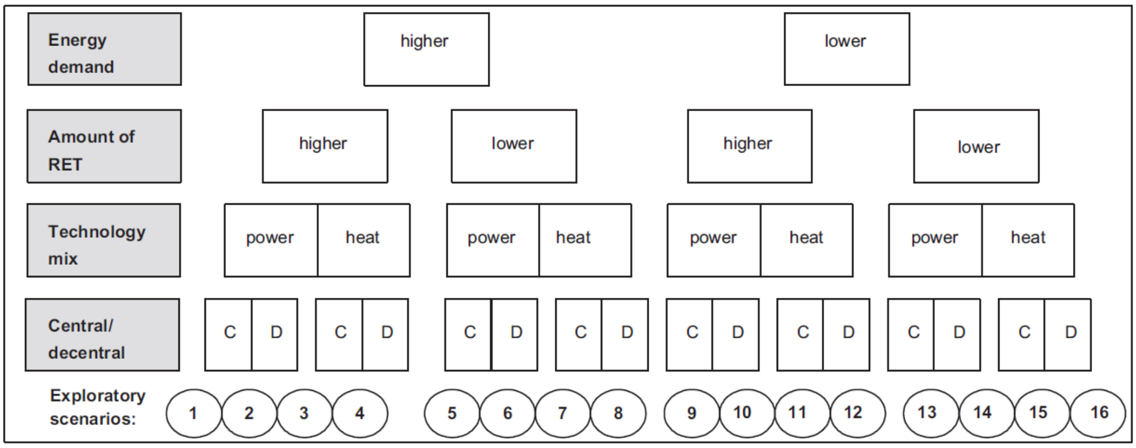

Figure 11. Systematic combination of the scenario parameters considered at the outset (C = centralised, D = decentralised energy supply; RET = renewable energy technologies)

From this point on, the finalisation of the renewable energy scenarios was reached in collaboration with key Austrian energy stakeholders by means of telephone interviews and a stakeholder workshop (ARTEMIS workshop I, 18 May 2005).

The main feedback given by the stakeholders resulting in changes of the number of scenarios and scenario compositions was:

- 5 scenarios were selected to be elaborated in detail
- Scenario F was considered the “business as usual” scenario and was voted out by the stakeholder present at the workshop, when asked to reduce the number of scenarios.
- The dichotomous structure of the scenario parameters was considered insufficient. Instead of that, a continuous structure is introduced along gradients.
- It was stated that energy efficiency should not be addressed via the total energy demand, which is affected by too many other factors. Instead, concrete examples of energy efficiency measures are added to the scenarios. The parameter “total energy demand” was cancelled.

The assumption that the Austria government funds either renewables or efficiency measures was declined. Practical experience shows that either there is an active energy policy in which case both strategies are followed, or there are not any great efforts for energy policy.
The share of renewable energy technologies should be part of the results rather than determined beforehand as a scenario parameter. The parameter “amount of renewables” was cancelled.
Heat and power production have to be together in all scenarios, consequently the parameter was changed.

The parameter “central versus decentralised capacities” is a key parameter, but should be understood not only as capacities but as scale of decision-making and ownership structure.
Additional scenario parameters were introduced:

- time frame: short versus long-term thinking
- innovation: systems versus individual technology innovation
- institutions: necessity of new institutions

Furthermore, the energy stakeholders discussed and agreed on key technologies in the technology profile of each scenario. A first draft of the scenarios along the new parameters was followed through at the workshop.

Reflecting on the scenario development process so far, the initial scenario structure was useful to identify the major development directions. The titles and basic storylines of the scenarios were accepted and agreed upon by the stakeholders. For the development of more detailed and practical scenarios the structure was perceived as too hermetical and the “either or” as not relevant in practice. A great amount of productive input was given by the stakeholders, changing the scenarios drastically. This showed the potential of working within a process of stakeholder participation. New perspectives, more practicability and improvement were added, especially concerning the key parameters.

Final scenarios

In this chapter, the methodological details of five final renewable energy scenarios are presented. Each scenario is comprised of two parts. On the one hand, the descriptive narrative was based on the qualitative scenario parameters which are:

- Time frame: short- versus long-term thinking frame
- Innovation: systems versus individual technology innovation
- Institutions: necessity for new institutions
- Capacity of technology and scale of decision making: central versus decentralisation

On the other hand, each scenario consists of a quantitative, modelled technology mix. Those two parts are interlinked. The narratives influence the detailed composition of technologies in the scenarios, and the narratives are an important basis to appraise the scenarios according to the qualitative criteria.

Narratives of the scenarios

Parameter 1, Time frame- short versus long term: This parameter addresses the time frame of policy decisions. The short term refers to a time period of around 5-10 years. This would be the usual time frame for economic decision-making. The long-term perspective is 30-50 years. This time frame includes long-term resource and environmental developments as well as long-term technological innovation. This parameter influences the technological compilation in the modelled part of the scenarios. In long-term scenarios also expensive technologies, such as e.g. photo-voltaic, are integrated to a wider extent. With a long time frame, higher investments make sense.

Parameter 2, Innovation-systems versus individual technology innovation: This parameter deals with two distinctively different types of innovation and efficiency improvements. On the one hand, systems efficiency which tries to identify and make use of as many synergies as possible by e.g. combining different production industries which complement each other with regard to their resource demand. This requires a systems thinking and interdisciplinary and trans-sectoral cooperation. According to the stakeholder discussion,[79] systems efficiency can improve cost and emission efficiency by approximately 10%.

Parameter 3, Institutions- necessity of new institutions: This parameter points out the differences between the scenarios with regard to the need for new institutions. It indicates the institutional innovation necessary for a structural change in the energy system. In this context, institutions are defined in a broad way and include organisations, rules, and, laws. This aspect of the descriptive part of the scenarios does not directly influence the compilation of neither technologies nor the concrete impacts. However, this parameter offers insight about the transition pathway and how fundamental the changes of the energy system might be.

Parameter 4, Capacity of technology and scale of decision making: centralised versus decentralised: This parameter stresses the structure of energy production in the future energy system. The production structure is defined as (a) the capacity of the technologies (small- versus large-scale technologies), (b) the scale of decision-making, and (c) the ownership structure.

It is assumed that the three dimensions (a, b, and c) have the same orientation and can be brought together in one parameter. In most cases small capacity technologies will be decided upon and owned by local bodies like communities, multi-family residents, and single households. Nevertheless, it is a simplified assumption. Especially in urban areas, multi-family residents are in some cases organised and owned by private companies. Nevertheless, in most cases the three dimensions do go together well and allow for discourse on social, technological, economic, and environmental topics. Table 4 displays the concrete definitions for "decentralised" and "centralised" in all three dimensions.

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[79] The representative of the Federal Ministry of Traffic, Innovation, and Technology offered a great amount of input on this discussion.

	Central production structure	Decentral production structure
(a) capacity of technologies	capacity of>100 kW	capacity of ≤ 100 kW
(b) scale of decision-making	decided on national level	decided by regional, community, or household level
(c) ownership structure	owned by government or large private companies	owned by private individuals, communities, or cooperative societies.

Table 4. Definition of the scale effect on a) the capacity of the technologies (small- versus large-scale technologies), (b) the scale of decision making, and (c) the ownership structure.

This parameter will have a direct affect on the compilation of the technologies and will also have a particular affect on the performance of the social criteria.

All parameters of the narrative are displayed in the form of a gradient. (Figure 12) The parameter gradient is characterised by trends towards certain opposing extremes e.g. long-term versus short-term time frame. This is appraised relative to the energy system today. The centre represents the situation today. There are four available positions extending from each end of the gradient. In that sense it is a graduation with nine positions. The gradient enables translation of the qualitative parameter information towards the modelling of the scenarios (see the following Quantitative modelling of the scenarios).

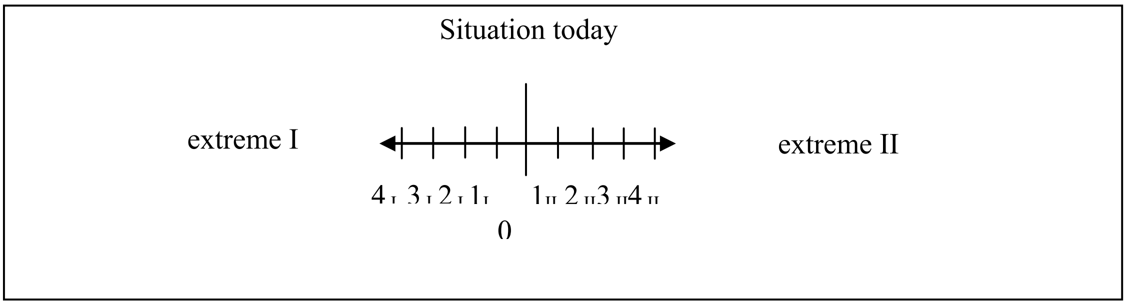

Figure 12. Gradient applicable for the qualitative scenario parameters.

Quantitative modelling of the scenarios

The quantitative part of the renewable energy scenarios describes alternative technology mixes in the year 2020. The scenarios project alternative technology profiles showing additional installation of renewable energy sources. The heat and electricity generating technology mixes are derived from 22 different types of renewable energy technologies. The technology types were selected from the GEMIS life cycle data base (UBA 2004a, Ökologie-Institut 2006) representing standard Austrian technologies to create a picture of the Austrian renewable energy technology park. These types of technologies differ in (a) the type of the input resource, and (b) the capacity. Large hydro power is not included (see Table5 for a summary of the technology types). The increase of overall capacity by 2020 is modelled for every technology type.

The scenario modelling is based on existing energy scenarios (e.g. Haas et al. 2001, Kratena and Schleicher 2001, Kratena and Wüger 2005) as well as on other selected reports and secondary statistics (e.g. Neubarth and Kaltschmitt 2000, Haberl et al. 2002). The definition of key technologies for each scenario, output of the scenario stakeholder workshop, enables the use of different technology profiles and respective capacity differences. The growth rates of existing Austrian scenario studies between 1999 and 2010 (Haas et al. 2001) are used as a basis, and are projected until 2020. For each scenario, more ambitious growth rates are assumed for the key technologies and only moderate rates for the other technologies. Ambitious growth rates are represented by exponential functions, and linear functions are used for the moderate types of growth. In the business as usual scenario (BAU) only linear extrapolations for all the technology types have been used in order to create a reference scenario. The results of the modelling were cross checked for plausibility with the input studies.

Particular attention is paid to the technologies based on biomass as feedstock. Here, two sources of biomass have been discerned: (a) primary biomass from e.g. forests and arable land, (b) secondary biomass, i.e. residues and wastes from biomass processing in food, feed and fibre industries. In the scenarios a maximum additional dry biomass residue potential of 4,500 GWh is assumed which is based on the biomass modelling of (Haberl et al. 2003) and is comparably more conservative, taking into account growing demand of other sectors. Depending on the focus of the scenarios, a different degree of this potential is realised by 2020. The qualitative scenario parameter ‘System efficiency’ is directly linked to the degree of realisation of biomass residues in the scenarios. Because wood is traded on the world market, and local wood harvest tends to be more expensive than e.g. in Eastern European countries, it is assumed that additional wood feedstock demand will be covered by imports.

Renewable technology	Capacity	Detail	Resource
Hydro power	small	new build and revitalised	water power
Wind park	small		wind power
Wind park	large		wind power
Photo voltaic	small	integrated in facades and roofs	solar radiation
Solar thermal power	small	solar thermal panels	solar radiation
Biogas	large	gaseous biomass	primary biomass
Biogas cogeneration	small	gaseous biomass, cogeneration	secondary biomass
Biogas cogeneration	large	gaseous biomass, cogeneration	primary biomass
Biomass cogeneration	small	solid biomass, cogeneration	primary biomass
Biomass cogeneration	small	solid biomass, cogeneration	secondary biomass
Biomass electricity	large	solid biomass	primary biomass
Biomass heat	small	solid biomass	primary biomass
Biomass heat	small	solid biomass	secondary biomass
Biomass heat	large	solid biomass	primary biomass
Biomass heat	large	solid biomass	secondary biomass
Wood gas cogeneration	large	gasification to wood gas	primary biomass
Wood gas cogeneration	large	gasification to wood gas	secondary biomass
Wood gas- electricity	large		primary biomass
Sewage cogeneration	large		sewage gases
Geothermal plants power	large		geothermal energy
Geothermal plants heat	large		geothermal energy
Heat pumps	small		geothermal energy

Table 5. Summary table of the 21 types of renewables technologies with details of their output capacity class (small and large) and specifically for the biomass section details on the input resources (primary or secondary biomass resources)

Tables 6 and 7 give two concrete examples of how the qualitative parameter gradients are transformed to quantitative information and then integrated into the modelling of technology capacity increase. Table 6 demonstrates the calculation of the ratios of large and small scale wind farms with respect to each scenario. In Table 7, the ratios of primary biomass and secondary biomass (biomass residues) are derived from the scenario parameter systems innovation versus individual technology innovation for the example of biogas technologies.

	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Qualitative gradient	++	++	-	+	----
Vector	-2	-2	1	-1	4
Step width	5%				
Change	-10%	-10%	5%	-5%	20%
Small scale	16%	16%	18%	17%	21%
Large scale	84%	84%	82%	83%	79%

Table 6: Translation of the qualitative parameter 'grade of decentralisation' into the quantitative technology modelling based on the example of wind parks.

	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Qualitative gradient	-	0	++	---	+++
Vector	-1	0	2	-3	3
Step width	10%				
Change	-10%	0%	20%	-30%	30%
Primary biomass	55%	50%	40%	65%	35%
Secondary biomass	45%	50%	60%	35%	65%

Table 7: Translation of the qualitative parameter 'systems innovation' into the quantitative technology modelling based on the example of large scale biogas plants.

The final scenarios were presented in the second stakeholder workshop (results workshop), and the results were scrutinised. The following stakeholder comments were given, and to a great extent they were incorporated into the modelling after the workshop:

- Large-scale hydro power should be addressed when considering future sustainable energy systems and integrated in a more long term scenario (Representative of State Owned Forest).
- The wind energy potential was considered too optimistic by the stakeholders from Chamber for Agriculture, Representative of State Owned Forest, and, Electricity Utility, Wien Energie. On the contrary, WWF refers to even higher wind energy potentials.
- The amount of photovoltaic energy in scenario C (2,032 GWh) is appraised as very high and rather unrealistic.
- Biogas has a higher potential, which could easily be realised by 2020 (Chamber for Agriculture, Representative of State Owned Forest, and, Electricity Utility, Wien Energie).
- The electricity generation with biomass is too low (Chamber for Agriculture).

- Not enough capacity increase according to the heat pumps.
- Some stakeholders do not agree with the overall assumption that no new technologies will emerge by 2020

Multi-criteria Analysis (MCA)

In the light of the high complexity associated with the consequences of different future development paths in the field of renewable energies, a multi-criteria analysis (MCA) is applied. Starting point for this analysis was a detailed indicator system, developed in a participatory process. MCA is a method for decision support (and decision-finding). It allows for a systematic comparison and appraisal of alternative developments with respect to a multitude of aspects. MCA has been extensively used for energy policy and energy system planning questions (e.g. Mirasgedis and Diakoulaki 1997, Haldi 2000, Haldi et al. 2002, Pohekar and Ramachandran 2004, Giannantoni et al. 2005, Gamboa et al. 2008). Most applications related to energy questions focus on technical planning (e.g. as described in Hobbs and Meier 2000), on technology siting, or short-term supply-oriented decisions (for a survey see Kowalski et al. 2009), and, typically do not include stakeholders in a systematic and participatory way. However, like in other sustainability research areas (Giampietro et al. 2006), a trend towards increased involvement of stakeholders can be observed in energy research. Examples include Banville et al. 1998, Haralambopoulos and Polatidis 2003, Greening and Bernow 2004, Konrad et al. 2004b, Madlener and Stagl 2005, Stagl 2006, MacDowall and Eames 2006, Anderson et al. 2006.

The benefits of combining participatory methods with analytical tools such as MCA are widely acknowledged (for a review see Stagl 2007). Recent methodological innovations such as Multi-Criteria Mapping (MCM; Stirling and Mayer 2001), and, Social Multi-Criteria Analysis (SMCA, Munda 2004) put particular attention to the importance of the legitimate diverse perspectives. SMCA is highlighting explicitly social and technical incommensurability and thus acknowledge the operational challenges of evaluating complex (reflexive) systems. Social incommensurability arises from multiple legitimate perspectives of a socio-ecological system. Technical incommensurability, in contrast, arises from the different assessments of complex systems by use of different types of models. Both types of incommensurability are addressed in this particular combination of participatory MCA and participatory scenarios.

A MCA of scenarios, integrating qualitative and quantitative data, is not trivial. Both, the overall picture, presented by a coherent storyline, as well as the individual, different parts, i.e.

the dimensions of sustainable development, have to be addressed within the assessment. The analysis, based on the integration of qualitative and quantitative indicators, requires a translation of the qualitative scenario parameters from the scenario storyline into quantitative data. By applying a multi-criteria algorithm, complexity is reduced by aggregating the multi-dimensional information given in the assessment matrix into a ranking of scenarios. MCA complements scenario development by offering an algorithm to systematically aggregate multi-dimensional information, and therefore reducing the scenario (information) complexity in a transparent way, in the so-called 'closing down' phase.

Different types of data and information can be integrated in the scenarios appraisal. Conflicting objectives are transparently structured and accounted for. MCA, used in a participatory manner, provides a method that fulfils the requirements of 'Integrated Sustainability Assessment' (ISA). (Omann 2004). ISA is an operational evaluation and decision support approach that is suitable for addressing complex problems characterized by high uncertainty, conflicting objectives, different forms of data and information, multiple interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic systems[80]. ISA aims to support the development of (long-term) cross-sectoral policies that specifically aim at sustainable development.

Applying an MCA method such as AHP or MACBETH is favourable in cases where when opinions or references, which are intricate to quantify, form the basis of the assessment. However, the subjective scaling of exact quantitative information needed for pair-wise comparison of elements in the same hierarchy may lead to losses in accuracy with such a method. (Nigim et al. 2004) In contrast, the MCA software PROMETHEE uses an outranking algorithm; based on impacts, weights and preference functions. It calculates a concordance index based on the principle of majority vote. Two indices (outgoing positive flow und incoming negative flow) are calculated and used for a partial ranking (PROMETHEE I) or for a complete ranking (PROMETHEE II). (Geldermann et al. 2000) The result of a pair-wise comparison undertaken with the PROMETHEE method (Brans and Mareschal 1990) is a ranking.

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[80] In the EU project MATISSE (6th Framework Programme, www.matisse-project.net) the following definition was developed and applied: "ISA is a cyclical, participatory process of scoping, envisioning, experimenting, and learning through which a shared interpretation of sustainability for a specific context is developed and applied in an integrated manner in order to explore solutions to persistent problems of unsustainable development" (Weaver and Rotmans 2006, p.12).

The aggregation process is based on a pair wise comparison of the alternatives according to each single criterion. There are two different ways of aggregation. In PROMETHEE I, no trade-offs between the criteria are assumed and there might be incomparability of the alternatives in the result. In contrast, PROMETHEE II always produces a complete ranking but includes the strong assumption that criteria can be traded off against each other. In practise, both aggregation processes can be applied and additional information from PROMETHEE II, with the strong assumption of trade-offs can be used to understand the incomparability of alternatives in the ranking of PROMETHEE I.

For the sustainability assessment of the renewable energy scenarios, the software PROMETHEE will be used, performing both partial and complete ranking procedures. The impact matrix forms the basis of the assessment and contains quantitative as well as qualitative information.

In the following, a detailed description of the applied PROMETHEE functions is given: (Brans and Mareschal 1990)

A	finite set of possible alternatives
$f_j(x)$	j = 1, 2, …k a set of k evaluation criteria
a_n	n Alternatives
$f_l(a_l)$	impact matrix value of the criterion 1 in scenario 1
f(a)	$f : A \rightarrow IR$ (to be maximised)

$f(a) > f(b) \leftrightarrow aPb$

$f(a) = f(b) \leftrightarrow aIb$

P	preference
I	indifference

This defines the dominance relation but doesn't account for the amplitude of deviation

d	amplitude of deviation

$d = f(a) - f(b)$

P (a,b)	Preference function for preference intensity of a over b

$0 \leq P(a, b) \geq 1$

The intensity of preference is between 0 and 1

$P(a, b) = 0$	if	$d \leq 0$	$(f(a) \leq f(b))$	No preference, indifference
$P(a, b) \approx 0$	if	$d > 0$	$(f(a) > f(b))$	Weak preference
$P(a, b) \approx 1$	if	$d >> 0$	$(f(a) >> f(b))$	Strong preference
$P(a, b) = 1$	if	$d >>> 0$	$(f(a) >>> f(b))$	Strict preference

$H(d) = P(a, b)$

$\pi(a, b)$	preference index of a over b over all the criteria
w_j	j= 1, 2, …, k are weights associated to each criterion

$\pi(a, b) = \sum w_j P_j(a, b)$

$\pi(a, a) = 0$

$0 \leq \pi(a, b) \geq 1$

$\pi(a, b) \approx 0$	implies a weak global preference of a over b
$\pi(a, b) = 1$	implies a strong global preference of a over b

For each pair a, b ε A the values π (a, b) and π (b, a) are calculated and an outranking matrix on A established. With the introduction of preference functions the impact matrix is transformed into an outranking matrix and differentiates intensities of preferences.

Two outranking flows:

$\Phi^+ (a) = \sum \pi (a, x)$ positive outranking flow
$\Phi^- (a) = \sum \pi (x, a)$ negative outranking flow

“The positive outranking flow expresses how each alternative is outranking all the others. The higher Φ^+ (a) is, the better the alternative. Φ^+ (a) represents the power of a, it gives its outranking character.

The negative outranking flow expresses how each alternative is outranked by all the others. The smaller Φ^- (a) is, the better the alternative. Φ^- (a) represents the weakness of a, it gives its outranked character.” (Brans and Mareschal 1990)

$a\ S^+\ b$	if	$\Phi^+ (a) > \Phi^+ (b)$
$a\ I^+\ b$	if	$\Phi^+ (a) = \Phi^+ (b)$
$a\ S^-\ b$	if	$\Phi^- (a) < \Phi^- (b)$
$a\ I^-\ b$	if	$\Phi^- (a) = \Phi^- (b)$

$a\ P^I\ b$	if	aS^+b and aS^-b
	if	aS^+b and aI^-b
	if	aI^+b and aS^-b
$a\ I^I\ b$	if	aI^+b and aI^-b
a R b	if	otherwise
P^I	preference in PROMETHEE I (partial ranking)	
I^I	indifference PROMETHEE I (partial ranking)	
R	incomparability	

$\Phi (a) = \Phi^+(a) - \Phi^- (a)$ complete ranking

$a\ P^{II}\ b$	if	$\Phi (a) > \Phi (b)$
$a\ I^{II}\ b$	if	$\Phi (a) = \Phi (b)$

Sustainability criteria forming the impact matrix

As a result of the literature review, the four scoping expert interviews, and intensive discussions of the ARTEMIS project team members[81] a proposal list of sustainability criteria was prepared. This list was the starting point for the discussions with the stakeholders. The criteria list was

81 The theoretical base of the discussions in the ARTEMIS expert group was formed by the Helmholtz approach of the sustainability criteria framework based on systems theory (’integrative sustainability concept’; cf. Coenen and Grunwald 2003; Kopfmüller et al. 2001).

adapted during the stakeholder telephone interviews and the stakeholder workshop I (18th of May 2005). In the course of the process, three new criteria were introduced:

- noise
- electromagnetic radiation
- effect on the national budget (need for taxes)

The criteria set was agreed upon at the end of the participatory workshop scenario workshop. However, after a final reviewing round, three criteria had to be cancelled, because the modelling of the energy scenarios did not allow generating the related information: (a) Electromagnetic Radiation, (b) Risk of Irreversible Investment, and, (c) Social Justice (see Table 8).

Between three and five criteria for each sustainability dimension were identified in the participatory process. For the appraisal of the criteria, respective indicators were defined (see also Table 8). This development procedure, which comprises the criteria in a bottom up stakeholder process and the indicators in a top down process (expert based) is adopted from (Fraser et al. 2006). Finally, both quantitative as well as qualitative indicators were selected for the sustainability appraisal.

To assemble the MCA impact matrix the scenario impacts along all 23 sustainability indicators were appraised. The qualitative impact matrix was developed on basis of two expert interviews (Dr. Beate Littig, a sociologist, and Prof. Reinhard Madlener, an energy economist). Some qualitative indicators were appraised in 3 and others in 5 rating scale, depending on the possibilities to make detailed differentiations with the scenario information at hand.

For the assessment of the quantitative indicators in the sustainability appraisal, the Life-cylce-assessment (LCA) database GEMIS 4.2 Austria and GEMIS 4.3 (Ökologie-Institut 2006, UBA 2004a) have been used, among other sources for costs (Neubarth and Kaltschmitt 2000) and ecological justice (sealed area equivalent; Haberl et al. 2002).

Criteria	Indicators	Short descriptions
Social sustainability dimension		
Quality of landscape	Quality of landscape	Qualitative indicator- aesthetic intrusion due to constructions
Social Justice	Affordability	-
Noise	Noise	Qualitative indicator- intrusion due to noise
Social cohesion	Social cohesion	Qualitative indicator- possibilities to create social capital by joined initiatives
Regional Self-Determinacy	Regional Self-Determinacy	Qualitative indicator- possibilities for regions to act self-organised and to decide independently
Environmental sustainability dimension		
Climate change properties	CO_2 equivalent/PJ	Quantitative indicator- summarising the effect of climate active gases such as CO_2, CH_4 NOx, N_20, Perflourmethan, Perflouraethan
Air quality	SO_2 equivalents/PJ	Quantitative indicator- summarising the effect of acidification causing gases such as SO_2, H_2S, NH_3, HCl, HF
	Troposphere Ozone TOPP/PJ	Quantitative indicator- summarising the effect of ground level ozone enhanced by e.g. Non-Methane Volatile Compounds (NMVOC), NOx
	Particulate Matter/PJ	Quantitative indicator- amount of particulate matter
Water quality	Phosphorus (P) /PJ	Quantitative indicator- excess phosphorus lead to significant water quality problems including harmful algal blooms, hypoxia and declines in wildlife and wildlife habitat.
	Nitrogen (N) /PJ	Quantitative indicator- excess nitrogen lead to significant water quality problems including harmful algal blooms, hypoxia and declines in wildlife and wildlife habitat.
	Inorganic Acids (Aox) /PJ	Quantitative indicator for measuring water quality
	Biological Oxygen Demand BOD /PJ	Quantitative indicator- measuring the degree of organic pollution of the water.
	Chemical Oxygen Demand COD /PJ	Quantitative indicator- measuring the degree of organic pollution of the water.
Rational Use of Resources	Cumulated Material Effort/PJ	Quantitative indicator - material intensity in t/PJ of the whole technology life cycle
	Cumulated Energy Effort/PJ	Quantitative indicator - energy intensity in PJ/PJ of the whole technology life cycle
Ecological Justice	Sealed Area Equivalent /PJ	Semi- quantitative indicator - Human appropriation of net primary production[1]
Economic sustainability dimension		
Economic Efficiency	Costs €/ PJ	Quantitative indicator- Investment costs & variable costs
Effect on Public Budget	Macroeconomic Costs /PJ	Qualitative indicator- public spending for technology subsidies
Employment Properties	Brut Employment /PJ	Qualitative indicator- additional employment capacities due to technology production, construction, and, maintenance
Technological sustainability dimension		
Resilience of the technological system	Diversity of Technologies	Qualitative indicator- Technological diversity in energy systems important for systems resilience and to avoid lock-in situation
Security of Supply	Likeliness of drop outs and number of affected consumer	Qualitative indicator - Likeliness of drop outs and number of affected consumer
Import Independency	Import Independency	Qualitative indicator - Amount of necessary energy resource import
Technological Leadership	Improvements in technological leadership	Qualitative indicator – economic advantages due to exporting technology know-how

Table 8. Overview of the sustainability criteria and indicators for the sustainability appraisal of the energy scenarios;
[1] for a more detailed description of the indicator development see text.

The indicator 'Sealed Area Equivalents' was developed in order to operationalise land use aspects and area demand in the renewable energy scenarios. This indicator is a simple approximation based on the concept and indicator 'Human Appropriation of Primary Production' (HANPP; Vitousek 1986, Haberl 1997, Haberl et al. 2007, Erb et al. 2009. The indicator is used as a metric for the criterion Ecological Justice, by operationalising 'colonizing interventions in ecosystems' (Fischer-Kowalski and Erb 2006, Erb 2006) as anthropogenic area demand. Its basic assumption holds that if a parcel of land is used by humans, e.g. by soil sealing or biomass harvest, the corresponding ecological energy flow is not available for other species. Because the data for the area demand calculation of each technology types is associated with high uncertainty (due to complex systems boundaries and shortcomings of the GEMIS database, Werner Pölz, personal communication) a semi-quantitative indicator was produced. Five types of area utilisation are characterised in the indicator 'Sealed Area Equivalent' and accounted for depending on the rate of appropriation and the intensity of appropriation: (1) sealed land (100% constant appropriation), (2) agriculture areas (80% annual appropriation), (3) SRC (70% every 3-5 years), (4) forest area (30% for more than 20 years), and finally (5) no appropriation (0%), in case build-up areas are used as in roof and façade solar power.

Preference functions

In the MCA application, preference functions were used to address data uncertainty. An expert workshop with four external experts was held (November 2005, SERI Institute, Vienna) to appraise the relevant thresholds of the preference function. During the workshop, the threshold of indifference was identified as the resolution of the data analysis and discussed for the quantitative indicators in the sense of data uncertainty (see Table 9). The outcomes of this workshop are the basis for the applied standard indifference thresholds of the preference functions of the quantitative indicators (see Figure 13 for a summary of the standard preference functions).

Quantitative Indicators	Grade of uncertainty	Short description
CO_2 equivalents	medium	The calculation of combustion emissions (CO_2) is very reliable and uncertainty low, but the CH_4 emissions have a high uncertainty grade
SO_2 equivalents	medium	
TOPP	medium	The uncertainty is medium
Particulate matter	medium	
Cumulated Material Effort	medium	Highly aggregated indicators with complex system boundaries
Cumulated Energy Effort	medium	
Phosphorus	high	
Nitrogen	high	
AOX	high	The data is not complete in the GEMIS data base and there are certain apparent data inconsistencies
BOD	high	
COD	high	
Costs	medium	A comparison of the costs data from GEMIS and other sources (Neubarth and Kaltschmitt 2000) showed a rather good resemblance.

Table 9. An overall approximation of the degree of data uncertainty according to the quantitative indicators as an outcome of the expert discussion Nov 2005.

The preference function transforms the impact matrix into a preference matrix and configures the differences among the scenario impacts within every criterion separately into preferences between 0-1, whereas 1 is strict preference and 0 is indifference. Six different specifications of preference functions are made available by PROMETHEE. (Bana e Costa 1990): preference functions for the (1) usual criterion, (2) the U-shaped criterion, (3) v-shaped criterion, (4) the level criterion, (5) the v-shaped criterion with indifference threshold[82], and, (6) the Gaussian criterion. The specification of the preference function and appointment of the thresholds are to be defined for every criterion by the user. Up to two thresholds are to be defined: q is the threshold defining the indifference area, whereas p is the threshold defining the strict preferences area (see Figure 13).

[82] In the presently applied PROMETHEE software decision lab the v-shaped criterion with indifference threshold is addressed as linear shaped criterion.

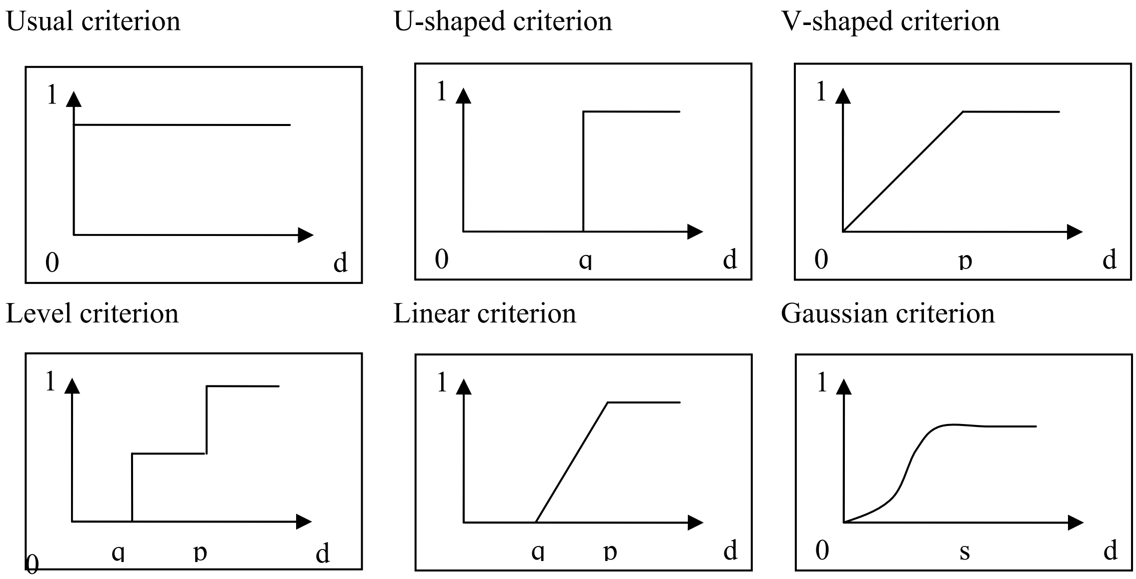

Figure 13. Schematic diagrams of the six alternative preference functions made available by PROMETHEE.
q denotes the threshold defining the indifference area, and, p is the threshold defining the strict preferences area, s is a parameter the value of which lies between p and q.

The preference function for the linear type of criterion was chosen for the quantitative indicators (see Figure 13.); while the indifference thresholds (d) of the preference functions represent the uncertainty grade. The strict preference thresholds are set in a way that all the data differences are within the linear phase of the linear preference function because there is no indication that there is a kind of saturation present.

The qualitative criteria have a v-shaped form preference function with strict preference thresholds. The strict preference threshold (p) was set in a way that all impact differences are accounted for and don’t fall beyond the strict preference threshold. The main assumption behind having no indifference thresholds for the qualitative criteria is that the level of uncertainty is expressed in the number of qualitative levels. Consequently no indifference thresholds are needed with those criteria.

Weights

The social preferences of the stakeholders are expressed by weightings of the individual sustainability criteria. The basic rationale of eliciting and including social preferences via weighting of the sustainability criteria (rather than directly prioritising the energy scenarios), is that this procedure hampers strategic acting.

In stakeholder interviews the rankings of the criteria have been elicited. The overall question for the interview was. “Which sustainability aims are most important in regard to transitions towards more sustainable energy systems?” The stakeholder is using printed cards to put the different sustainability criteria in a ranking order. To clarify the meanings of the 19 sustainability criteria particular attention was paid to discuss different interpretations, in order to come to a common understanding and to minimize effects of contextual or implicit interpretations on the ranking result (see above).

Each rank can be occupied by a blank card or by one or more criteria in order to allow for equal weights and larger distances between criteria as well. Also, stakeholders had to express their perception of the distance between highest and lowest ranked criterion. This is usually a number between three and 20 (see Maystre et al. 1994a, for further details). The individual criteria rankings of all stakeholders are displayed in Table A.6., Table A.7. and Figure A.2. in the Appendix.

In order to transform the criteria rankings into weightings, the revised version of the SIMOS method was applied (Figueira and Roy 2002). In the SIMOS method, the weights for the criteria are calculated from (1) the ranking of criteria and (2) by defining the ratio between the most important and the least important criterion.

GAIA plane

PROMETHEE offers a visual modelling technique, Geometrical Analysis for Interactive Aid (GAIA plane). The plane contains a projection of the criteria and the alternatives and in addition the decision axis, which represents the preference according the weighting of the criteria (for an example and explanation see Figure 14). (Geldermann and Zhang 2001, Brans and Mareschal 1990).The GAIA plane provides information for understanding and interpreting the conflictual character of the criteria. On the one hand, the GAIA plane allows identifying conflicting and supporting criteria, which is not possible merely from the impact matrix, and, on the other hand, it illustrates discrimination strength and direction of each criterion according the scenarios.

The Gaia plane is a graphical representation of the impact matrix. The distribution of the criteria and scenarios in Gaia plane are influenced by the impact matrix and preference functions. The weights are represented by the decision stick pointing towards certain scenarios more than to others.

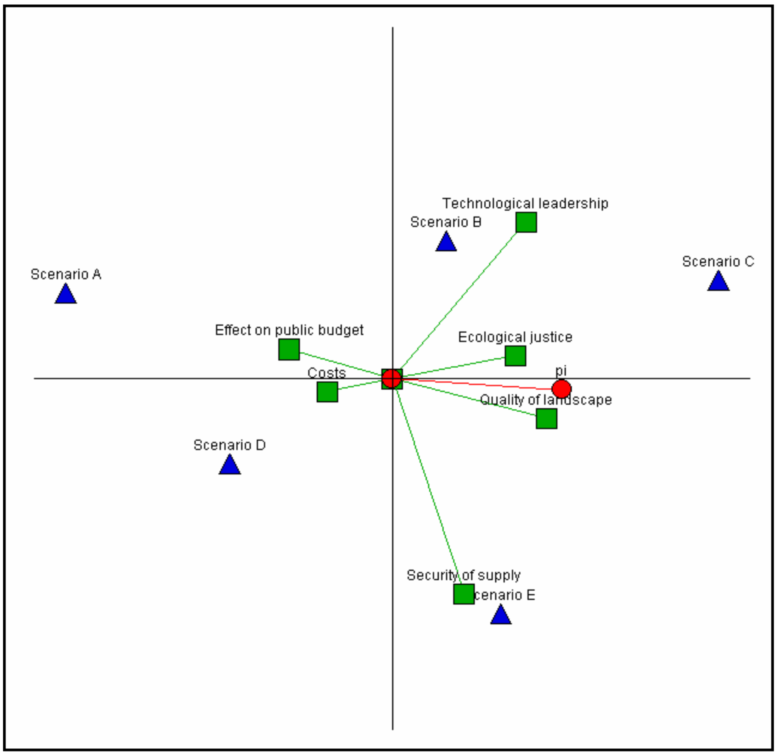

Figure 14. Schematic representation of the GAIA plane: This exemplary decision problem includes 6 criteria (rectangular boxes with axes). In this case, the GAIA plane is obtained by projection of a 6-dimensional space on a plane such that as few information as possible get lost (principle component analysis). Alternatives of action (scenarios) are represented by triangles. The conflicting character of the criteria appears clearly: criteria expressing similar preferences on the data are oriented in the same direction; conflicting criteria are pointing in opposite directions. In this case the criterion Cost is in strong conflict with the criterion Ecological Justice. It is also possible to appreciate clearly the quality of the scenarios with respect to the different criteria. Scenario B is particularly good in Technological Leadership and Scenario E performs well according the criterion Security of Supply. In addition to the representation of the alternatives and criteria, the projection of the weights vector in the GAIA plane corresponds to an additional axis (pi, the PROMETHEE decision stick; bullet with axis) that shows the direction of the compromise resulting from the weights allocated to the criteria. Scenario C represents in this case the most promising alternative. (http://homepages.ulb.ac.be/~bmaresc/PromWeb.htm)

Normed net flows γ_j (a) are built for the sake of presentation, which are referred to as associated unicriterion flows. "Each alternative is then characterised by k unicriterion flows. Therefore it can be represented as a point in a IR^k space, the axes of which correspond to the different criteria. In general the number k of criteria is larger than 2, so that it is impossible to obtain a direct visual view of the cloud." (Brans and Mareschal 1990) All the unicriterion flows are projected orthogonally on a plane. Whereas $\hat{a}_i$ is the projection of a_i (the alternatives) and γ_j is the protection of the unite vector e_j of the j-axis of IR^k (the criteria).

"By using the Principal Components Analysis technique, it is possible to obtain the plane on which as few information as possible gets lost by projection. For this purpose the expression u'Cv + v'Cv has to be maximised. It can be proved that:" (Brans and Mareschal, 1990)

$$\text{MAX } \{u'\,C\,u + v'\,C\,v\} = \sum_{j=1}^{k} c_{jj}\,\|\varsigma j\|^2 + 2\sum_{j=1}^{k}\ \sum_{s\neq j} c_{js}\,(\varsigma_j, \varsigma_s) = n(\lambda_1 + \lambda_2)$$

C	co-variance matrix of the γ_j= 1, 2,…, k.
c_{jj}	variance of γ_j (criterion j)
c_{js}	covariance between γ_j and γ_s (criteria j and s)
$\|\varsigma j\|$	length of ςj
(ςj, ςs)	scalar product between ςj and ςs
λ_1 and λ_2	the largest and second largest eigenvalues C
u and v	the corresponding eigenvectors (u v)

When visualising the projection of the criteria on the GAIA plane they have different lengths and different orientation. "The length of ςj is therefore a measure of how criterion j differentiates the alternative. The longer ςj, the more criterion j differentiates the alternatives." (Brans and Mareschal 1990) The direction of the criteria is interpreted by the authors in the following way: "Similar criteria have large positive co-variances. When ςj and ςs are orientated approximately in the same direction, the criteria j and s will be strongly correlated and therefore express similar preferences." Conflicting criteria, on the contrary, have negative co-variances and the scalar product will be strongly negative. Consequently, conflicting criteria have ς vectors in opposite direction. Between the supporting and the conflicting criteria are the independent criteria positioned, their co-variances are nearly zero and ς vectors are almost orthogonal.

Cluster analysis

A cluster analysis is applied in this study to gain insights in regard to the similarities (1) between the stakeholder preferences, and, (2) between the ranks of the criteria.

The hierarchical cluster analyses (a) nearest neighbour, (b) furthest neighbour and (c) between groups' linkage are applied. Hierarchical cluster analyses are producing clusters that are hierarchically related in contrast to partition cluster analysis methods. Within the hierarchical cluster analysis methods, the characteristic for agglomerative methods is that they begin with each observation in a separate group. Then the closest two groups are combined and this process continues till the defined number of clusters is reached (in this case 5 clusters). This is in contrast to the divisive methods which are based on dividing groups into hierarchically related sets of cluster.. The general disadvantage from the nearest neighbour method is that it produces "chaining" what can result in long thin clusters. The furthest neighbour method is the opposite of that and leads to spatially compact clusters (“clumping”). The between groups’ linkage has properties that are intermediate to nearest neighbour and furthest neighbour. (Rabe-Hesketh and Everitt 2007)

Sensitivity analysis

In order to test the robustness of the MCA ranking results, several sensitivity analyses are performed. The sensitive analyses, furthermore, allow gaining systematic insights on the particular influence of the impact matrix, the weights, and the preference functions on the final MCA result. Additionally two specific scenario parameters are modulated to investigate the reactivity of the quantitative modelling in the scenarios.

Figure 15 summarises the MCA input components and their overall function. Social preferences are integrated in the form of weightings on the sustainability appraisal criteria and in the form of scenario parameters and storylines in the renewable energy scenarios. Data uncertainty is integrated via preference functions, which are a prerequisite for this particular kind of MCA. Weightings and preference functions have to be defined for every individual criterion. The impact matrix comprises of the scenario impacts along the sustainability appraisal criteria. The final scenario ranking is the result of the pair-wise comparison outranking mechanism of the impact matrix by PROMETHEE.

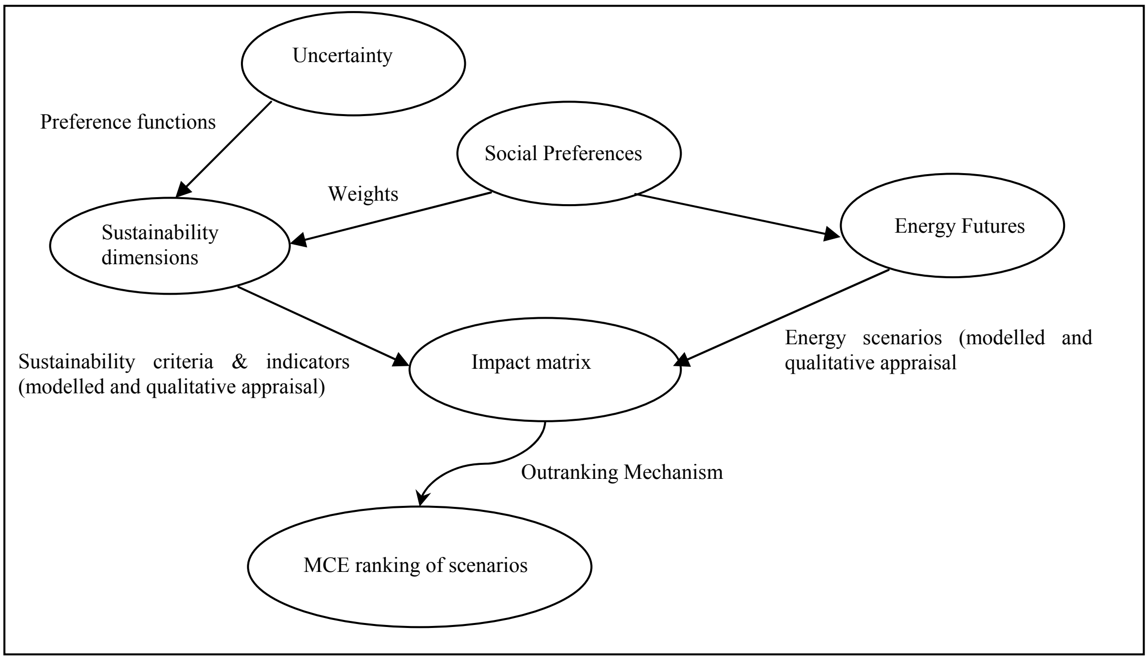

Figure 15. Graphical summary of the basic MCA input components and their overall function

The sensitivity analyses of the results look at the role of the weighting, the preference functions, certain scenario parameters attempting to deepen understanding of the particular influences and consequently their effects on the final scenario ranking.

SA renewable Energy Scenarios

The aim of the sensitivity analysis of the renewable energy scenarios is to investigate the reactivity of the quantitative modelling in the scenarios towards changes of specific scenario parameters. Thereby, the robustness of the quantitative data feeding into the impact matrix is tested. In doing so, insights into the quantitative modelling of scenario parameters can be drawn. In these sensitivity analyses, changes of average impacts across the scenarios A-E are investigated and analysed.

Sensitivity Analysis 1: Small-scale versus large-scale technologies

One of the central scenario parameters is the degree of decentralisation of the future energy systems. This issue had been integrated in the modelling by respective shares of small and large scale technologies. In order to investigate the reactivity of the quantitative modelling towards the scale of technology, the additional capacity of all technologies, which demonstrate a differentiation between small and large scale, are changed to 100% small scale or 100% large scale.

This differentiation is not meaningful for some technologies, e.g. for photovoltaic cells and solar power heat technology. In these cases, emissions are basically proportional to the installed area (m^2), and no scale effects are accounted for. For other technologies scale differentiated data is not available (e.g. for wood gas technologies). Small-scale wood gas technologies are not feasible yet and therefore it is not available in the data set. Unfortunately, there is also no reliable scale differentiated data for biomass cogeneration technologies available in the GEMIS data base. However, a differentiation of scale is conducted for the following technologies: wind technologies (600kW; 1800kW), biogas technologies (500kW; 2000kW), biomass heat technologies (10-100kW; 1000-2000kW), and sewage gas technologies (250kW; 1000kW).

Sensitivity Analysis 2: Primary versus secondary biomass resources

In the second sensitivity analysis of the renewable energy scenarios focuses on the biomass sector and scrutinizes the effects of primary vs. secondary feedstock. This is a key differentiation for the sustainability issues of the biomass energy sector. (Haberl et al. 2003, Madlener et al. 2007) The secondary use of biomass refers to the cascade logic of resource utilisation.

Since biomass production is generally energy intensive, (alike all industrialised growing of agricultural biomass), in certain cases labour intensive (e.g. timber harvest in alpine areas), and results in large anthropogenic pressures on terrestrial ecosystems (e.g. disturbance, fragmentation, fertilization, etc.) the cascade utilization of biomass is one of the most important goals in economic as well as in environmental terms. The general principle of cascaded biomass use can be applied in (a) either the utilization of biomass residues and (b) heat and power co-generation. The latter is a common practice which is highly-subsidised in Austria. In the scenarios A-E the co-generation technologies play an important role and are applied in all scenarios with a high growth rate.

Biomass residues are used to a large extent already and additional potentials for renewable heat and power generation are being explored[83]. In the present energy scenarios, a maximum additional dry biomass residue potential of 4.500GWh is assumed. This assumption is based on the biomass scenarios developed by Haberl et al which is a conservative estimate, taking into account growing demand of other sectors. (Haberl et al. 2003) Depending on the storyline of the scenarios, a varying fraction of this potential is realized in 2020. The qualitative scenario parameter ‘system’s efficiency’ is directly linked to the degree of realization of biomass residues in the scenarios.

In the present sensitivity analysis, in one case it was assumed that all biomass resources stem from primary sources, in a contrasting case that all biomass is secondary. Both cases are hypothetical extreme positions which would not be feasible in the real world due to limited

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[83] The main suppliers for biomass residues are the wood industry and the paper and pulp industry (black liquor). Active demand is in the paper and pulp industry itself, the furniture industry, the composite panel industry, and, the energy sector in form of wood chips. The additional potential for dry biomass residues is therefore very limited and only a shift towards the energy sector possible, which will create tensions and resources problems in other sectors. The growing biogas sector is also an additional recipient but in a sense not as much conflicting since the demand for wet biomass is lower.

resource potentials and economic reasons. Nevertheless, these assumptions allow for further insights into the reactivity of the quantitative modelling. The differentiation between primary and secondary biomass resources could be applied for the following technologies: Biogas small scale and Biogas large scale, Biomass cogeneration, and Biomass community and district heating. According to the data base GEMIS, the wood gas technology uses only secondary biomass resources, whereas the biomass technologies for power generation are assumed to run on primary biomass resources only. The small-scale biomass heat technologies, such as pellet furnaces, are based in this application only on primary biomass resources. This is due to the homogenous fuel demand of most small-scale heating technologies, which hampers the usage of the relatively inhomogeneous secondary biomass.

SA Weights

The key questions for the sensitivity analyses performed to investigate the effects of the weighting sets are: (1) what is the overall effect of the weighting sets on the final scenario rankings? And (2) how can the social preferences be integrated via weighting?

To understand the effect of the weighting sets on the final scenario ranking, the first analysis examines the final scenario ranking without any effect of weightings. This is operationalised by setting all the weights equal.

In a second analysis, the effect of weightings is investigated by putting high weightings on the different sustainability appraisal dimensions. To reveal a pronounced change of the scenario rankings, the weighting on each appraisal dimension is set to 70%. This modulation is performed for all 16 stakeholder scenario rankings. It should be noted that this weighting represents an extremely biased preference that is chosen for purpose of studying the internal structure of the MCA.

SA Preference functions

The preference functions basically have a powerful role in the MCA because they define how the impact matrix is transformed according to the preference matrix. The preference functions are defined individually for every single criterion. This sensitivity aims at analysing the effects of the preference functions on the final scenario ranking results, and to reflect on how data uncertainty of individual criteria can be integrated via the preference functions.

Three sensitivity analyses of the preference functions are preformed (SA 1 'PF_Usual', SA 2 'PF_Higher', SA 3 'PF_Level' ; see Table 10 for an overview). The modulations affected qualitative and quantitative criteria differently in the different analyses.

SA	PF of quantitative indicators	PF of qualitative indicators	Expected of Change
Standard PF	All Linear (q: 6, 10, 10, 10, 10, 10, 30, 30, 30, 30, 30, 10) (p: 60)	All V-Shape (p: 2, 4)	Standard
SA 1 'PF_Usual'	All Usual	All Usual	Reacts at smallest difference with full preference and then no further change; totally insensitive to different values → very weak discrimination. Uncertainty taken into account: very low
SA 2 'PF_Higher'	All Linear (q: 10, 15, 15, 15, 20, 20, 40, 40, 40, 40, 40, 15) (p: 60)	All Linear (q: 1) (p: 2, 4)	Reacts later in the quantitative and qualitative indicators to data differences with preference than in Standard; Uncertainty taken into account: higher. Intervals in qualitative indicators are further reduced.
SA 3 'PF_Level'	All Linear (q: 6, 10, 10, 10, 10, 10, 30, 30, 30, 30, 30, 10) (p: 60)	All Level (q:0.5) (p: 1.5)	PF only for qualitative criteria changed towards a reduction of qualitative intervals for translation into preferences. Effect in between Standard and PF_higher. Uncertainty taken into account: higher, only in the qualitative criteria

Table 10. Overview of sensitivity analysis of the preference functions summarizing the manipulations of the preference functions including the altering definitions of the threshold for the quantitative and qualitative indicators and summarizing the expected change

Results and Sensitivity Analysis

This chapter presents the results of the participatory scenario-building process and the results of the MCA. For a clear presentation, the results are divided into three subchapters: (a) renewable energy scenarios, (b) Indicators and evaluation matrix, and (c) MCA ranking of the renewable scenarios.

Detailed sensitivity analyses are performed to understand the impacts and interplays of the various information inputs on the final results. Furthermore, the overall robustness of the results is scrutinized. Sensitivity analyses are carried out according to: (a) the renewable energy scenarios, (b) the indicators and evaluation matrix, (c) the weighting, and, (d) the preference functions.

Results

The focus on a single case study allows for in-depth analysis of the results. The aim is to generate insights into the specific methodology and also to critically reflect upon the methodology itself. Based on a systemic understanding of sustainable development, the resulting key challenges are multi-dimensionality, uncertainty and social preferences. The systemic understanding of evolving energy systems requires a solid awareness of technological change as well as the underlying socio-economic and environmental mechanisms. The focus of this study is to determine in which ways this methodology can reveal more information regarding these aspects in contrast to comparable studies in Austria.

Renewable energy scenarios

In the participatory scenario-building workshop (see case-study presentation), the scenario parameters, the scenario storylines and consequently the final set of scenarios have been discussed and decided upon. Four scenario parameters were defined and five scenario storylines along with their key technologies were selected by the stakeholders to be modelled and evaluated in further detailed scenarios. The scenarios were commonly understood as descriptions of the variable renewable energy profiles of Austria in 2020, which aim to have an optimistic-realistic character in order to increase future options. The overall increase in capacity of renewables till 2020 was a result of the modelling exercise, mainly determined by the definition of particular key technologies and their respective growth potentials till 2020.

The first scenario parameter is the time frame of the underlying decision. Depending on the time frame, short term or long term, distinct strategies that entail particular renewable energy technologies appear reasonable. The second scenario parameter describes what kinds of innovations are desirable, based on a gradient between systems innovations and individual technology innovation. The third scenario parameter addresses the institutional changes that are needed for unfolding the scenarios. Finally, the fourth scenario parameter points to the degree of decentralisation of the renewable energy system in 2020. As discussed in more detail in the case study presentation, the scenario parameters were changed fundamentally in the scenario workshop.

The following five scenario storylines were selected to be translated into a quantitative technology profile and modelled as forecasting scenarios by the researcher:

Scenario A: "Fast and known"

In this scenario, the main logic is a short-term optimisation of available resources and renewable capacity building in established ways. The focus is primarily on technologies that exhibit low specific investment costs and promise rapid capacity expansion. Existing institutions are seen as sufficient since known pathways are used. Individual technology innovation is the centre of attention, since there is no long-term thinking of a systems change being inherent but an economic rationale of harvesting 'low hanging fruits' and of gaining a quick reduction of carbon emissions. By trend, large-scale technologies are preferred in order to gain capacities quickly. (Figure 16)

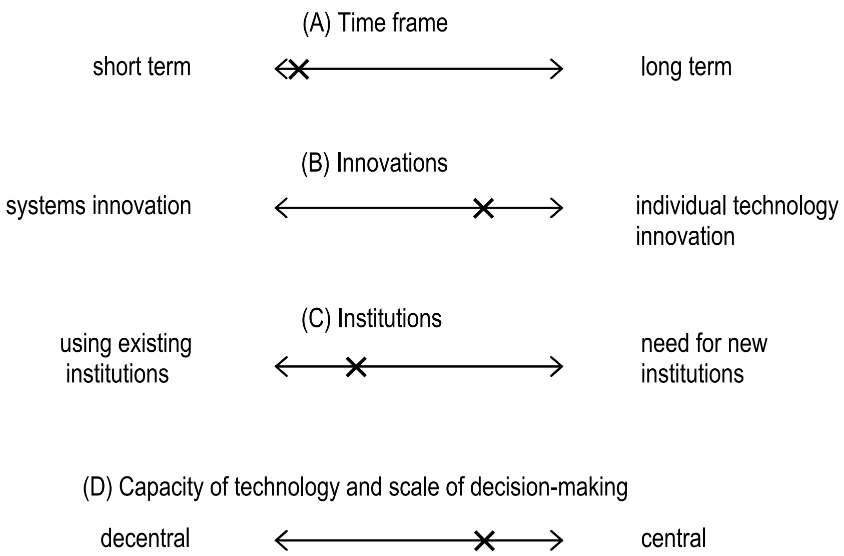


Figure 16. Characterization of Scenario A

Scenario A is the most short-term scenario among the alternatives. Austria's known and well-established technologies such as biomass and wind power have increased markedly, as well as solar thermal and sewage gas plants, both offering a very easy and reasonably inexpensive source of energy. The use of biomass resources in particular is carried out in such a way that the domestic potentials of biomass residue are more or less self sufficient (i.e. no need for large biomass imports).

Key technologies: solar thermal, biomass (heat and CHP only), wind power, sewage gas.

The enforced new construction of low-energy buildings is an efficiency mean that accompanies the scenario storyline well.

Scenario B: "Extension of competitive advantage"

The main strategy in this scenario is to enforce those technologies in Austria which currently have the highest technology export success. It is therefore an economically-driven strategic scenario combining trade policy aims and, energy and environmental policy aims.

Austria is a successful technology exporter for certain renewable energy technologies such as solar thermal plates, biomass district heating plants, rotor components for wind turbines, etc. Offering incentives to develop those technologies for the domestic market provides certain competitive advantages to domestic producers of the technology on the world market. The important goal is to retain technological leadership. In this scenario, the immediate economic potentials of a change in the energy system are the main focus. The reduction of CO2 emissions is not primary in this mindset but a generally proactive environmental policy might be a supportive image campaigning for the technology producers.

The time frame is still rather short term in the sense that only existing trade advantages are on the radar rather than a long-term investment in technology leadership in less mature technologies. The technical improvement of the individual technologies, such as increased efficiency, plays a key role in the innovation policy. By contrast, systems innovations can not be traded and therefore do not create a profitable competitive advantage. (Figure 17)

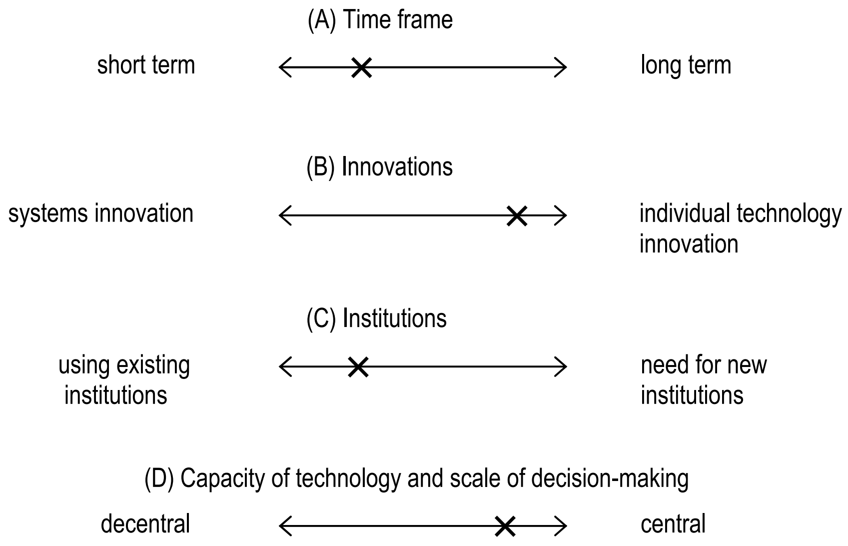


Figure 17. Characterization of Scenario B

The existing institutions are sufficient and already well adapted to trade policy. The scenario is understood to follow a rather central logic in the sense that trade policy is a matter of federal policy, even though the key technologies are of small scale.

Key technologies: community-based biomass cogeneration (CHP), small hydropower plants, small-scale biomass heat production, solar thermal power, wind power, geothermal power

Edificial efficiency means for this scenario could involve passive housing, since Austria has a well-established passive house domestic and export market.

Scenario C: "Investments into the future"

Scenario C concerns a long-term investment strategy which takes the necessity of a structural change of the energy system into account. In this concept, it is obvious that extensive investments have to be made now in order to develop and establish new production and consumption structures in the future, ultimately building a new and more sustainable energy system. Great importance is placed on R&D and innovation policy is a characteristic of this scenario. In this context, the decentralised generation of electricity is seen as a promising development, opening up the strict role division between energy producer and consumer towards a more heterogeneous system with a more aware and responsible handling of energy. This scenario is characterised by the highest degree of systems innovation. Synergies are used wherever possible, such as cascade energy use or the local combination of energy production and energy use (multifunctional energy centres). This focus does require new institutions to give structures and incentives for developing such intelligent energy systems. (Figure 18)

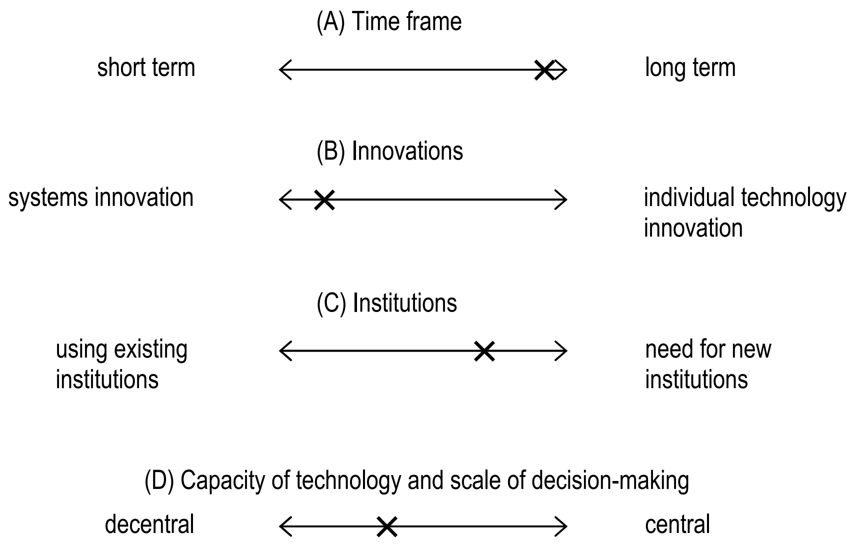


Figure 18. Characterization of Scenario C

The promotion of capital-intensive but at the same time promising technologies (e.g. photovoltaic, PV) are at the technological centre point. Growing electricity demand can only be met partially by the slowly increasing contribution of renewables, but trend-setting structural investments in building stock are being made (e.g. equipping public buildings with PV systems).

Key technologies: PV (primarily on rooftops and façades), biogas feed-in, geothermal energy

In this mind set, energy conservation due to efficient energy supply systems, more efficient energy infrastructure, passive and zero energy buildings (new constructions), and the renovation of old building stock, plays a very important role.

Scenario D: “Extensive use of biomass”

The focal point in this scenario is a far-reaching utilisation of biomass resources from the agriculture and forestry sectors. In this view, Austria is seen as a biomass-abundant country with large unused potentials and a long tradition of biomass utilisation. An additional feature of this scenario is the expansion of the market, which would create positive employment perspectives for Austrian agriculture. To a certain extent, this scenario represents a conservative Austrian environmentalist mind-set - that seeks to combine agricultural, agroeconomic and environmental objectives. Energy plantations are regarded as an important future strategy. The realisation of a biomass-based energy system shows, though, the inevitable need to import biomass. Even today, large amounts of timber or oil bearing fruits are imported from e.g. East European countries, mainly due to economic reasons. (Figure 19)

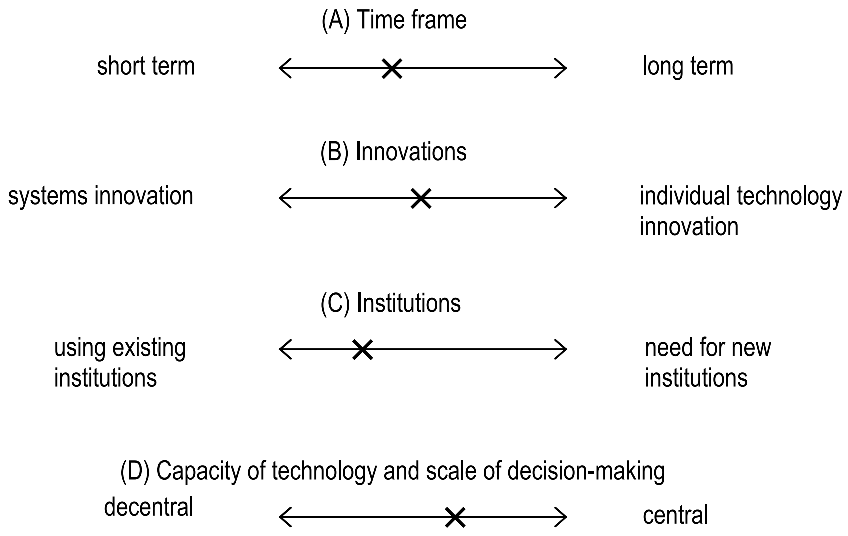


Figure 19. Characterization of Scenario D

Scenario D is seen as a medium-term solution since the natural potentials and especially the economic potentials are not sufficient within Austria, or even, for that matter, within the EU in the long run. Biomass represents a land-intensive energy source that is in direct competition with alternative area needs, e.g. for natural habitats and for the production of comestible goods. Regarding the type of innovation, scenario D discriminates neither against systems innovation nor individual technology innovations and takes a neutral position. The existing institutions are to a large extent sufficient based on the agricultural and forestry interests groups and regulations. To achieve large-scale capacity, this scenario strives toward large-scale technologies and therefore fits into the structure of agriculture production today.

Key technologies: biomass combustion and gasification (esp. CHP), where the biomass used also stems from dedicated energy plantations and from imports, biogas (esp. CHP), solar thermal, and wind farms.

Since this scenario is mostly characterised by a certain resource focus, no specific efficiency mean was associated with it.

Scenario E: “Large impact in small-scale use”

Scenario E envisages a considerable structural change of the energy system towards extensively decentralised energy generation modes. Local initiatives and the local availability of resources govern the concrete development of renewable energy technologies. The traditional split between energy producers and energy consumers becomes obsolete. Single households are increasingly involved in making decisions regarding the source of heat and electricity. They are also often owners or co-owners of the power plant. Within this mindset, there is the attending assumption that energy is consumed in more responsible ways. Therefore, one can surmise that decentralised generation gives more incentives for energy saving. This scenario offers more individual, local or regional independence regarding energy-related matters and decisions.

The time frame of scenario E is long term. Time is needed to adapt infrastructures to a decentralised energy system and to build up new institutions (new policy incentives, establishing decentralised decision modes, organising feed-in regulations) and build infrastructure which is compatible with a decentralised generation mode, etc. (Figure 20)

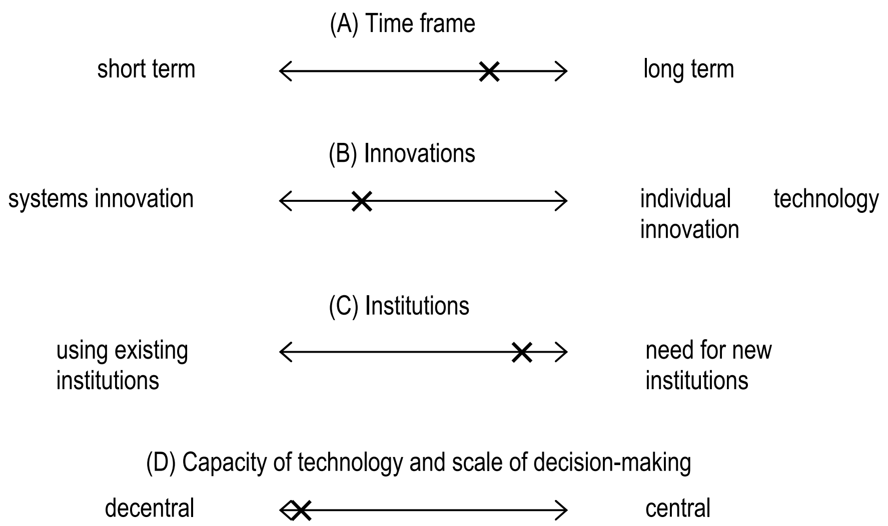


Figure 20. Characterization of Scenario E

The scenario aims towards an increase in systems innovation, which is an important aspect to consider when optimising the small energy supply units and responding to peak demand. It is the most decentralised renewable energy scenario of all those considered.

Key technologies: biomass (individual and communal CHP plants with district heating), biogas (single systems, CHP), heat pumps, wind power, solar thermal, photovoltaic

The building of passive houses is also part of this scenario, and is seen as a necessary and applicable edificial energy efficiency mean.

An overview of the qualitative descriptions of the scenarios can be found in the appendix Table A. 4.

Absolute renewables capacity increase till 2020

One of the main scenario results is the absolute realised additional capacity of renewable energy supply in 2020 (see Table 11). In the following, the capacity increase of the scenarios is described in absolute terms as an increase since the reference year 2002 according to the IEA report of 2003 International Energy Agency 2003 and in contrast to a "business as usual" scenario modelled till 2020.

	Scenario A "Fast and Known"	Scenario B "Extension of Competitive Advantage"	Scenario C "Investments into the Future"	Scenario D "Extensive Use of Biomass"	Scenario E "Large Impact in Small-Scale Use"
Amount of renewable energy in 2002 (PJ/a)			125		
Additional electricity production from renewables (PJ/a) in 2020	32.8	32.2	28.4	33.8	30.1
Additional heat production from renewables (PJ/a) in 2020	66.3	61.5	34.8	93.4	64.1
Total additional amount in 2020[1] (PJ/a)	99	93	63	127	94
Total amount of renewable energy in 2020 (PJ/a)	224.1	218.7	188.2	252.2	219.2
Total increase in renewable energy use from 2002 to 2020 (%)	79%	75%	50%	101%	75%
Total increase in renewable energy use from 2002 - 2020, compared to a linear increase (BAU) 2002 - 2020[2] (%)	64%	55%	5%	111%	56%

Table 11. Additional capacity of renewable energy supply in 2020 according to the scenario results. [1] This additional amount of renewables in 2020 excludes additional large hydropower plants. [2] The BAU scenario assumes a linear growth trend based on all renewable energy technology capacities till 2020 and amounts to an additional 60 PJ/a, the base of this calculation.

The BAU scenario assumes a linear growth trend for all renewable energy technology capacities till 2020. Additionally, Table 11 presents a differentiation between heat and electricity supply increase. A detailed breakdown of the results to the individual technologies can be found in the Appendix (Table A.3).

All the scenarios depict a significant increase of renewables. The additional electricity generation by renewable energy technologies in 2020 varies within the scenarios between 28.4 and 33.8 PJ/a, whereas the additional heat generation lies at between 43.8 and 93.4 PJ/a. In comparison, the amount of renewable energy supply in the base year 2002 was 125 PJ/a.

Scenario D "Extensive use of biomass" reaches by far the highest increase of renewables by 2020, namely a doubling of the renewable energy use in 2002. This increased renewable energy capacity is compared to the BAU scenario in 2020, and is also more than twice as extensive.

With an additional supply of 63 PJ/a, approximately 50% of the amount of renewable energy in 2002, the smallest increase in renewables can be seen in scenario C "Investment into the future". This is only half as much as in the maximum found in scenario D, which delivers an additional 127 PJ/a. The three other scenarios show a rather similar increase of around 75% compared to the BAU scenario 2020 which offers an additional capacity of 93-99PJ/a. The total increases of scenarios A-E are between 5% (scenario C) and 111% (scenario D) larger than the linear increase in the BAU scenario.

All scenarios have a rather similar increase in electricity by 2020 (plus 28.4 – 32.8 PJ). Hence, the more drastic differences in the total capacity increase by 2020 stem mainly from the renewable heat generation potential that is achieved.

Scenario technology profiles

The detailed scenario technology profiles show that of all the scenarios, the major contributor of renewable heat generation is biomass combustion (Figure 21) The absolute contribution varies across the five scenarios, as does the specificity of the combustion technology (CHP, etc.), the load, and the origin of the biomass (energy plantations versus biomass residues). The second highest contribution to the renewable heat supply for all the scenarios is provided by additional solar thermal installations. In scenario C "Investment into the future", the biogas and sewage gas technologies play a particularly noticeable role as future technologies with high synergy potentials. In comparison with the technology profile of the BAU scenario, the share of non-biomass combustion technologies is larger in all five scenarios. This requires an overall increase of technological diversity compared to business as usual.

The contribution of biomass in heat-only and cogeneration systems is by far the largest, ranging from 17.8 to 62.7 PJ and 3.6 to 10.8 PJ in scenarios C and D, respectively, followed by solar thermal, which contributes between 4.9 PJ (Scenario C) to 13.6 PJ (all other scenarios) (see Figure 21). In Scenarios B and C, geothermal heat is also assumed to make a significant contribution of 6.3 PJ (and only 2.5 PJ in the other scenarios), and heat pumps are assumed to contribute 2.5 PJ in Scenario E. The remaining other renewable energy technologies covered in this study, i.e. the heat provided by biogas and sewage gas cogeneration, provide less than 1 PJ.

The electricity generating technology profiles of the scenarios generally show a more evenly distributed technology mix (Figure 22). Small-scale hydropower represents a large share in all scenarios contributing almost half of the additional capacity. In contrast to the BAU scenario, it is remarkable that all the scenarios have a larger share of wind power. This indicates that the growth rate of wind power has been more optimistic in all the scenarios than in BAU. Scenarios A, B and E show the greatest wind power increase, though, differing in the scale of wind turbines. Scenarios C and E are characterised by a profound increase in PV. The "Extensive use of biomass" scenario stands out in this context by having a rather high share of biomass electricity production. The corresponding plots in Figure 22 for renewable electricity show that the additional contribution of small-scale hydropower is slightly below 7.2 PJ/a (8.5 PJ/a in Scenario B -- "Extension of Competitive Advantage") and that the contribution from wind power ranges from 5.9 PJ/a (Scenario D) to almost 14.4 PJ/a (Scenarios A and B). PV is assumed to only contribute markedly in Scenarios C and E, with roughly 7.2 PJ/a and 1.8 PJ/a, respectively. Electricity from biomass cogeneration provides between 3.2 PJ/a (Scenario C) to 9.8 PJ/a (Scenarios A and D), while electricity-only generation from biomass, which is highly contested because of its low conversion efficiency, is shown to only contribute significantly in scenario D (6.1 PJ/a), and less so in Scenarios C (1.6 PJ/a), B (1.0 PJ/a), and A and E (0.7 PJ/a). Biogas cogeneration is assumed to contribute about 4.0 PJ/a in Scenario D and 1.3 PJ/a in Scenario C. The contribution of geothermal electricity is always less than 0.4 PJ/a (between 0.04 and 0.2 PJ/a) and that of sewage gas around 0.0.2PJ/a (with the exception of Scenario A, where it contributes 0.4 PJ/a).

Figure 21. Scenario technology profiles: heat energy in PJ/a from renewables. Right side: absolute numbers, left side: additional capacity compared to 2002.

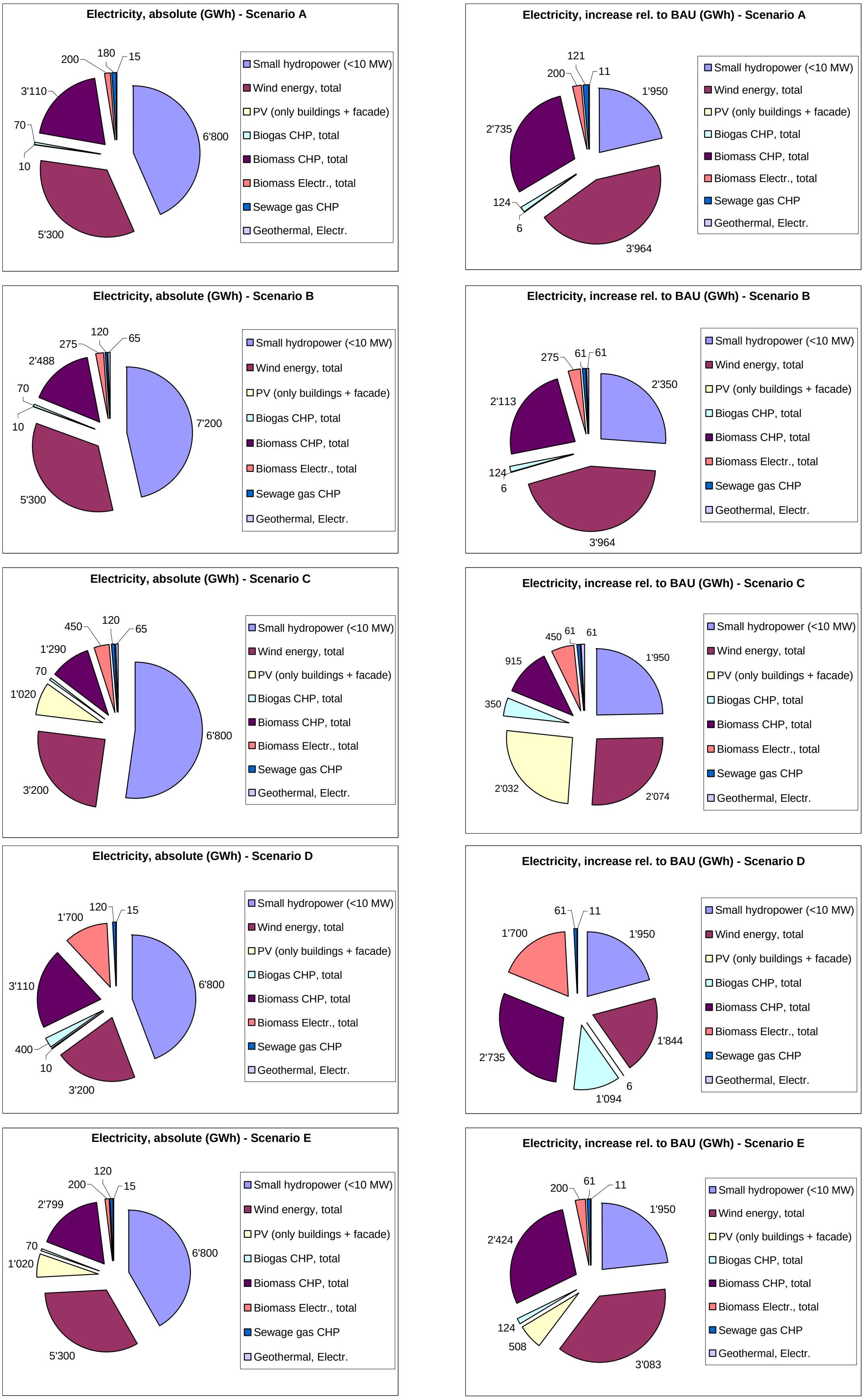


Figure 22. Scenario technology profiles: electricity in GWh/a from renewables (1 GWh = 3.6 TJ = 0.0036 PJ). Right side: absolute numbers, left side: additional capacity compared to 2002

Indicators impact matrix

The impact matrix is comprised of 17 qualitative and quantitative criteria built by 24 indicators evaluating the sustainability of the scenarios. The set of indicators are a product of the participatory stakeholder process. All the indicators are measured per TJ, so they can give an impact profile per energy unit independent from the absolute capacity increase. This unit was chosen in order to best compare the different renewable energy technologies. It clearly demonstrates that renewable futures are not equally beneficial concerning all the sustainability dimensions (see appendix A. 5 for the impact matrix). The differing capability to increase renewable energy capacity till 2020 is a scenario result and as such is presented there.

The sustainability criteria are put into four analytical groups: environmental, economic, social, and technological criteria. The grouping is based on: (a) the common dimensions of sustainable development (environmental, economic, and social dimension), and (b) an additional category of technological criteria which addresses the technological system's dimension. The groups are of similar size (3-5 criteria) whereas the economic criteria group is smallest. In the following, the data structure of the impact matrix is presented and key underlying assumptions are addressed.

Environmental criteria

All of the environmental criteria are mainly operationalised by quantitative indicators. The criterion Ecological Justice, with the indicator sealed area equivalent, is put into qualitative intervals 5- 1 (high- low) and is based on underlying appraisals of the specific area demand.

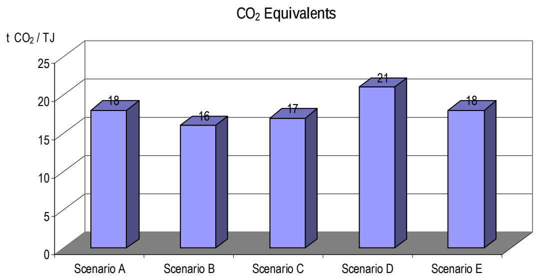
The highest amount of CO_2 Equivalents per energy unit that accrue in the entire life cycle of the energy service is in the specific technology combination of the scenario D with 21t/ TJ. That is followed by scenarios A, E, and C, whereas the CO_2 equivalents are lowest in scenario B. The most likely explanation for the high CO_2 equivalents emissions in scenario D is the associated transport, the energy intensive fertilisation processes in industrialised agricultural techniques, and the combustion processes which are entirely captured in the life-cycle data. However, these four scenarios have rather similar CO_2 equivalent quantities per TJ (between 16-18 t/ TJ) (see Figure 23).

Due to the inevitably associated combustion processes of biomass applications, scenario D performs worst according to all the indicators describing the criterion Air Quality. In contrast to wind, hydro, and sun power utilisation, biomass technologies use combustion engines and consequently have emission issues. SO_2 Equivalents, Tropospheric Ozone, and Particulate

Matter impacts have a similar distribution across the scenarios. Scenario C performs by far best in all the Air Quality indicators. (see Figure 23 for details)

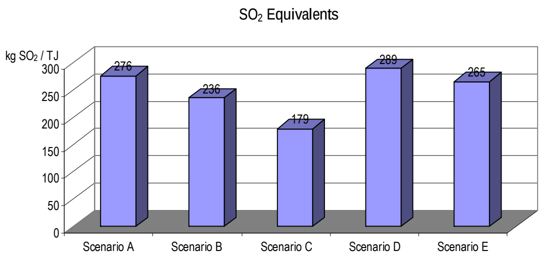
Criterion: Climate Change Properties

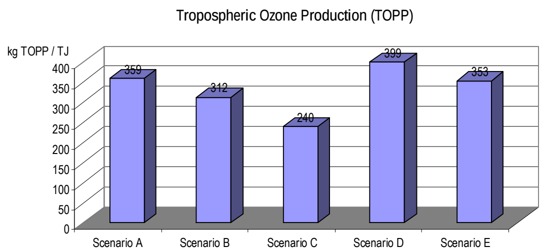
Indicator: CO_2 Equivalents

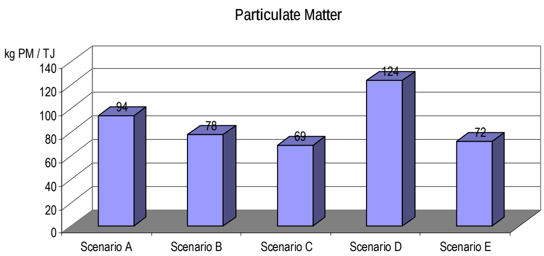


Criterion: Air Quality

Indicator: SO_2 Equivalents, Tropospheric Ozone, Particulate Matter

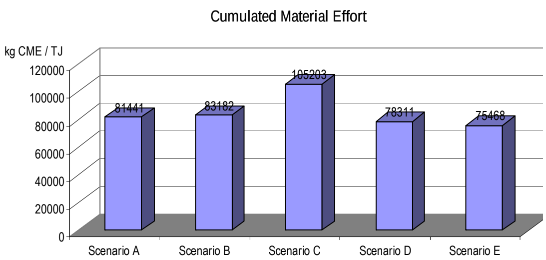






Criterion: Rational Use of Resources

Indicator: Cumulated Material Effort (CME) and Cumulated Energy Effort (CEE)



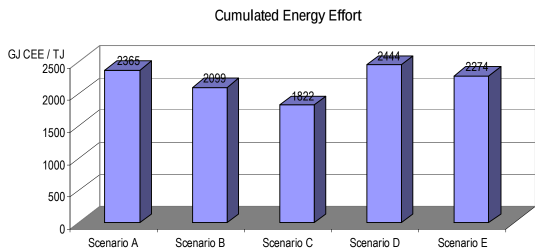


Figure 23. Comparison of the performance of the renewable energy scenarios A-E across the environmental criteria Climate Change, Air quality and Rational Resource Use, and their specific indicators

Cumulative Energy Effort basically follows the impact pattern known from the Air Quality indicators in the sense that scenario D performs worst (high Cumulative Energy Effort) and scenario C has the lowest Cumulative Energy Effort. The Cumulative Material Effort shows the opposite picture, meaning that scenario C performs worst and scenario D is reasonably good. (see Figure 23 for details) The reason behind the high impacts of scenario C might be related to the fact that photovoltaic technology requires material-intensive mining of the silicates, which is pro rata accounted for in the GEMIS data base following the life-cycle concept.

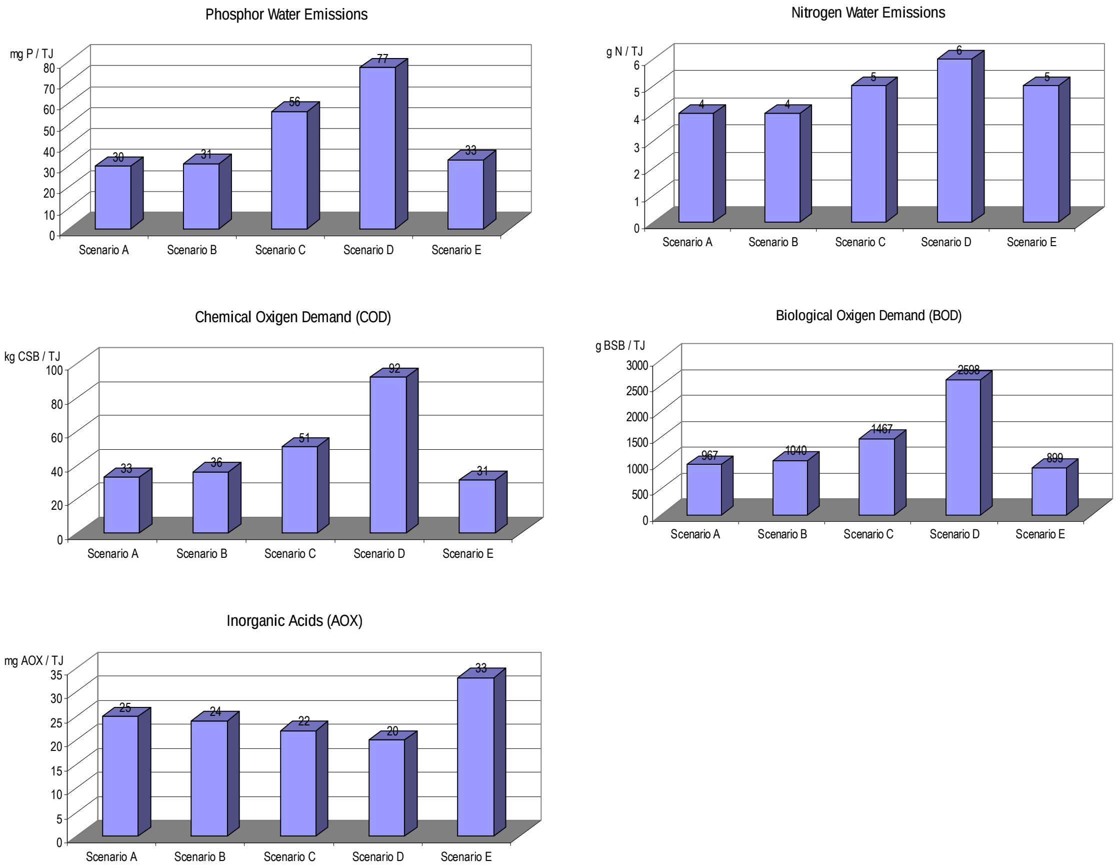
The Water Quality criterion is composed of five environmental indicators (Figure 24): Phosphorus, Nitrogen, Inorganic Acids and Biological (BOD) and Chemical Oxygen Demand (COD). The indicators Phosphorus, Nitrogen, and Biological and Chemical Oxygen Demand follow a similar pattern to the environmental indicators presented earlier, in the particular sense that scenario D causes by far the highest water quality impacts. In particular, Phosphorus impacts and BOD and COD are 2-3 times higher in scenario D compared to the best performing scenario. Scenario E has the best performance in terms of water quality. . The indicator Inorganic Acids performs conversely and is best in scenario D. (Figure 24)

The data availability for the Water Quality indicators is limited and incomplete, hence very high uncertainty is accounted for in the evaluation. Available data for the entire category of biomass technologies present in the GEMIS data base is poor, and no Water Quality data is yet available for recent wood gas technologies. Consequently, the apparent patterns in the impact matrix have to be handled with great care when making interpretations.

The structure of the impact matrix according to the criterion Ecological Justice, represented by the indicator Sealed Area Equivalent, is similar to most other indicators of the environmental evaluation dimension in the sense that scenario D performs badly and scenario C performs well. (Figure 24) The highest negative impacts accounted for in this indicator are, on the one hand, the sealed areas and on the other hand the arable crop land areas. (See Methods chapter, indicators discussion for more details) Those scenarios with high capacities in energy crops and/or in hydropower (high sealed area demand) perform badly in this indicator, as do scenarios D and A. Since the photovoltaic cells are only located on roofs and facades, other building areas are not accounted for in the sealed area and therefore show no negative impact.

Criterion: Water Quality

Indicators: Phosphorus Water Emissions, Nitrogen Water Emissions, Inorganic Acids (AOX), Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD)



Criterion: Ecological Justice

Indicator: Sealed Area Equivalent

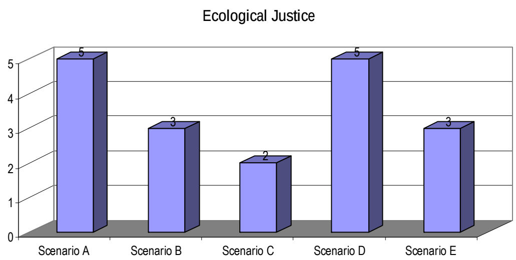


Figure 24. Comparison of the performance of the renewable energy scenarios A-E across the environmental criteria Water quality and Ecological justice, and their specific indicators; Ecological Justice with the indicator Sealed Area Equivalents is described in qualitative intervals: 5…high, 4…rather high, 3…medium, 2…rather low, 1…low

Social sustainability criteria

The criteria which represent the social sustainability dimension in the appraisal are all of a qualitative nature, and the specific scenario impacts are derived from expert interviews. Two expert interviews[84] were performed to appraise the scenarios according to the social criteria and clarify underlying assumptions. The criteria are in 3- or 5-step qualitative intervals according to the specific uncertainty and the particular possibility of estimating differentiated impacts with respect to the information made available about the scenarios at hand.

The criterion Quality of Landscape is differentiated in three qualitative intervals and performs best in the scenarios E, C, and B. (Figure 25) According to the interviewee, the main factor for the impact on the quality of landscape is essentially the size of the plants, correlating with the degree of centralisation of the energy systems. In general terms, it can be assumed that the larger a plant is the more it stands out from the landscape and the more the aesthetic perception is disturbed. This is, of course, an oversimplification albeit one which allowed an approximation with the scenarios at hand. The bad performance of scenario A is also significant, and is due to the particular combination of large-scale biomass and large-scale wind power that is installed in this scenario till 2020.

The degree of Regional Self Determinacy is differentiated in five qualitative intervals and follows in general terms the parameter of decentralisation. Hence, it is highest in scenario E and second highest in scenario C. The worst performance is in scenario B, which can be explained by the export orientation in this scenario. The underlying assumption is that external commitments in the form of contracts and trade relationships to other countries, firms etc. reduces the degree of regional self determinacy. (Figure 25)

Scenario E is appraised highest according to the criterion Social Cohesion. This social criterion correlates strongly to the degree of decentralisation. According to the concrete definition of the criterion, understanding social cohesion as social capital and the active engagement of civil society on the regional level, the degree of decentralisation of energy systems enables potential

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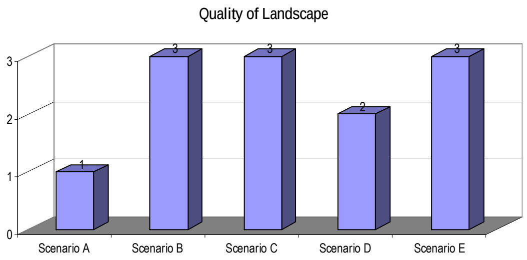
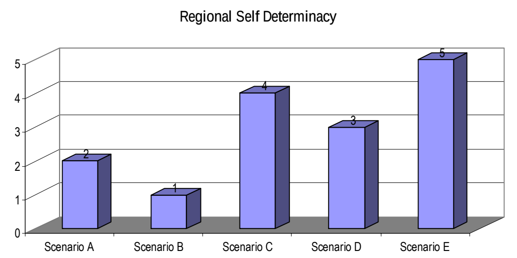
[84] Dr. Beate Littig, Sociologist, IHS Vienna, Personal Interview Jan 2006; appraisal of the criteria: regional self determinacy, social cohesion, social justice, and employment

Dr. Reinhard Madlener, Energy Economist, CEPE, ETH Zurich, Telephone Interview Dec 2005; appraisal of criteria: landscape quality, noise, effect on public budget, diversity of technology, security of supply, import dependency, technological leadership social cohesion. Least encouraging for social cohesion are scenarios A and B, which are the most centralised scenarios. (Figure 25)

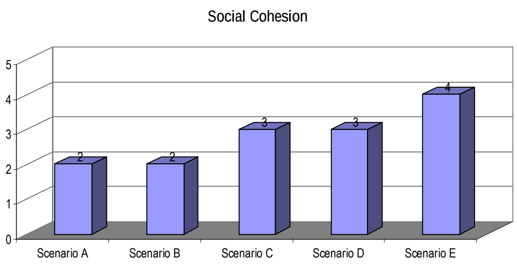
Criterion & indicator: Quality of Landscape



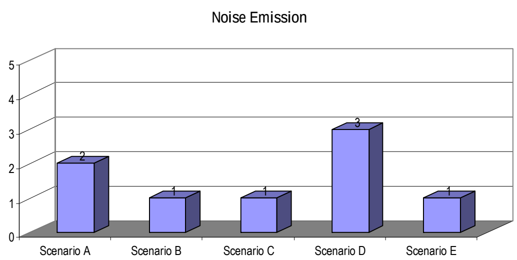
Criterion& indicator: Regional Self Determinacy



Criterion & indicator: Social Cohesion



Criterion & indicator: Noise Emission



Criterion & indicator: Social Justice

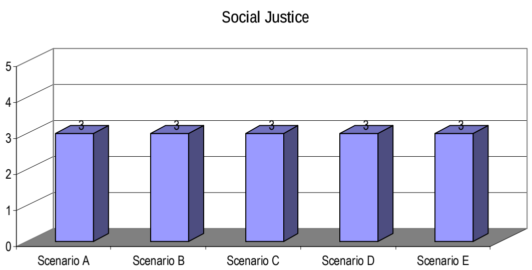


Figure 25. Comparison of the performance of the different scenarios across the social criteria. All the social criteria were appraised with qualitative intervals (1- 2- 3; low- medium- high or 1- 2- 3- 4- 5, low- rather low- medium- rather high- high)

The criterion Noise is appraised in three qualitative intervals and performs worst in scenario D (Figure 25). This high noise impact is due the combustion engines necessary for biomass technologies.

Both interviewees made clear that the degree of Social Justice can not be judged from the information available in the scenarios. The indicator was set equal for the scenarios and has therefore no impact on the ranking result (see Methods chapter for further details).

Economic sustainability criteria

The economic dimension of more sustainable energy systems was appraised with three indicators: Costs, Brut Employment Effect, and, Macro Economic Costs. The latter two were appraised in expert interviews whereas the Costs were modelled based on the GEMIS data base. The economic criteria are the smallest group of sustainability criteria.

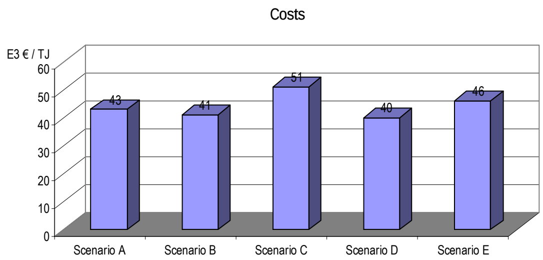
The indicator Costs operationalising the criterion Economic Efficiency is based on quantitative data modelling. The differences between all of the scenarios are not very large (roughly between 40,000 and 50,000 € per TJ; Figure 26). Scenario D is associated with the least costs, taking into account investment costs and variable costs (see Methods chapter for detailed criteria definition). In contrast, scenario C creates the highest costs, which is not surprising since photovoltaic installations are currently (still) expensive per energy unit.

A correlation to the degree of decentralisation also underlies the appraisal of the Brut Employment Effect. Hence, scenarios E and C have the highest additional employment due to production, supervision, and service of a great amount of small-scale technologies. (Figure 26) It is assumed that the work intensity is higher in decentralised energy systems. Not as much additional employment is required for growing energy crops, as in scenario D, since the industrialised agriculture practises are not labour intensive.

The macro-economic criterion Effect on Public Budget considers the public spending necessary for the installation of future energy systems. It does not include income into the exchequer. The indicator Macroeconomic Costs is appraised in five qualitative intervals, and correlates directly with the maturity of the applied technologies and the consequential need for governmental subsidies as well as the need for new institutions. The highest public spending is appraised for scenario C, following by scenario E. (Figure 26)

Criterion: Economic Efficiency

Indicators: Costs €/ TJ



Criterion: Employment

Indicator: Brut Employment Effect

Criterion: Effect on Public Budget

Indicator: Macroeconomic Costs

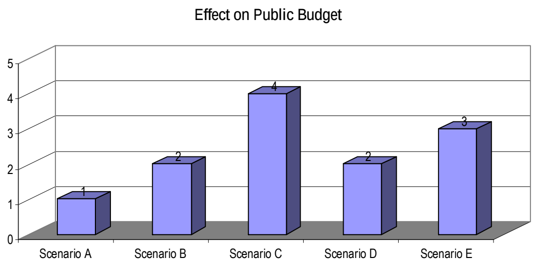


Figure 26. Presentation of the performance of the five renewable energy scenarios across the economic criteria and indicators, some of the economic criteria are evaluated with qualitative intervals (1- 2- 3 standing for: low- medium- high and 1- 2- 3- 4- 5 standing for: low- rather low- medium- rather high- high)

Technological sustainability dimension

The fourth dimension, the technological systems dimension, introduced in this specific case to judge the long-term sustainability of the energy systems, is comprised of four criteria. The scenarios were appraised in an expert interview and their performance presented in a three qualitative intervals.

The scenarios B, C, and E perform best in the indicator Diversity of Technologies. (Figure 27) In those scenarios the broadest variety of technologies are realised. Scenario D, which per se focuses on one renewable resource, biomass, performs worst.

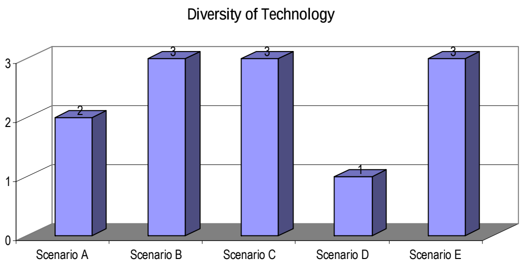
According to the criterion Import Independency, only one scenario is differentiated to create more import independency and that is scenario C, the long-term innovation scenario. (Figure 27) The optimisation of systems efficiency and decentralisation allows for the most efficient use of resources and offers a fair chance to deal with the future domestic electricity and heat demand without increasing the import dependencies. The biomass scenario D, based in principle on a domestic resource, is assumed to create a biomass import dependency in the long run, and therefore demonstrates average performance.

Regarding Technological Leadership, scenario C is outstanding. (Figure 27) It is based on an enhanced R&D policy focusing on future technological leadership. Scenario B is ranked second as it aims at extending the present competitive advantage in trading leading renewable technology and technology components, but lacks a long-term strategy.

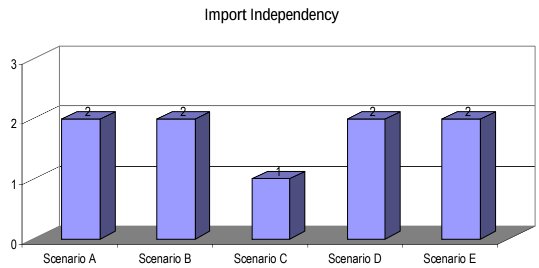
Scenario E, the decentralisation scenario, performs best in the sustainability criterion Security of Supply. (Figure 27) The main assumption is that the possibility of electrical power failures and especially the number of affected people is lower, and the time span of power failure is shorter in decentralised energy systems. Furthermore, it is assumed that there is a tendency in decentralised energy systems to use local resources, which decreases the possibility of being subject to international fall outs. (Haas et al. 2006)

Criterion: Resilience of the technological systems

Indicator: Diversity of Technology

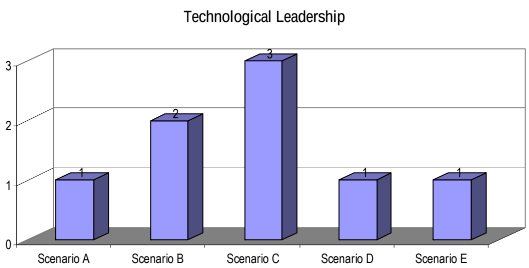


Criterion & indicator: Import Independency



Criterion: Technological Leadership

Indicator: Improvements of technological leadership



Criterion: Security of Supply

Indicator: Likeliness of drop outs and number of affected people

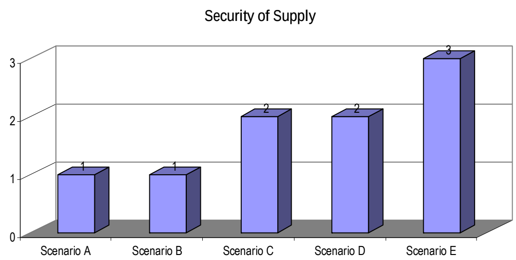


Figure 27. Comparison of the performance of the five scenarios across the technological criteria, all of the technological criteria were appraised with three qualitative intervals (1- 2- 3 standing for: low- medium- high)

It can be concluded that, in general, indicators and criteria from the same evaluation dimension (environmental, social, economic, and, technological) have a similar performance in the scenario calculations.

Trade-offs and synergies between the sustainability criteria

The GAIA plane is a very helpful tool to analyse the potential trade-offs and synergies between the appraisal indicators. (Bana e Costa 1990, Geldermann and Zhang 2001). The differentiation power (length) and orientation indicates which scenarios the criteria favour, and furthermore it visualises how the criteria are positioned in relation to each other. The longer the axis of each criterion on the GAIA plane is, the more discriminating it is. It means that a long axis will differentiate strongly the alternatives while a short axis, on the other hand, will have a smaller role in differentiating them (see Figure for a schematic example).

As can be seen in the visualisation of the impact matrix of this case study in a GAIA plane (see Figure 28) the criteria (indicated by green rectangular boxes) spread across an approximately 270° area. Scenario D (scenarios are indicated by a blue triangles) is most clearly outlying the criteria cloud. Scenario E is located closest to the decision stick. The position of the decision stick is representing the particular preferences of the stakeholder.

The overall environmental dimension structurally points in the opposite direction of scenario D and towards scenarios E and C. An exception to that is the Cumulative Material Effort, which points toward scenario A. The social criteria are directed towards scenario E and against scenarios A, B and D, with no real exceptions. The good performance of scenario E directly correlates to the maximum degree of decentralisation in this scenario. The economic indicators are closest towards scenario D with the exception of Employment, which points towards scenario E. The criterion Effect on Public Budget is closest to scenario A. The other two criteria of the economic dimension are the least supportive of scenario C, because of the high costs and the necessary profound investments from public budget, especially for photo voltaic technology. The technological evaluation dimension is mostly in favour of scenario C with the exception of Security of Supply, which points toward scenario E. (Table 12) Overall, the results from the impact matrix show that scenarios A and D are the least favourable and scenarios E and C the most favourable renewable energy scenarios since they are closest to the decision stick.

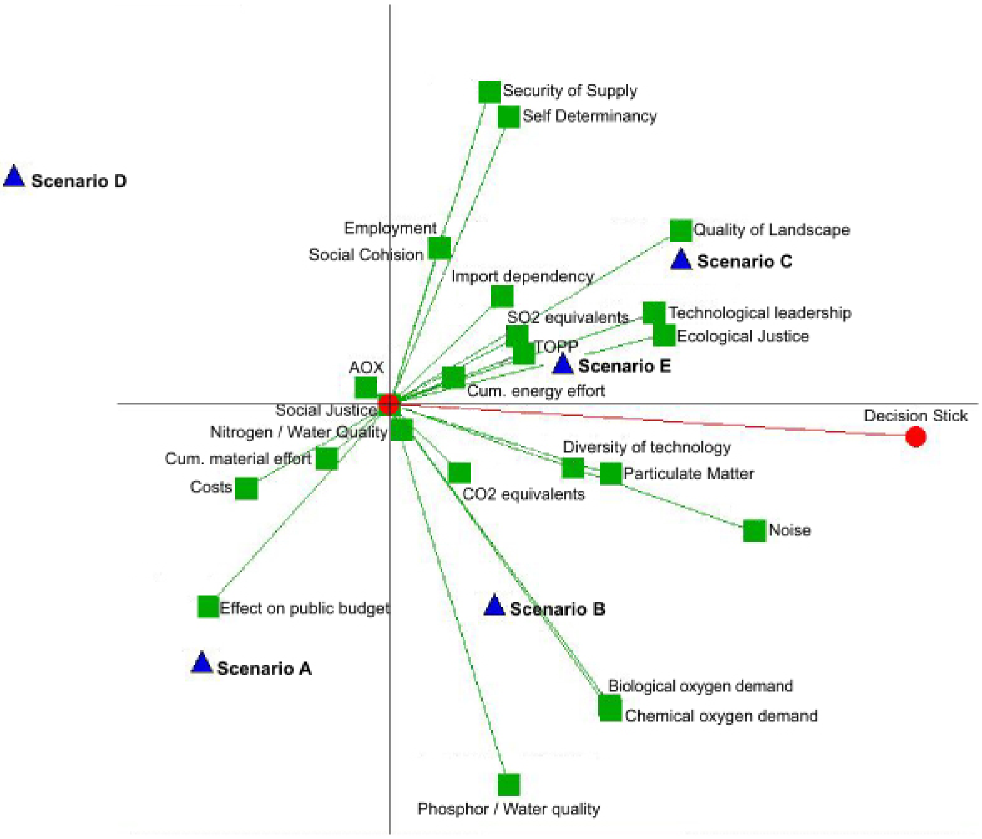


Figure 28. Visualization by GAIA of the overall impact matrix representing the sustainability criteria impacts across the five scenarios; the red line is the decision stick pointing out the overall favourable direction based on the weighting.
Note that the scenarios A-E, indicated with blue triangles, are for graphical reasons brought closer in to centre, whereas the relative positioning is transposed.

Environmental criteria and their indicators

The environmental indicators are most broadly spread across the GAIA plane. The indicators cover the highest range of 270°. Nevertheless most criteria are grouped in quadrant 2 (SO_2 Equivalents, Tropospheric Ozone, and Ecological Justice) and in quadrant 3 (CO_2 Equivalents, Particulate Matter, Nitrogen, Phosphor, BOD, and COD). Two indicators can be considered as exceptions. Inorganic Acids (AOX), an indicator for water quality, in quadrant 1 and Cumulative Material Effort, an indicator for Rational Use of Resources, are positioned in quadrant 4. Overall, the environmental indicators support each other, but some are clearly in conflict.

Even indicators of the same criterion point in opposite directions, as in the case of e.g. Water Quality and Rational Use of Resources. Generally, discordances between indicators are not surprising and do confirm the variety of indicators. For example, the indicators used to express water quality are nitrogen water emissions (N), phosphorus water emissions (P), inorganic acid water emissions (AOX), and biological and chemical oxygen demand (BOD; COD), (see detailed indicator description in the Methods chapter). From these indicators, 4 out of 5 point to the same quadrant, quadrant 3, whereas BOD and COD are also in the same position. Inorganic Acids point to the opposite quadrant, quadrant 1. The opposing indicators of the criteria Rational Use of Resources, Cumulative Material Effort and Cumulative Energy Effort, are opposite to each other (in quadrant 2 and 4) with a similar distance to the centre point.

Within the criterion Air Quality, the indicator SO_2 Equivalents and Tropospheric Ozone are very close to each other and Particulate Matter is in supporting distance in quadrant 3. The similar positioning of SO_2 Equivalents and Tropospheric Ozone seen in the result is explained by the linked emission calculations in the underlying data base.

The environmental Indicators are positioned in supporting and neutral position in relation to social and technological indicators, but not to the same extent towards economic indicators. One exception from that is the indicator Cumulative Material Effort which points in the same direction as the main area of the economic indicators (Costs, and Effect on Public Budget) in quadrant 4.

	Environmental indicators	Social indicators	Economic indicators	Technological indicators
Environmental idicators	X		X	
Social indicators			X	
Economic indicators	X	X	X	X
Technological indicators			X	

Table 12. Conflicting sustainability dimensions indicating respective trade-offs observable in the GAIA representation

Social criteria and their indicators

Social criteria cover an area of 90° in the GAIA plane. A strong clustering can be observed in quadrant 2. Noise is the only criterion located outside the main cluster in quadrant 2, pulling towards the direction of quadrant 3, as do some of the environmental criteria.

Regional Self Determinacy and Social Cohesion point in a similar direction. This is due to their similar data structure (see Table 12). Both criteria relate to the degree of decentralisation in energy systems. A special case and an exception from the clustering in quadrant 2 is the criterion Social Justice, which is incorporated in the evaluation but has no effect on the ranking. The criterion Social Justice was planned to be addressed in terms of affordability of heat and power, and so express social fairness within all income groups. As the scenario work developed, the political pathways of the scenarios were not integrated as much as originally planned and consequently no basis was created on which energy prices and therefore the affordability could be estimated. For this reason all scenarios are given the same value in this analysis and no differentiation has been made. Therefore, it is located in the centre point of the matrix and doesn't have discrimination power in the ranking.

None of the social criteria are in conflicting positions to each other. On the contrary, they are in supportive or neutral position to each other. Furthermore they are supportive or neutral to all the technological indicators and to most of the environmental indicators. Particularly the overlap with technological indicators is noticeable; most evident is the proximity of Regional Self Determinacy and Security of Supply. The general explanation for the parallel performance of those categories is the common relation of these criteria to the degree of decentralisation of the energy systems. Also striking about the allocation of the social criteria in the GAIA plane is that the economic indicator, Employment, is in supporting position to the social criteria and even completely overlaps with the social criterion, Social Cohesion, which refers to their symmetrical distribution in the impact matrix. The social criteria are in conflicting position to the rest of the economic indicators in quadrant 4.

Economic criteria and their indicators

The economic criteria are the least in number in this analysis, yet they play an important role concerning the weights given by stakeholders. The economic indicators span across a 160° area, while Costs and Effect on Public Budget point in a similar direction (quadrant 4). The third economic criteria, Employment, is nearly opposite in quadrant 2 in which shows strong opposition to Effect on Public Budget and weaker opposition to Costs according to the GAIA plane in Figure 28.

Aside from Costs and Effect on Public Budget only one other indicator is positioned in quadrant 4 which belongs to the group of environmental criteria, Rational Use of Resources, Cumulated Material Effort. This indicator is in supporting relation to Costs and Effect of Public Spending. Obviously, there are conflicting interests within the group of economic criteria. Even more significant is that Costs and Effect on Public Budget stand neutral or in conflict with almost all of the other criteria and indicators (see Figure 28).

Technological criteria and their indicators

The technological indicators span across an area of 90° in the GAIA plane. This means that all technological indicators are in support of or are neutral towards each other. Striking is the similarity of the display of the technological indicators with the social indicators area in GAIA, as mentioned earlier. Furthermore, the technological indicators are in supporting or neutral positions towards the environmental indicators. In accordance, they are in conflict with the economic indicators Costs, and Effect on Public Budget and the specific environmental indicator Cumulative Material Effort.

There are three technological indicators that are especially close to indicators from other sustainability appraisal dimensions, which shall be presented briefly. In the case of Security of Supply and Regional Self Determinacy there is a common causality, namely the degree of decentralisation, whereas the other two couples don't seem to have an obvious common causalities (Technological Leadership and Ecological Justice; Diversity of Technology and Particulate Matter). The similar positioning of Technological Leadership and Ecological Justice stems from the fact that both indicators, for diverse reasons, perform best in scenario C.

Stakeholder weighting of the sustainability appraisal criteria

In personal interviews, key energy stakeholders were asked which criteria are most important in their personal opinion for more sustainable future energy systems. The stakeholders arranged the specially prepared cards with 17 sustainability criteria according to their importance. Several criteria could be ranked at the same level and extra levels could be inserted to indicate an extra distance between ranks. See appendix Figure A.2. for photographs of the sustainability appraisal criteria made for each stakeholder during the ranking interview. The criteria rankings were transformed into weighting sets with the SIMOS weighting method (see Methods chapter for more detail), adding up to a total of 100 weighting points.

In the box plot diagram below (Figure 29) the highest ranked criteria (highest median) Climate Change Impact is at the far left, whereas the other criteria are presented according to their weighting downwards. The box plot diagram gives us the statistical median (indicated by the horizontal line in the box) of the criteria. The box indicates the weighting range where 50% of the weightings are located, whereas the vertical lines give the maximum and minimum weightings.

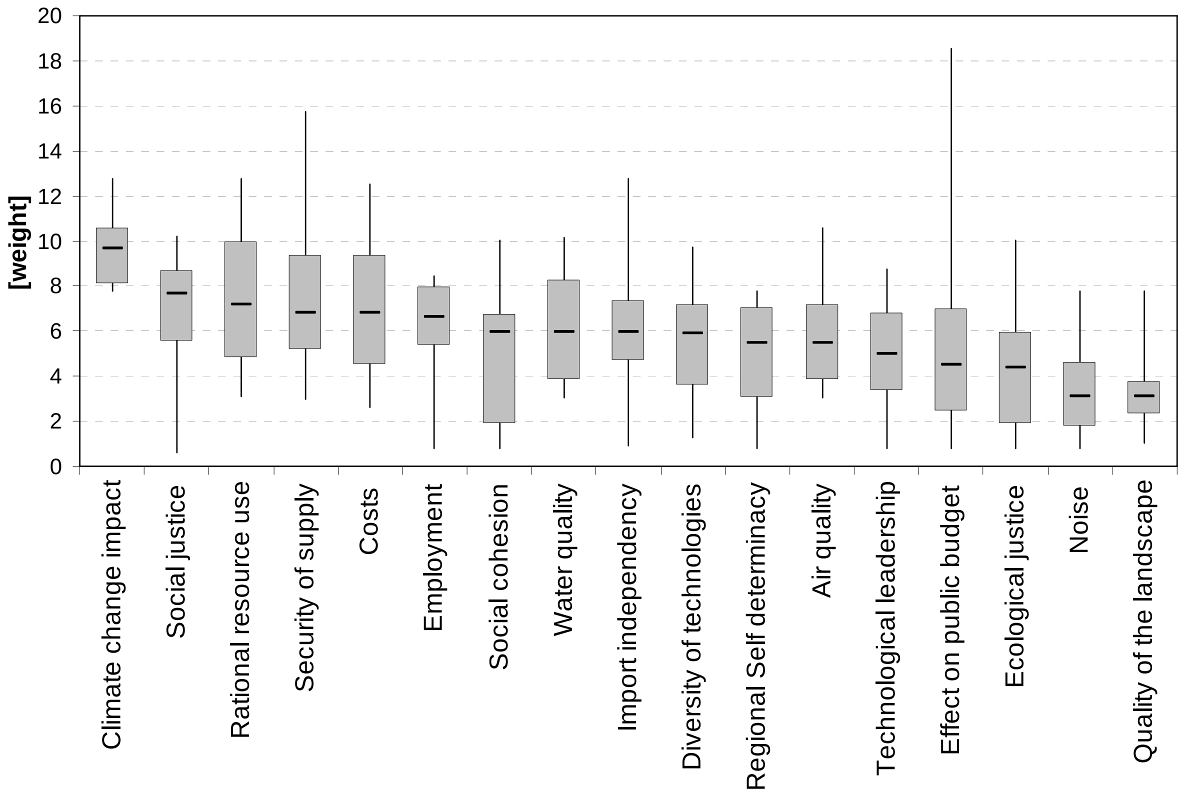


Figure 29. Box plot of the weight of each indicator by the 16 Stakeholders. The small horizontal line indicates the median of all weights, the grey shaded box the area between second and third quartile (i.e. containing 50% of all stakeholder weights). The whiskers indicate the range of weights (minimum and maximum).

The weighting patterns of the stakeholders show that the top three sustainability criteria are: (1) Climate Change Properties (9.65 weighing points), (2) Social Justice (7.66 weighing points), and, (3) Rational Use of Resources (7.16 weighing points). Applying the statistical mean, the criterion Social Justice slides to the fourth rank and Security of Supply is ranked equal with Rational Use of Resources. This is already indicated in the box plot by a rather unbalanced box and the large scatter of weightings with an extremely small minimum weight of 0.6 weighting points. In contrast to that, the criterion Climate Change Properties has the lowest scattering of all criteria, meaning that there is broad consensus within the stakeholders that good climate change properties are the main aim of future sustainable energy systems. The criterion Rational Use of Resources, ranked in the top three, has one of the highest standard deviations which indicate very contradictory preferences.

Most noticeably, there are no economic criteria within the top three weighted criteria. The highest ranked economic criterion is Costs on rank 5 with 6.8 weighting points, followed by Employment on rank 6 with 6.6 weighting points. The third economic criterion, Effect on Public Budget, is on the 14th rank with 4.5 weighting points. Yet the box plot diagram shows that the criterion Effect on Public Budget has an extremely high maximum weighting (18.6 weighting points). Stakeholders obviously have very different opinions regarding future sustainable energy systems which are financed by the public budget.

The lowest weighted criteria according to the median are (14) Ecological Justice (4.4 weighting points), and, (15) Noise (3.1 weighting points) equal with (16) Quality of Landscape. A striking aspect of the weighting results is that the “local” issues, such as Quality of Landscape, Noise, and Regional Self Determinacy (rang 13 of 17 criteria) are weighted very low. This might have to do with the institutional level of this case study, which included only national energy stakeholders. A parallel case study undertaken on the local level reveals a completely different weighting structure, and Quality of Landscape and Noise have a much more prominent position in the preference structure. Omann et al. forthcoming

Figure 30 shows that with the exception of Regional Self Determinacy and Technological leadership, even the low-ranked criteria are highly ranked by individual stakeholders. This indicates great diversity of social preferences. Climate Change Properties also stand out in this diagram as the number-one criteria.

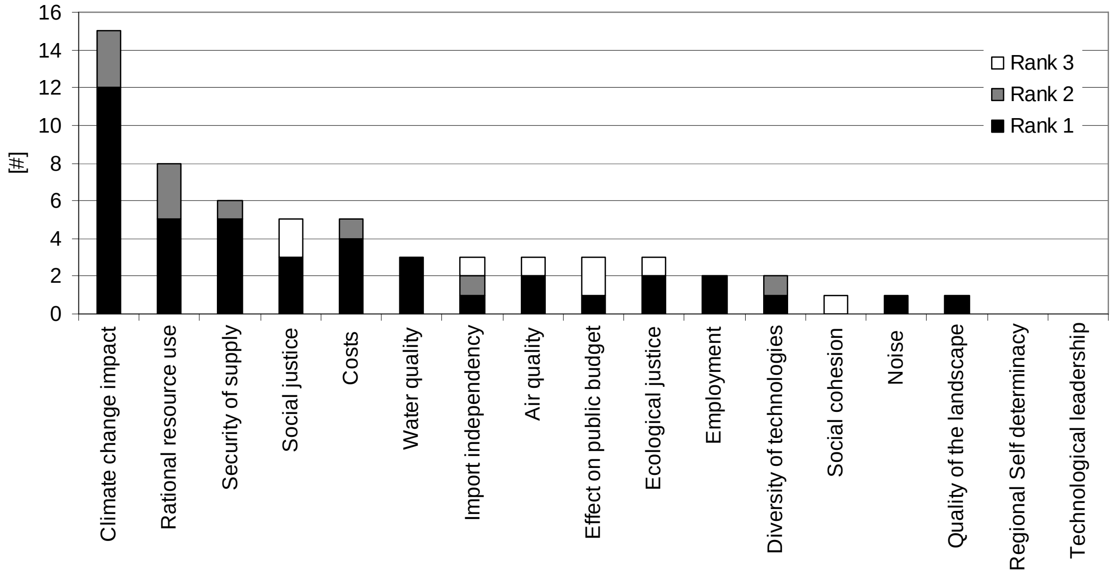


Figure 30. Number of top-three ranks of the sustainability appraisal criteria

Similarities between stakeholder concerning their weightings

The present analysis aims to identify similarities between the stakeholder weighting sets. Three cluster analysis methods have been applied (Furthest neighbour, Nearest neighbour, Between groups' Linkage) See Table 13 for the comparison of the cluster memberships. The nearest neighbour method arrives at one large cluster, whereas both the furthest neighbour and the between groups' linkage method brings out similar clusters. This seems to offer a more robust result and is taken as the basis for further presentations and discussions on the results. For the detailed cluster diagrams see Figure 31 and Figure A.3. in the appendix.

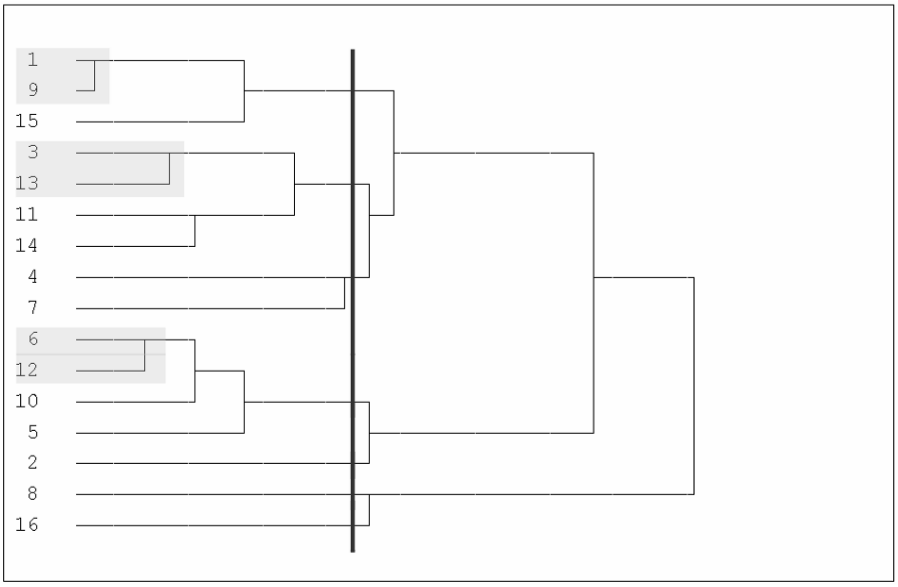
	Cluster membership1	Cluster membership 2	Cluster membership 3	Cluster membership 4	Not clustered
Furthest neighbor	1, 9, 15	3, 13, 11, 14	4, 7	6, 12, 10, 5, 2	8, 16
Nearest neighbor	1, 9, 10, 6, 12, 5, 11, 14, 15, 3, 13,				2, 4, 7, 8, 16
Between groups' Linkage	1 ,9, 15	6, 12, 10, 5	3, 13, 11, 14		2, 4, 7, 8, 16

Table 13. Comparison of stakeholder clusters (1-4) according to their weighting set by different agglomeration methods.

The individual numbers denote the different stakeholders (in the order of the furthest n. method): 1 (ZSI), 9 (Euro Solar), 15 (WWF), 3 (BMVIT), 13 (VKI), 11 (Small Water Power), 14 (IG-Wind power), 4 (BMLFUW), 7 (AEE), 6 (AK), 12 (ABCSD), 10 (Global 2000), 5 (Chamber of Agriculture),2 (Representative of State-Owned Forest)

The closest stakeholders' preference structures according to their weighting set are 1 and 9, followed by 6 and 12, and then, 3 and 13 (see Figure 31). The stakeholders 8 (Electricity Utility, Wien Energie) and 16 (Industrialists' Association) are not included in any cluster.

a)



b)

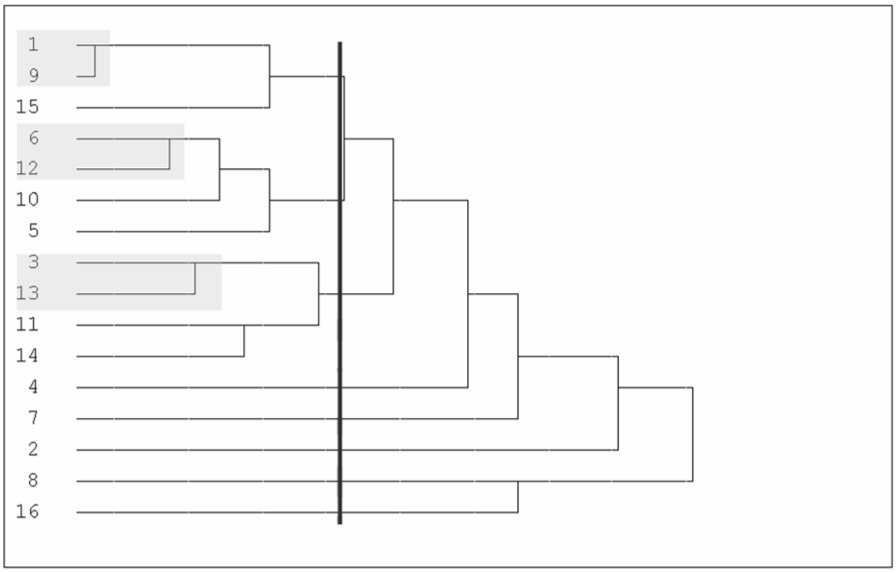


Figure 31. Dendrogram of a hierarchical cluster analysis of the stakeholders according to their ranking of the sustainability appraisal criteria. a) method 1: furthest neighbour, complete linkage; b) method 3: between groups' linkage, average linkage)

MCA ranking of the renewable energy scenarios

The scenario ranking is performed for each stakeholder weighting set culminating in the 16 final scenario rankings. The multi-criteria aggregation mechanism PROMETHEE is applied to appraise by a pair-wise comparison mechanism the five renewable energy scenarios across the 24 sustainability appraisal indicators. The MCA allows integration of social preferences in the form of weights into the analysis. The scenario ranking result is presented on an ordinal scale.

Overall ranking result

On the overall the 16 final scenario rankings are very similar in the sense that scenario E and C are always in a top cluster, scenario B is in a middle position and scenario A and D are always in a bottom cluster. A mean scenario ranking has been carried out to give an overall picture (see Figure 32 and Table A.8. in the Appendix). The individual scenario rankings according to the stakeholder weight sets are then presented in detail.

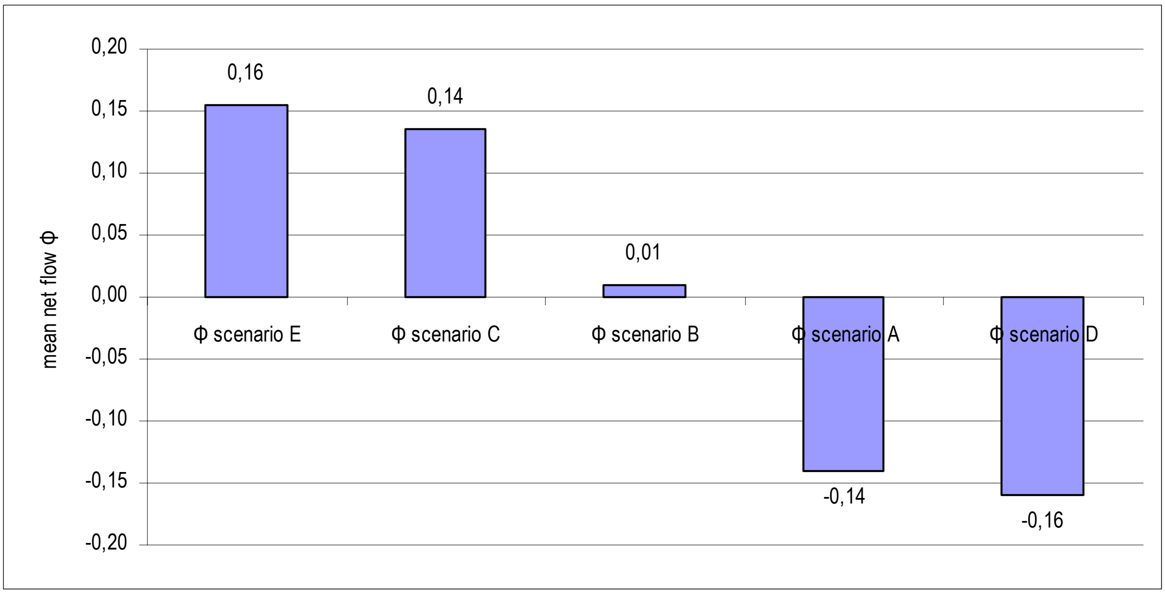


Figure 32.The mean ranking derived from all 16 scenario rankings, whereas the net flows of the complete ranking are the basis for the mean.

Table 14 gives an overview of all individual stakeholder scenario rankings. In essence, the overall rankings result in three clusters of scenarios, which can be identified in all the final scenario rankings. This structure is very robust in the sensitivity analyses: Scenario E “Large impact in small-scale use” and scenario C “Investment into the Future” rank high, while scenario B “Extension of competitive advantage” takes a middle position, and scenarios A “Fast and Known” and D “Extensive Use of Biomass” rank distinctively lowest

None of the rankings of the scenarios are shifted in a profound way by the specific stakeholder weights set on the sustainability criteria. Only the ranks within the top and bottom cluster of scenarios vary due to the individual stakeholder weights sets.

Participant	Complete ranking	Partial ranking	Institutional background of participant
P1	C, E, B, D, A	C / E, B, D, A	Research Centre for Social Innovation
P2	E, C, B, A, D	E, C / B, A, D	Representative of State Owned Forest
P3	E, C, B, A, D	E, C, B, A / D	Federal Ministry for Traffic, Innovation and Technology o
P4	E, C, B, A, D	E, C, B, A / D	Federal Ministry of Agriculture, Forestry, Environment, and, Water Management / Environment Section
P5	C, E, B, A, D	C / E / B, A / D	Chamber for Agriculture
P6	E, C, B, A, D	E / C, B, A / D	Chamber for Labour
P7	E, C, B, A, D	E / C, B, A / D	AEE Renewable Energy Association, NGO
P8	E, C, B, D, A	E / C / B, D / A	Electricity Utility, Wien Energie
P9	C, E, B, A, D	C / E, B, A / D	Euro Solar, NGO
P10	E, C, B, A, D	E / C, B, A, D	Global 2000, Environmental NGO
P11	E, C, B, A, D	E, C, B, A / D	Renewable Energy Representative, Small Hydro Power
P12	E, C, B, D, A	E / C, B, D / A	Austrian Business Council for Sustainable Development (ABCSD)
P13	E, C, B, A, D	E / C, B, A / D	Consumer Interest Council, VKI
P14	E, C, B, D, A	E / C, B, D / A	Renewable Energy Representative, Wind Power
P15	C, E, B, A, D	C / E, B, A / D	WWF, Environmental NGO
P16	E, C, B, A, D	E / C / B, A / D	Industrialists' Association

Table 14. Complete and partial scenario ranking results according to the different weight sets of the stakeholders. The "/" indicates a parallel position of scenarios in the partial rankings.

When summarizing the scenario ranking results according to the different weighting sets of the stakeholders (see Table 14), scenario E "Large impact in small-scale use" ranks first in 12 out of 16 scenario rankings (=75%). Yet despite the fact that it is only visible in the partial ranking, it stands alone at the top rank 4 times and in a parallel ranking with another scenario 8 times. Whenever scenario E does not rank first, it ranks at least second.

Scenario C "Investment into the future" is in four cases rank 1 and 12 cases out of the 16 rank 2 (=75%). In the partial ranking, scenario C is always in the highest parallel ranked scenario cluster except in three cases.

Scenario B "Extension of competitive advantage" receives rank 3 of all the final stakeholder rankings. In the partial ranking it is in the highest parallel ranked scenario cluster 4 times. But more often, 12 times out of 16, it is in a middle position between scenario clusters C, E and A, D.

Scenario A, “Fast and Known”, is in most cases rank 4 (12 of 16 rankings) and ranked last four times (=25%). The partial ranking reveals that scenario A is most often in the lowest ranked parallel scenario cluster (with D), ranked fourth on its own two times and ranked last on its own only once.

Scenario D “Biomass on a large scale” is ranked last in most stakeholder rankings (12 out of 16 times) and therefore ranked last most often (=75%) compared to all the other scenarios. In four rankings it is positioned on the fourth rank. The partial ranking shows that scenario D is two times ranked last on its own two times and also ranked fourth by itself on one occasion, but in most cases ranked in the lowest scenario cluster with A.

Complete ranking

The advantage of the complete ranking is to arrive to an unambiguous ranking and complete information according to the ranking distance between the scenarios. The overall net flow range is valuable information according the overall distance of the scenarios from each other. The general weakness is that this purported preciseness can not always be supported by the underlying data and assumptions. (see previous discussion in the Methods chapter). Nevertheless, the complete ranking brings additional information and informs the results.

In this specific case the complete ranking has been used to identify the different rankings among the 16 final scenario rankings. Four different scenario rankings appear. The most common ranking shows that scenario E “Large impact in small scale use” is ranked first, followed by C “Investment into the Future” and B “Extension of competitive advantage”. Scenario A “Fast and Known” and scenario D “Extensive Use of Biomass” clearly rank lower (see Table 15 and Figure A.4. in the appendix).

9 time	E –C –B –A –D	participant: 2, 3, 4, 6, 7, 10, 11, 13, 16
3 time	E –C –B –D –A	participant 8, 12, 14
3 time	C –E –B –A –D	participant: 5, 9, 15
1 time	C –E –B –D –A	participant: 1

Table 15. Summary of the final scenario rankings and the respective stakeholder groups

Two more types of scenario rankings occur among the respective three stakeholders: on the one hand, E, C, B, D, A, receive a ranking which is similar to the most common scenario ranking, whereas D and A have switched places. And three participants have produced, on the other hand, the ranking C, E, B, A, D. In this case, the first rank is taken by scenario C "Investment into the Future", which is in contrast to the most common ranking,. The least common ranking, emerging only once, is the same as the later sequence and the last rank is scenario A "Fast and Known".

According to the complete ranking, the distance between the first two and the last two positioned scenarios is very small in all four groups (see Appendix for Figure A.4.). The total range of the net flows varies from ±0.13 (participant 2 in Figure A.4. in Appendix) to ±0.25 (participant 3 and 13 in Figure A.4. in Appendix), which is a moderate difference. In the rankings with an especially low net flow range, the scenarios are much closer together than it looks in the comparison. A small range of net flow suggests that the scenario impacts are due to the weight set in these rankings not as distinctly different inform the scenario rankings with a higher range of net flow. In other words, comparatively low net flows can be explained by the way that high weights were put on criteria which are characterised by low differences between the scenarios in the impact matrix.

Summarising the information of the complete ranking, the differences between the four scenario ranking groups, represented by the four different sets of rankings, is not considerably distinct. The main reason for that is the fact that the overall robustness of the characterising scenario rankings is not high. The partial ranking promises to reveal more detailed information on the overall ranking pattern of the scenarios.

Partial ranking

The partial ranking provides additional information in the sense that the positive and negative performances from the comparison of the pairs of scenarios are accounted for in separate positive and negative outranking flows. Given the assumption that bad performances can not be compensated by good performances across criteria it provides important information. In the partial ranking, a scenario is only ranked higher than another one if it is better in the positive (higher $\Phi+$) and negative performances (lower $\Phi-$).The disadvantage of this kind of ranking is that the result is more complicated and presents scenarios in parallel position, if the performances in $\Phi-$ and in $\Phi+$ are not better than the subsequent scenarios.

To investigate the groups of scenario rankings apparent from the complete ranking further Figure A.5. (see Appendix) is comparing the equivalent partial rankings. A comparison of the ranking patterns within group 1 shows that the majority of rankings include just one parallel cluster, comprised of either scenarios A and D or of E and C. A parallel position between C and B occurs only once in this group. But there are also "x-shaped" rankings with B in the middle position and two parallel clusters. This shows that the first and/or the last rank are ambiguous in most cases. In the second group the partial rankings are all “x-shaped” rankings with B in the middle but the position of scenarios A and D points the other way. (see Figure A.5. in Appendix) This indicates that if the scenario A is in last position in this configuration, then only one can be in parallel ranking with scenario D. Group 3 presents rankings with scenario C on the first rank but always in parallel ranking with scenario E. The last cluster of scenarios is also exclusively in parallel position. The last group, consisting of just one ranking, presents a ranking with only one parallel cluster between scenarios E and C and is the only ranking with scenario A in last place by itself.

Comparing the patterns of the four groups of rankings revealed by the partial ranking, further illustrates the insufficient discriminatory power of the group differences which were found by the complete rankings. Nevertheless, there is interesting additional information from the partial ranking: the most common ranking, E –C –B –A –D is also the ranking with the least parallel scenario positions, so it is the least ambiguous ranking.

Sensitivity analyses

In the following, the sensitivity analyses of the MCA results are presented and the final scenario rankings scrutinised. The sensitivity analyses of the results look at the role of the weighting, the preference functions, certain scenario parameters attempting to deepen understanding of the particular influences and consequently their effects on the final scenario ranking.

Sensitivity analysis of the renewable energy scenarios

SA 1: Small-scale versus large-scale technologies

The overall result of the sensitivity analysis shows in Figure 33 that the small-scale technologies perform worse in the environmental dimension and have more emissions per TJ. In general, this is the expected result since small scale technologies often have less effective filter systems or less efficient emission factors in the combustion for various economic reasons or simply because they don’t exist for small scale technologies on the market. This is often argued as a basic disadvantage of decentralised energy systems.

The more intense transport emissions associated with most large scale technologies are explicitly accounted for in the life cycle data-base, are outweighed by the more efficient energy transformation systems of large scale technologies. Nevertheless, the emissions from transport are visible in the way that CO_2 equivalents increase to a lesser extent for small-scale technologies than the Air Quality emissions (+ 5% versus + 13-19%; see Figure 33 for further detail).

Worse resource efficiency is also true for the sealed area equivalents; respectively more land per TJ is used with small-scale technologies than with large-scale technologies. The only indicator structurally better in the small-scale sensitivity analysis is Particulate Matter (-57%), an indicator for the criterion Air Quality. This is most likely due to data artefact. Also the indicators for Water Quality also do not react plausible way in this sensitivity analyses: an enormous decrease of water emissions per TJ with small scale technologies (up to -90%). Since there are known data gaps and high data uncertainty in the indicators for Water Quality, these specific sensitivities are treated with great care.

Not surprisingly do the overall costs also increase in the sensitivity analysis maximising small scale technologies on scenario average. This corresponds with the well-known fact that costs per energy unit are higher in small-capacity technologies. The subsidies scheme gives a counterbalance to the economic disadvantages, which encourages small-scale technologies with higher feed-in tariffs to overcome economic scale problems.

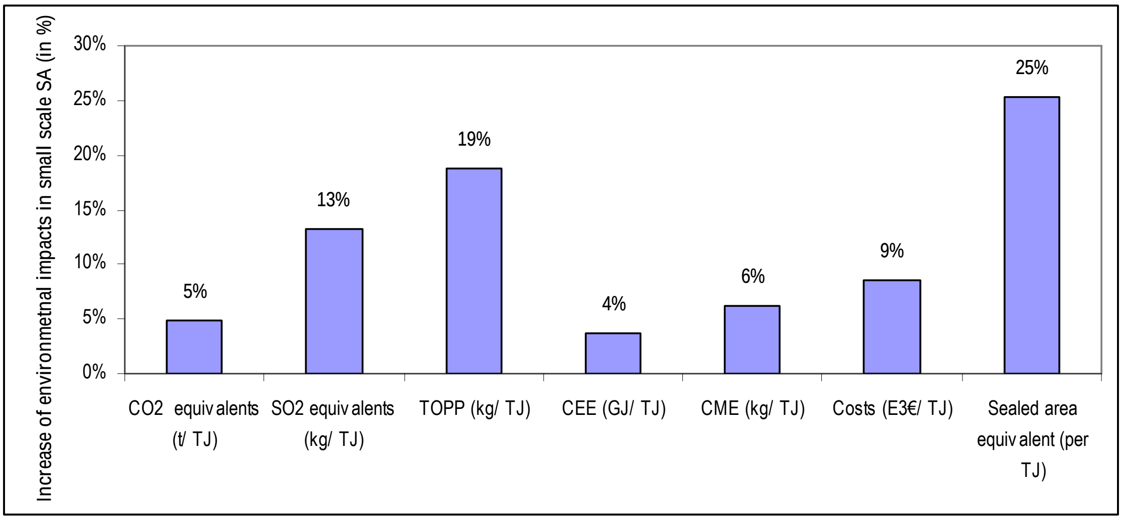


Figure 33. Increase of environmental impacts and economic costs in the small scale SA

The differences in the averaged data of the two sensitive analyses, all small-scale technologies versus all large-scale technologies, are between 4 and 25% (excluding the suspicious data artefacts from water quality indicators and particulate matter). This could be considered a defined difference indicating that the data is transporting this specific differentiation well, even though it can not be applied to all technology types. Also, the overall direction of change seems plausible. This provides the general conclusions that the used data base assured the present discussion of emissions and costs efficiency of small-scale technologies but has profound inconsistency for the indicators of Water Quality and the indicator Particulate Matter.

SA 2: Primary versus secondary biomass resources

Most prominent from these sensitivity analysis results is the enormous increase of the sealed area equivalent with maximised use of primary biomass (almost five times higher than in the SA maximising secondary biomass and more than double than the standard scenario modelling). (see Figure 34:) This is by all means plausible since energy crops create very high sealed area equivalents (for details see Methods chapter, sustainability criteria). Another outstanding sensitivity analysis results is the increase of particulate matter. In this case the trend is based on the other indicators but to a more extreme extent, which indicates once more that the data might not be quite reliable. The two highest sensitivities apart from the outlier are accordingly the CO_2 equivalents (+38%) and the Cumulated Material Effort (+33%). When maximising primary biomass utilisation, the lowest increase is with Cumulated Energy Effort (+4%). This is surprising since primary biomass requires extensive transport and machinery and therefore cumulated energy effort.

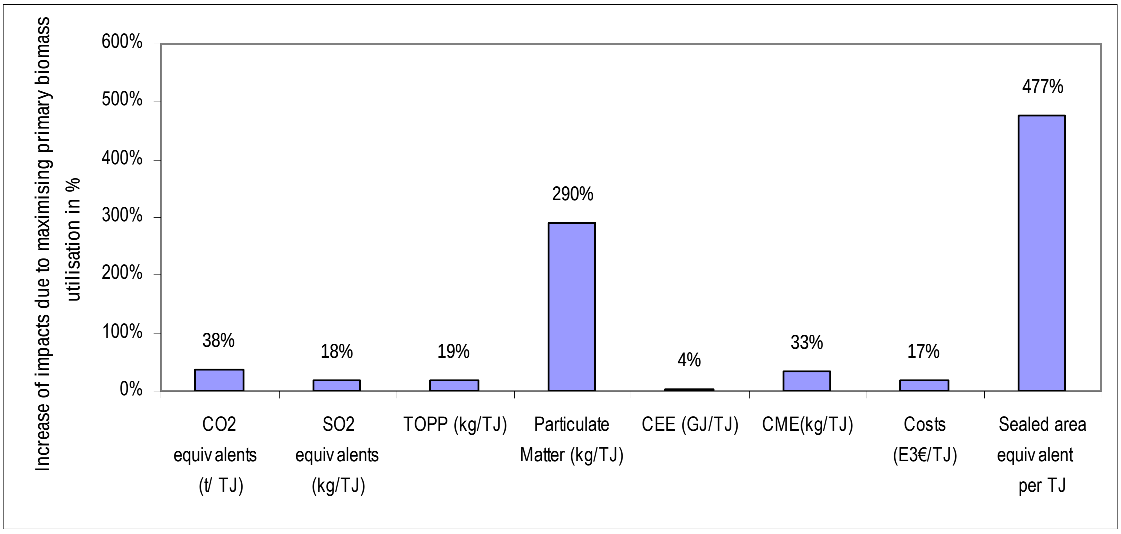


Figure 34. Increase of environmental impacts and economic costs due to maximising primary biomass in SA2

The differences in the averaged data of the two sensitivity analyses, maximising primary biomass technologies versus secondary biomass technologies, are between 4 and 477%. The water quality indicators have to be excluded again showing a drastic implausibility as in the first SA. The air quality indicator, particular matter, is in analogue trend in this SA but has a very strong effect which might be due to data artefacts.

The overall effect in this SA can be considered highly defined. The data demonstrates this specific differentiation very well even though it addresses only the biomass section (which is the main additional renewable energy section in these scenarios). Also the overall direction of change seems plausible and coherent with published argumentations in Haberl and Geissler 2000 assuring the present discussion of emissions reduction and costs efficiency of secondary biomass utilisation.

Sensitivity analysis on the role of the weighting sets

Equal weights

Figure 35 presents the resulting partial ranking of the energy scenarios in the case that all weightings are set equal. Basically, this ought to reveal the pattern of the impact matrix itself and of the distribution, in this case asymmetrical distribution, of the appraisal criteria across the social, environmental, economic, and technological sustainability dimension. Since all the criteria have equal weights, the initial number of criteria is more decisive for the ranking. This is true especially when assuming that all the criteria and indicators of one sustainability dimension are discriminating towards the same scenario. As discussed before in the results section, this is more or less the case for the social and technological appraisal criteria but is not valid for the environmental and economic sustainability dimensions.

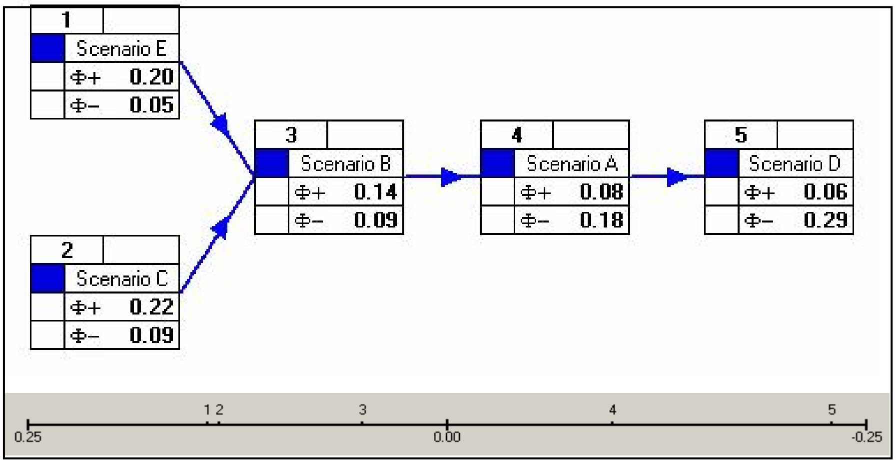


Figure 35. Result of the sensitivity analysis on the effect of the weighting sets: partial ranking of the renewable energy scenarios with weighting set equal for all the sustainability appraisal criteria

The most obvious insight from the sensitivity analysis with equal weightings is that the ranking of scenarios is does not differ from the overall ranking structure of the final scenario rankings. A slight difference is that the top scenarios E and C rank very closely together. They are in parallel position towards each other since scenario E has a lower negative outranking flow (Φ-), expressing that it is less dominated (less weakened) by other scenarios, and scenario C has a higher positive outranking flow (Φ+), which means that it is more dominant over other scenarios. (Brans and Mareschal 1990)

Distinct visible distance can be seen between the other scenarios in the ranking. The distance between scenarios A and D stands in contrast to most of the stakeholder rankings. This indicates that scenario D worsened with equal weightings or that scenario A improved. An even lower ranking of scenario D could have to do with the fact that scenario D performs well in the economic criteria, especially in the criterion Costs, which are the smallest number of criteria per evaluation dimension (3 criteria) based on the ranking with equal weights. This effect is abrogated in the stakeholder rankings by the generally high weights on economic criteria, especially Costs. This explains the low ranking of scenario D in the sensitivity analysis.

The scale on which the scenarios are ranked is medium large (± 0.25) which is represented by the range of the net flow (Φ). This is as high as the maximum net flow of the stakeholder rankings and clearly higher than the mean net flow (± 0.19) of the stakeholder rankings.

The stability of the sensitivity ranking with equal weights is shown in Table 16, the decision lab stability intervals, indicating that it has a very stable rank despite the top ranked scenario cluster E and C. One third of the indicators and criteria (8 out of the 24) are not stable in the sense that the stability interval is beyond ±50% of the weight. The changes in the ranking, though, are all between scenarios E and C which is obvious from the approximate position in the ranking (see Figure 35).

Stability Intervals

Stability Level: 5 first actions ☑ AutoLevel

	Weight	Interval		% Weight	% Interval	
		Min	Max		Min	Max
CO2 equivalents	1.0000	0.0000	4.7526	4.17%	0.00%	17.12%
SO2 equivalents	1.0000	0.0000	1.3030	4.17%	0.00%	5.36%
TOPP	1.0000	0.0000	1.3113	4.17%	0.00%	5.39%
Particulate matter	1.0000	0.0000	5.7983	4.17%	0.00%	20.13%
Cum. energy effort	1.0000	0.0000	1.6679	4.17%	0.00%	6.76%
Cum. material effort	1.0000	0.5463	6.9991	4.17%	2.32%	23.33%
Phosphorus/Water quality	1.0000	0.7439	3.8403	4.17%	3.13%	14.31%
Nitrogen/Water quality	1.0000	0.0000	74.7284	4.17%	0.00%	76.47%
AOX	1.0000	0.0000	2.2816	4.17%	0.00%	9.02%
CSB	1.0000	0.4744	9.2072	4.17%	2.02%	28.59%
BSB	1.0000	0.4582	9.4057	4.17%	1.95%	29.02%
Costs	1.0000	0.5516	4.2908	4.17%	2.34%	15.72%
Self determinancy	1.0000	0.4511	11.0176	4.17%	1.92%	32.39%
Social cohesion	1.0000	0.4511	11.0176	4.17%	1.92%	32.39%
Diversity of technology	1.0000	0.0000	Infinity	4.17%	0.00%	100.00%
Employment	1.0000	0.4511	11.0176	4.17%	1.92%	32.39%
Effect on public budget	1.0000	0.4511	4.2768	4.17%	1.92%	15.68%
Import dependency	1.0000	0.0000	1.2744	4.17%	0.00%	5.25%
Quality of landscape	1.0000	0.0000	6.0088	4.17%	0.00%	20.71%
Noise	1.0000	0.0000	Infinity	4.17%	0.00%	100.00%
Social justice	1.0000	0.0000	Infinity	4.17%	0.00%	100.00%
Technological leadership	1.0000	0.0000	1.1372	4.17%	0.00%	4.71%
Ecological justice	1.0000	0.0000	1.5489	4.17%	0.00%	6.31%
Security of supply	1.0000	0.7256	6.0088	4.17%	3.06%	20.71%

Table 16. Sensitivity intervals of the scenario ranking with equal weightings

Sensitivity analysis with strongly dominating sustainability dimensions

Social appraisal dimension

A weighting of 70% on the social criteria Regional Self Determinacy, Social Cohesion, Social Justice, Quality of Landscape, and Noise shows a very stable change of the rankings when compared to E-C-B-D-A (see Figure 36). The social criteria correlate strongly with the degree of decentralisation of the energy systems, which is highest in scenario E “Large impact in small-scale use”. The scenario E rises therefore to the first rank and scenario A, the most centralised scenario, lowers to the last rank. This change of rankings is shown in Figure 36 in an exemplary ranking of participant 9. An increased net flow can be asserted as well, which means that the scenarios are on a wider range and are more differentiated from that extreme point view of social sustainability.

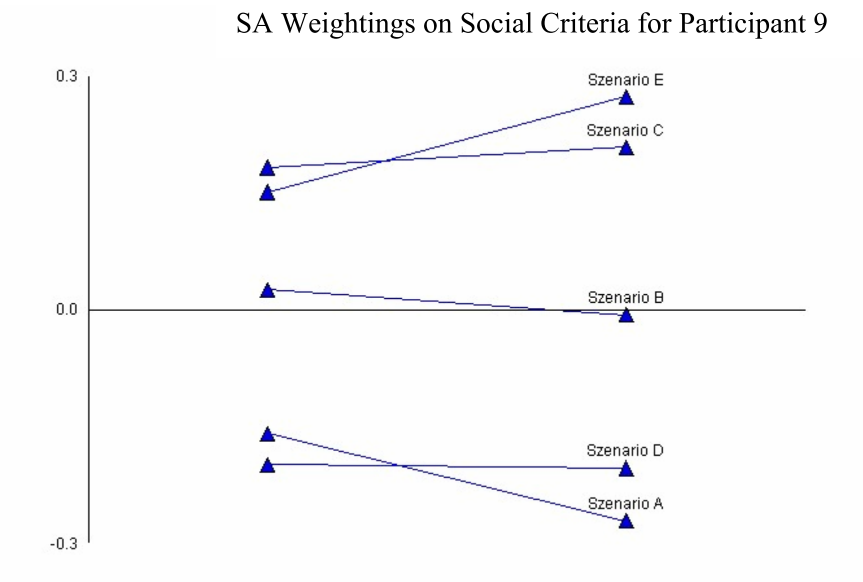


Figure 36. Exemplary changes of the scenario ranking of participant 9 due to high weight (70%) on the social appraisal dimension (right side) compared to the scenario ranking with individual weights (left side).

Economic appraisal dimension

If the economic dimension of sustainability appraisal criteria (Costs, Effect on Public Spending, and, Employment) is dominant with 70% of the overall weight, the most sincere ranking changes can be observed. No uniform ranking is produced as in the case of the social dimension. A striking effect across all of the scenarios is that scenario D “Extensive use of biomass” and scenario A “Fast and Known” rank distinctively higher (see Figure 37). In the exemplary sensitivity analysis ranking of participant 5 in Figure 37, scenario D clearly improves due to the high weighting of economic criteria, from the last rank to the second highest rank. In contrast, scenario C "Investment into the future" is clearly ranked lowest.

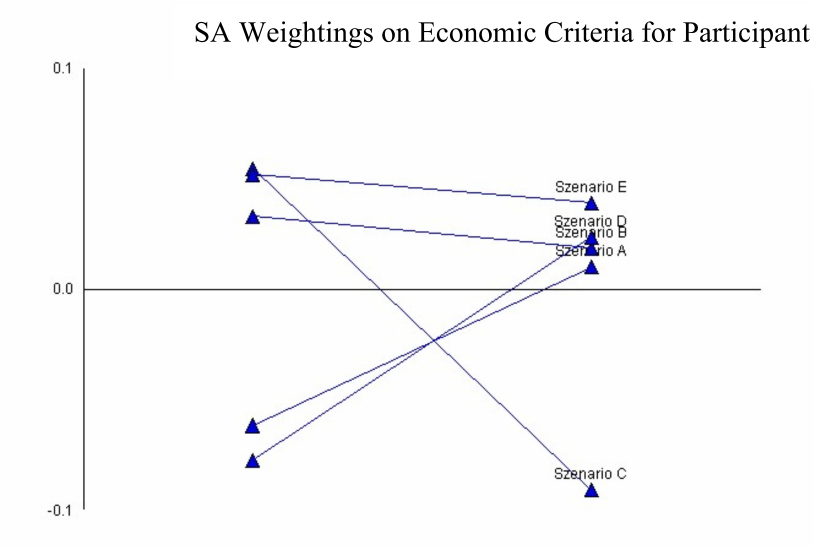


Figure 37. Characteristic changes of the scenario ranking of participant 5 due to high weight (70%) on the economic appraisal dimension (right side) compared to the scenario ranking with individual weights (left side).

The net flows are only marginally smaller in contrast to the original rankings mainly due to the fact that scenario C is ranked so low. All the other four scenarios rank very rather closely together when the economic criteria are ranked very high.

Environmental appraisal dimension

The foremost weighting on the environmental sustainability dimension (Climate Change Properties, Air Quality, Water Quality, Rational Use of Resources, and, Ecological Justice) shows in contrast to the latter sensitivity analysis that scenario D ranks lowest and scenario C ranks highest in all rankings (see exemplary ranking of participant 16 in Figure 38). Another common effect is that scenario B improves the rank and builds a cluster with C and E.

Overall, the net flow range of the rankings becomes somewhat larger in this sensitivity analysis but not as much as with high weighting on social or technological evaluation dimension.

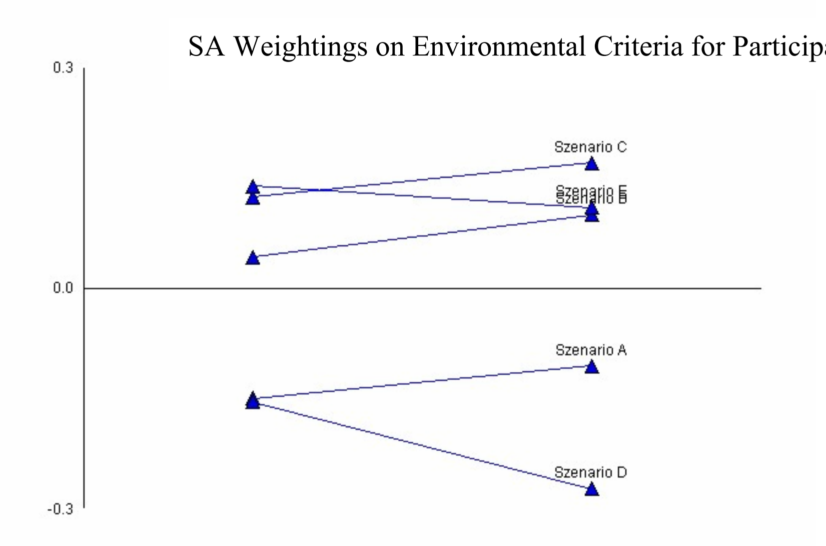


Figure 38. Characteristic changes of the scenario ranking of participant 16 due to high weight (70%) on the environmental appraisal dimension (right side) compared to the scenario ranking with individual weights (left side).

Technological appraisal dimension

When weighting the technological appraisal dimension (Diversity of Technology, Import Dependency, Technological Advantage, and, Security of Supply) very high, the ranking changes in the sense that scenario C ranks first whether or not no other systematic changes of the rankings appear. An exemplary, characteristic ranking of participant 13 in Figure 39 shows the changes. The range of net flows is clearly larger than the individual stakeholder scenario rankings, which indicates that the scenarios differ more distinctly.

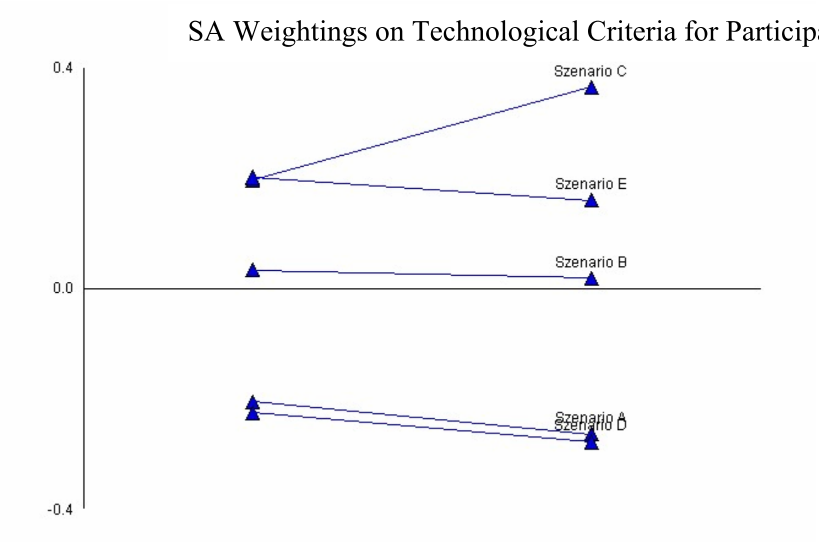


Figure 39. Characteristic changes of the scenario ranking of participant 13 due to high weight (70%) on the technological appraisal dimension (right side) compared to the scenario ranking with individual weights (left side).

Similarities of criteria concerning their weighting

To understand whether certain criteria are weighted in a common manner another cluster analysis is presented here. The question addressed here is whether certain criteria are often of similar importance to the stakeholders to a significant extent. For that reason three cluster analyses are performed (Furthest neighbour, Nearest neighbour, Between groups' Linkage; see Dendrograms in Figure 40).

According to the cluster analyses of the criteria concerning their weighting structure, the following criteria are often weighted very similarly:

- Air Quality (9) and Water Quality (17)
- Noise (8) and Quality of Landscape (7)

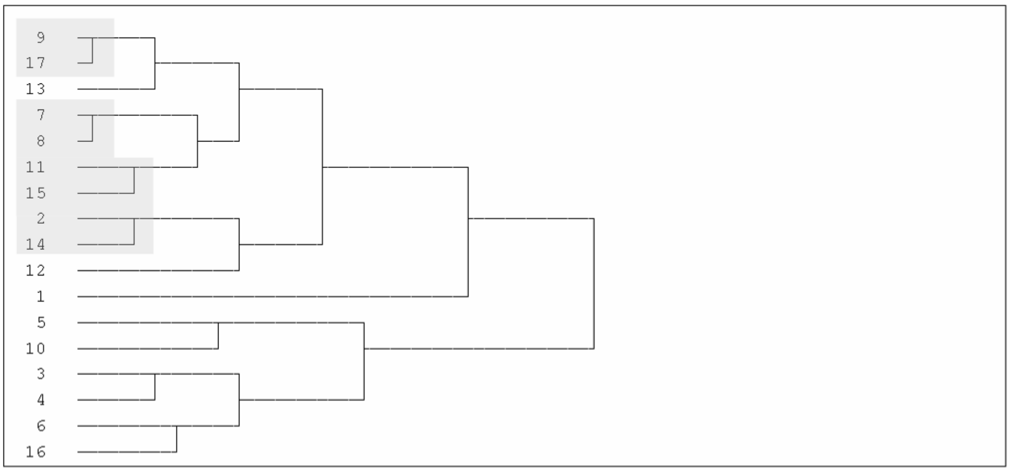
The first pair of criteria is related in the sense that they are two environmental dimensions put together. This might indicate that certain stakeholders don't discriminate between those two environmental media in their preference scheme. Noise and Quality of Landscape are both weighted very low, showing relative disinterest of the national stakeholder in these mostly local social issues. This stands in contrast to studies pointing to an public discourse on the intrusion of the landscape and major public rejection of for example, wind mills.

And also these criteria are weighted quite similarly:

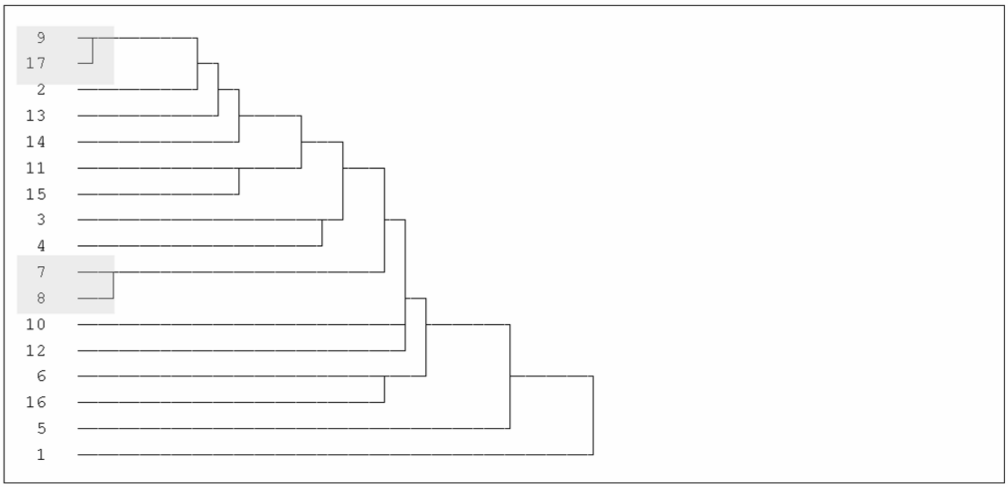
- Regional Self Determinacy (11) and Ecological Justice (15)
- Diversity of Technology (3) and Import Independency (4)
- Employment (2) and Technological Leadership (14)

The pair number three, Regional Self Determinacy and Ecological Justice, does not have a clear relation to each other than a rather low ranking at an average. Diversity of Technology and Import dependency are both criteria of the technological sustainability dimension and are weighted medium high on average. Both are associated with a certain importance but are not of priority. Similar is the pair number five, Employment and Technological Leadership, positioned in the middle position in the average weightings.

a)



b)



c)

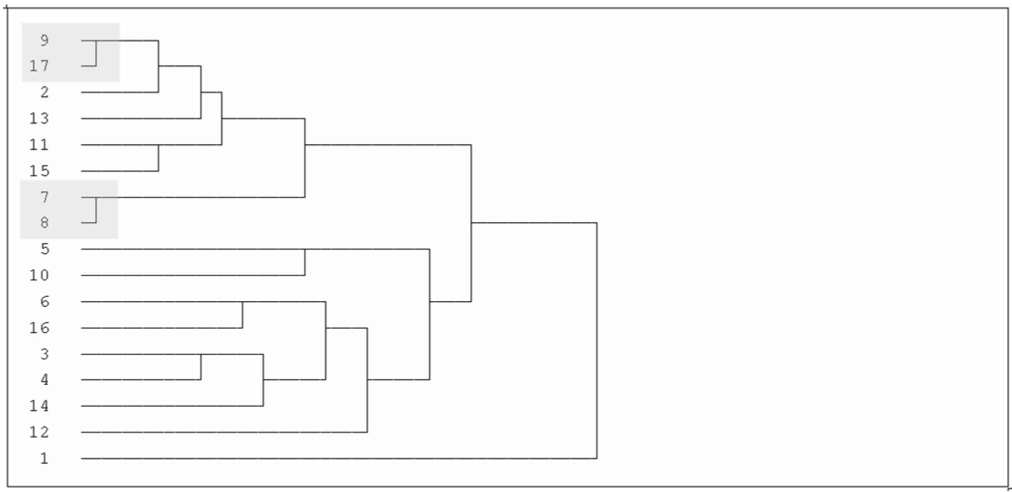


Figure 40. Cluster analysis of the criteria according to their weightings; a) furthest neighbour method, b) nearest neighbour, c) between groups method.

Sensitivity analysis on the role of the preference functions

Modulations of the preference functions

In the first sensitivity analysis (SA1 PF_allUsual) all the preference functions are set to the Usual type of function (see Figure 13 in Methods chapter). This means that even the smallest difference (d) according the scenario impacts within one criterion is translated to strict preference (1). In this case, no differentiation is made between smaller and larger impact differences (see Table 10 in Methods chapter, expected change). There is no indifference threshold and so the resolution is at a maximum, giving meaning to even the smallest data difference. Hence the assumed data uncertainty is at a minimum in this sensitivity analysis.

The overall effect of the sensitivity analysis, SA 1 PF_Usual, on the final ranking is:

- A change in the complete ranking: 12 of 16 rankings change the complete ranking of scenarios, mostly changes within first (E, C) and last (A, D) scenario cluster including a change of scenario B to the first rank. Prominent is the general trend concerning the last rank. In the SA 1 PF_Usual scenario A ranks last in most of the rankings (13 from 16 rankings in contrast to 4 from 16 rankings with standard PF). Concerning the first rank a characteristic change is also noticeable: scenario C is on top rank more often than with the standard PF (8 times in contrast to 4 times).
- Change in the partial ranking: there is a tendency to less parallel rankings including some rankings without any parallel sections, something which doesn't occur with the standard set of preference functions at all. Remarkable is that scenarios A and D, the bottom scenario cluster, are within this sensitivity analysis in linear position to each other in most rankings (15 times in contrast to three times). So scenario A is not only last in many scenarios but also last on its own in most cases.
- Change in net flow: net flows get larger (up till ± 43), so the scenarios are on a wider range due to these changes in the preference function.

In the next sensitivity analysis, SA 2 PF_Higher, a contrary effect is attempted than in the first sensitivity analysis. Here all the indifference thresholds are set higher for the quantitative criteria and an indifference threshold is introduced for the qualitative criteria. This analysis takes into account a higher degree of data uncertainty. An additional differentiation within the quantitative indicators is made concerning the data uncertainty. The indicators Cumulative Material and Energy Effort are associated with even higher uncertainty in this SA addressing their systemic nature and therefore immanent ambiguity of the system's boundaries resulting in higher uncertainty than in the indicators for air emissions (see Table 10 in the Methods chapter). The expected overall changes are basically contrary to the first sensitivity analysis.

The effect of the sensitivity analysis, SA 2 PF_Higher, on the final ranking is:

- Change in the complete ranking: 7 of 16 rankings change the complete ranking of scenarios, while only changes within the first (E, C) and last (A, D) scenario clusters occur. Scenario E is ranked first a bit more (14 times) than with the standard PF (12 times). Scenario D lands a bit more often on the last rank than in the standard PF (15 times in contrast to 12 times).
- Change in the partial ranking: there is a tendency to less parallel rankings including 6 rankings without any parallel sections, which doesn't occur with the standard set of preference functions at all and also less often in SA1 PF_Usual. Also striking is that in this SA the parallel ranking of scenarios A and D occurs less often. In 14 out of 16 rankings they are in a linear ranking in contrast to three rankings with the standard preference function. The highest ranked scenario E is more often ranked first exclusively (11 times in contrast to 4 times in the standard PF) and not in parallel ranking with scenario C.
- Change in net flow: net flows smallest of all PF SA (low till ± 0.06)

In the third sensitivity analysis, SA 3 PF_Level, the preference functions of the qualitative criteria are specifically manipulated. Since these preference functions are set without concrete stakeholder discussions, an additional sensitivity check is performed. All the preference functions of the qualitative criteria are changed to a Level function. This means that there are only 0, 0.5 and 1 (strict preference) available, which reduces the differences in data in the impact matrix to three classes of preferences in the preference matrix (see Table 10 in Methods chapter). This represents the assumption of higher uncertainty of all qualitative criteria independently if they are 3 or 5 level criteria. In that sense there is a homogenous uncertainty assumed for all criteria. The expected changes refer particularly to criteria with five qualitative intervals. The overall changes are expected to lie within the standard PF and the PF_Higher, where for all the criteria and indicator higher uncertainty is operationalised.

The effect of the sensitivity analysis, SA 3 PF_Level, on the final ranking is:

- Change in the complete ranking: eight out of 16 rankings change the complete ranking of scenarios, only changes within the first (E, C) last (A, D) scenario clusters. In 15 rankings scenario E is ranked first in contrast to 12 top ranks of scenario E with the standard PF. This effect is therefore even a bit stronger than in the SA 2 PF_Higher. Surprising is that scenario A ranks last in 11 times in contrast to four times with standard PF and two times in SA 2 PF_Higher.
- Change in the partial ranking: there are still numerous partial rankings with two parallel sections (6 "x-rankings"), more than in SA 1 and 2, which only have one ranking with

two parallel sections each. And there is only one partial ranking with complete ranking character (no parallel features) in this sensitivity analysis. One extraordinary ranking (participant 2) appears in this sensitivity analysis with scenario E high on top rank and then a three scenario cluster with C; B, and A; and D being bottom of the ranking. This is an uniquely bad ranking for C and B, which results in a parallel ranking with scenario A.

– Change in net flow: net flows get slightly higher (up till ± 0.30)

The stability of the scenario rankings towards chances of preference functions differs. Here rankings are identified which react to changes of the preference function to a larger extent than others. This contributes to the discussion of the overall stability of the final scenario rankings. The aim is to identify final stakeholder rankings that are more sensitive to changes in the preference function, and finally, to conclude on the stability of the rankings.

The sequence of scenarios in the complete rankings is robust in the following rankings.

– P1, P4, P12, and, P15 have the same sequence of scenarios in the standard PF and the PF_Usual.
– P2, P3, P4, P6, P9, P10, P11, P13, and P16 have the same scenario sequence in the standard PF and the PF_Higher
– P4, P8, P10, P12, P14, and P15 have a robust scenario sequence when preference function is changed towards PF_Level.
– P4 has the most robust scenario ranking. The sequence of scenarios is identical in the standard PF and all the SA of PF.

The complete ranking remains most constant when the preference functions are changed to PF_Higher. The sequence and position of the partial ranking stays the same in none of the 16 rankings throughout the PF sensitivity analysis. Dramatic changes occur according the sequence and the position in the parallel ranking of the scenarios through out the SA of the preferences functions in the rankings of P5, P7.

Discussion

This section discusses the empirical results from the case study application in the context of other relevant studies and current Austrian policy goals. It will discuss the individual results of the different scenarios, the results of the sustainability appraisal of the scenarios with the impact matrix, and the results of the MCA ranking exercise.

Scenarios

Overall renewable energy capacities

All scenarios show an increase in renewables compared to the base year 2002: scenario C +50%, scenario D + 101%. This increase is significant, even when compared to a linear extrapolation of the renewable capacities between 2002 and 2020 (+60 PJ/a), and still amounts to +5% or +111%, respectively. The scenarios generate between 188 PJ/a (scenario C) and 252 PJ/a (scenario D) in 2020, and the linear extrapolation resulted in 185 PJ/a, excluding large hydro power. In contrast, the respective renewable energy contribution amounted to 125 PJ/a in 2002.

A direct comparison of the scenario results with other prominent energy scenarios for Austria is problematic because they have either a different time frame or do not follow a specific focus on renewables and are thus too general. The only detailed renewable energy scenario was developed by Haas, Berger, and Kranzl (Haas et al. 2001), which extends only until 2010. It was used as the input database for the present case study modelling. Another study, by Kratena and Schleicher (Kratena and Schleicher 2001), extends until 2020, but represents an econometric energy scenario analysis with a strong economic focus and a high aggregation level in the renewable sector, which prevents direct comparisons. Furthermore, Kratena and Schleicher modelled the disaggregated electricity generation capacity of renewables only until 2010; it reaches 29.3- 37 PJ for three distinct scenarios (Baseline, Kyoto, and, Sustainable). The scenarios presented here, in contrast, reach between 47.3 and 59.2 PJ renewable electricity generation capacity in 2020 and are thus almost double the value of Kratena and Scheicher. This indicates that the assumed growth rates of the present renewables study are more optimistic, since a doubling within ten years would not otherwise be possible, but is basically within the same range.

In the present scenario analysis, an overall renewable capacity in 2020 of 188.2- 252.2 PJ/a is calculated. This is much higher than the overall results by Kratena, who estimates a respective capacity of 141.3PJ/a in 2020 (excluding hydro power). (Kratena and Wüger 2005) This result, however, is even lower than the linear extrapolation result reached in this study (185PJ/a) and thus probably a severe underestimate.

Austria is committed by the EU to increase the total renewable energy demand to 34% in the year 2020. Austria's current energy strategy assumes a development of the overall energy demand of 1,100 PJ/a for 2020, which would represent a stagnation at the level of the year 2005. (BMLFUW and BMWFI 2010) In this case, the renewables' commitment would amount to 390 PJ/a. Without the drastic underlying efficiency increases of this estimate, total energy demand in 2020 would probably rise to 1,300 PJ/a according to the Austrian strategy, and the renewable share would proportionally increase to 450 PJ/a. Table 17 provides a comparison of this target and the contribution of renewables modelled in this study.

3	Scenario A "Fast and Known"	Scenario B "Extension of Competitive Advantage"	Scenario C "Investments into the Future"	Scenario D "Extensive Use of Biomass"	Scenario E "Large Impact in Small-Scale Use"
Total energy demand in 2020[1] (PJ/a)			1,100 – 1,300		
Total amount of renewable energy in 2020 (PJ/a)	224.1	218.7	188.2	252.2	219.2
Share of renewables from total energy demand in 2020[1]	17.2 - 20.4%	16.8 - 19.9%	14.5 - 17.1%	19.4 - 22.9%	16.9 - 19.9%
Large-scale Hydro power in 2008[2] (PJ/a)			137		
Large-scale Hydro power in 2008 (%)			10.5-12.5%		
Total renewables (this study & large hydro power) 2008 (PJ/a)	361.1	355.7	325.2	389.2	356.2
(%)	27.8 - 32.8%	27.4 - 32.3%	25.0 - 29.6%	29.9 - 35.4%	27.4 - 32.4%

Table 17. Comparison of the renewable energy production and total energy demand in 2020, and the contribution of renewable energy modeled in the scenarios, excluding large-scale hydro power. For details, see text.
[1] (renewable energy strategy Austria) [2] Assumed to be at the same level as in the year 2008. (Biermayr 2009)

The renewable energy presented here contributes 14 to 23% to the total energy demand of approximately 1 100 – 1 300 PJ/a. It should be noted at this point that large hydropower is not included in the present study. Therefore, the development of the large hydropower by 2020 is taken from other studies to arrive at a comparable renewable share. In 2008, hydropower generates 140 PJ/a, of which 2.5%is contributed by small and intermediate hydro plants. (Biermayr 2009, Kratena and Schleicher 2001) estimate the total, i.e. large, intermediate and small, hydropower contribution at 154.52 PJ/a, whereas in a more recent energy modelling study, Kratena and Wüger 2005) estimate 128.3 PJ/a for 2020 (the reduction in capacity is assumed to be caused by measures relating to the Water Framework Directive of the European Union). For the matter of comparison, it is assumed that large hydropower will produce 137 PJ/a in 2020 (the same amount as in 2008), which is 10.5 to 12.5% of the total energy demand. Adding this amount to the amount of renewable energy resulting from the five scenarios, the results are comparable with the Austrian renewable strategy target overall. The scenarios reach between 25 -35.4% of the overall demand, depending on the scenario outputs as well as on the overall demand assumption for 2020 (see Table 17 for a scenario comparison). Only one scenario (D "Extensive Use of Biomass") clearly reaches the 34% goal, and only as long as the stagnating energy demand (1,100 PJ/a) is taken as basis of the comparison. All other scenarios fall well below this threshold.

The largest renewables capacity is reached by scenario D. It amounts to 252.2 PJ/a. Scenario D is maximising the biomass potential in Austria and reaches the highest additional capacities (see Table 11 in the Results chapter), especially in the heating section. Scenario A "Fast and Known" reaches only the second highest additional capacity with 224.1 PJ/a till 2020 and doesn't quite live up to its name. The main reason here is that scenario A has a much smaller bioenergy capacity for heat generation than scenario D (see Table 11 and Figure 21 in the Results chapter). The total renewables capacity of scenario B is the third highest with 218.7 PJ/a. The scenario arrives therefore at a renewables share in 2020 between 27.4 and 32.3%. Scenarios A and B come rather close to the EU aim of 34%. Scenario E reaches an intermediate renewable energy capacity of 219.2 PJ/a. Outstanding is the large electricity generating capacity in this scenario (a total of 59.2 PJ in 2020), which offers as much electricity supply as in scenarios A and B. One would imagine that the small scale technologies cannot amount to the same additional electricity supply. However, the institutional barriers associated with the transitions towards small scale energy systems are not yet captured in the modelling. The absolute increase of renewable energy supply is lowest in scenario C "Investment into the future" with merely 188.2 PJ/a. Technologies such as PV will not be able to reach large potentials till 2020, even if the growth rates are very ambitious. In that sense, the long-term scenarios in this mid-term case study have a definitive disadvantage, emphasising not yet fully mature technologies.

Biomass utilisation

The case study presented here attempts to contribute to the discussion on bioenergy by offering a detailed appraisal of the biomass technologies for heat, electricity and co-generation: first, by distinguishing between primary biomass utilisation and the use of biomass residues; second, by taking the life-cycle impacts of bioenergy generation into account; and finally, by introducing an indicator for the demand for area addressing the potential area conflicts. (Madlener et al. 2007) Scenario D “Biomass on a large scale” represents an ambitious biomass future not taking ecological systems limitations into account. The ranking of the scenarios is discussed in the section MCA rankings. With the exception of scenario D, biomass use was assumed to be for heat generation or for heat-power cogeneration, and not for electricity supply in the model. This is the most sensitive option with regard to greenhouse gas emissions and economic efficiency. (Kalt et al. 2010)

In the Austrian political discussion on renewable energy resources, biomass features prominently and constitutes a key element for the future heat and power production in recent governmental programs (e.g. BMWA 2004; International Energy Agency 2003, International Energy Agency 2005; Biomasse-Verband 2006). Biomass resources are, generally speaking, a land-area dependent resource, and (unlike wind or roof and façade solar power) are exclusive in their land area demand. Consequently, the demand for land used for bioenergy is in immediate conflict with other land use factors, such as the demand for agricultural areas to produce comestible goods, natural conservation areas, and recreational areas. Furthermore, the conflicting interests within the energy sector as well as in the competition of area for energy crops for heat and power generation and for biofuels for transport are acute in the present situation[85] (e.g. UBA 2004). Bioenergy scenario analyses by different authors do take these

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[85] The additional opportunities for producing energy crops on agricultural land areas are frequently pointed out in (bio-) energy discussions in Austria, as well as in other countries, and especially the cultivation of short-rotation coppice (SRC) has considerable potential as an alternative to cereal crops (cf. Haberl et al. 2003, Panoutsou 2007). Fallow agricultural land was heavily subsidised by the EU in the 1990s in order to mitigate overproduction, and constitutes an important reserve potential for biomass production (Haberl et al. 2002). Note, however, that the potential of fallow land that could be reactivated by growing energy crops has to be estimated in a conservative way and with great caution, since it has to be assumed that the farmers declared mainly those areas as fallow land which exhibited the lowest productivity.

Other institutional and economic obstacles, such as the new machinery and the longer periods of commitment of farmers (despite rapidly changing market conditions which create new risks), are important issues for the implementation of energy crop production. On the other hand, energy crops might have a future role in conflicting conditions into account at variable degrees; as a result there is much dissent related to the technical and economic potentials of additional biomass energy resources from forest biomass, biomass residues and energy crops (Neubarth and Kaltschmitt 2000, Haas et al. 2001, Haas et al. 2006, Kratena and Schleicher 2001, Kratena and Wüger 2005, Haberl et al. 2003).

In the present scenarios, a maximum additional dry biomass residue potential of 16.2 PJ/a (4,500 GWh) is assumed, which is based on the biomass modelling of Haberl and colleagues (Haberl et al. 2003) It is comparably more conservative, taking into account the growing demand of other sectors[86]. Depending on the focus of the scenarios, a different degree of this potential is realised until 2020. The qualitative scenario parameter 'System efficiency' is directly linked to the degree of realisation of biomass residues in the scenarios.

The sensitivity analysis of the scenarios show that the appraisal indicators respond to the share of primary biomass in the expected way: the sealed area equivalent, the CO_2 emissions and the cumulative material effort increase significantly.

The main reason for the maximum capacity increase in scenario D is that the biomass combustion sector, generating heat (175.2 PJ/a in 2020, which is 99.3 PJ/a additional capacity compared to the year 2002) is so much larger than in the other scenarios (25 PJ more than the next largest biomass combustion sector in scenario A). Scenario D "Extensive use of Biomass" reaches therefore a total of 252 PJ/a in 2020. The other scenarios range between 188.2- 224.1 PJ/a. Nevertheless, the assumption of scenario D is in line with the studies by Kranzl (Kranzl 2002) and Haas (Haas et al. 2006), who claim that an additional 100 PJ until 2020 would

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providing a new business opportunity for Austrian farmers, helping to mitigate or even reverse migration into the cities and, related to it, infrastructural problems in the countryside.

An alternative to SRC that is in discussion too is the utilisation of traditional comestible cereals, such as wheat, maize etc. for energy generation. In this case, though, there are pressing ethical matters at hand

[86] The utilisation of biomass residues is already carried out to a large degree and additional potentials for renewable heat and power generation is in question. The main suppliers for biomass residues are the wood industry and the pulp and paper industry (black liquor). Active demand comes from the pulp and paper industry itself, the furniture industry, particle board industry, and the energy sector in the form of wood chips. The additional potential of dry biomass residues is therefore very limited, and a possible shift towards the energy sector is likely to create tensions and resource scarcity in other sectors. The growing biogas sector is an additional recipient for wet biomass and here the overall market demand is still lower.

represent sustainable and feasible increases of the biomass combustion sector. With this amount of heat energy, up to 44% of households could be supplied with biomass heating systems in 2020, assuming parallel increases in efficiency. (Kranzl 2002)

Indicators- Impact matrix

The scenarios were all evaluated on the basis of 25 sustainability appraisal indicators. Compared to other multi-criteria appraisals of energy scenarios (e.g. Renn et al. 1984, Georgopoulou et al. 1997, MacDowall and Eames 2006, Gamboa et al. 2008), this represents an exceptionally extensive number. The evaluation aimed at covering the entire sustainability dimensions spectrum, plus an additional technological dimension. Therefore, qualitative as well as quantitative appraisal indicators were applied.

Performance of the scenarios with regard to selected indicators

The indicator 'CO_2 equivalents emissions' is one of the most prominent sustainability parameters. It reflects the importance of climate change as a key issue in the overall energy debate. It should be noted at this point that, even though renewable energy is a viable means for reducing carbon emissions and mitigating climate change, renewable energy technologies are not CO_2 neutral: their production and the installation of infrastructure require energy inputs in form of fossil fuels (Pehnt 2006). Nevertheless, renewable energy provision in general is associated with fewer emissions when compared to conventional, fossil fuel based energy provision. For example, even modern fossil fuel based energy generation, based on a co-generation gas turbine) is associated with CO_2 equivalents-emissions of 158.6 t/ TJ during the entire life cycle, whereas renewable energy technologies, according to GEMIS (Ökologie-Institut 2006), range between 0 and 84 t/ TJ CO_2 equivalents.

It is sensible to consider the associated CO_2 emissions of renewable energy technologies, as it is the net-effect of reducing GHG emissions to the atmosphere that is of importance. The substitution potential for fossil fuels has to be reduced by GHG emissions that accrue during the establishment and operation of renewable energy technologies.

In particular the share of biomass-based energy provision has a large impact on the GHG performance of the scenarios. The GEMIS database (Ökologie-Institut 2006) indicates that biomass for energy provision, in particular for non-heat forms, is associated with especially large emissions per unit of energy provided. These emissions occur during the transport, fertilisation, drying and in some cases gasification processes.

The scenarios A-E are all similar according to their CO_2 emissions, ranging from 16 to 21 tCO_2 equivalents /TJ/a. Scenario D, the biomass scenario, clearly shows larger emissions (21t CO_2 equivalents/TJ/a). Since the scenarios comprise only parts of the Austrian energy supply systems, and focus on electricity and heat generation only, it is not possible to compare CO_2 results with the other studies available in Austria for 2020 (see above). A comparison with partial results of existing studies reveals that the results are well in line with other scenario analyses.

According to the impacts on air quality which are approximated by the indicators SO_2 equivalents, TOPP (surface near ozone) and particulate matter, the overall picture shows that in a life cycle perspective renewables perform much better than fossil fuels. However, scenarios are different due to the different mix of renewable technologies applied which all show different profiles with regard to these indicators. Biomass utilisation, which always includes a combustion process and therefore air emissions, is associated with large emissions. In particular, the emission of particulate matter is relevant for biomass combustion processes. (Baumbach et al. 2010) This causes the weak performance of scenario D. On the other hand, small scale technologies are characterised by comparably larger air emissions, owing to difficulties in reaching high efficiency standards which require installation of costly and sophisticated filter systems. A sensitivity analysis that investigates the specific effects of the degree of decentralisation of future energy systems clearly illustrates that fostering decentralised energy systems results in severe rises with regard to these environmental indicators (for further detail see section Sensitivity Analysis). The scenarios C and E, in contrast, are of a more large-scale nature with high systems efficiency and a high share of cascade utilisation. In consequence, it is no surprise that these scenarios perform well with regard to these environmental criteria. Scenario E always ranks lower than scenario C, because the negative environmental impacts of decentralised technologies outweigh the positive environmental effects of cascade utilisation.

The criteria Ecological Justice was operationalised by the indicator Sealed Area Equivalents (see Method section). This indicator is based on the basic accounting principle of the sustainability indicator Human Appropriation of Net Primary Production (HANPP; Vitousek 1986, Haberl and Erb Haberl 1997 Haberl et al. 2004b, Erb et al. 2009), The indicator is an estimate of the ecological pressure associated with the operation of renewable technologies, resulting from instalment of production plants and also the harvest of biomass. It estimates the amount of area that would have to be sealed – and thus deprived of vegetation – in order to exert the same pressure as the sum of installation and biomass harvest (see Method section). Thus, this indicator can be interpreted as a proxy for the appropriation of biological production by human society which, in consequence, is not available any more for other heterotrophic species. This indicator is specifically sensitive to the extent of primary biomass use, as the biomass harvest impact is by far larger than the impact on production exerted by the installation of power plants. Only a large share of hydropower, which itself has a disproportionately high sealed area demand is also relevant in this context. In other words, the area required to install land-based infrastructure is much smaller than the area required for harvesting the required amounts of biomass. This finding is well in line with the recent study by Haberl and colleagues (Haberl et al. 2007), that found that from the total of 24% of the global human appropriation of net primary production in the year 2000, only 4% are due to infrastructure, the lion's share (50%) being due to agricultural activities. The differences of the individual scenarios related to the criterion Ecological Justice are similar to most other indicators of the environmental evaluation dimension: scenario D performs poorly and scenario C performs well. Sealed area equivalents are proportionally linked to the use of primary biomass and are insensitive to the use of biomass residues, a fact that is also demonstrated clearly in the sensitivity analysis. Those scenarios with large-scale photo voltaic energy generation perform particularly, as it is assumed that PV cells are only installed on rooftops and facades of buildings and are thus not accounted for in the sealed area equivalent calculation.

The indicators Cumulated Energy Effort and Cumulated Material Effort are highly aggregated environmental pressure indicators with complex definitions of system boundaries (Haberl Haberl et al. 2004a, Haberl 2001, . They can be understood as indicators of overall environmental burdens exerted by certain activities. However, it is difficult to associate these flows directly and unambiguously with their direct environmental impacts (van der Voet et al. 2004), which sometimes hampers straightforward interpretation of the results. Nevertheless, it is commonly agreed in the literature (Baccini et al. 1991, Adriaanse et al. 1997, Weisz and Duchin 2006; Weisz and Schandl 2008, Matthews et al. 2000) that these indicators are particularly indicative for the analysis of trends, and, in combination with economic indicators, are able to give evidence for relative and absolute decoupling, i.e. the de-linking of economic value added from resource use. This is the reason why the stakeholder in the participatory process have agreed to use this indicator set for indicating environmental burdens beyond climate change, air quality and ecological justice. Cumulated Material Effort is particularly large in scenario C, with 105.2 t per TJ/a, which is a result of the material intensive silicate mining processes associated to the production of photovoltaic (PV) cells. All other scenarios range between 75.5 and 83.2 t /TJ/a Despite the energy intensive production process of PV, scenario C is much less pronounced when calculating cumulative energy flows, where scenario C performs best. A possible explanation might be that even PV technology production processes are rather energy intensive; the running of the technology might be counterbalancing this effect. Overall, PV offers good performance according the cumulative energy flows. However, this might indicate data distortion, owing to insufficient input data in the GEMIS database. Thus, further analysis of this indicator will have to be handled with care.

One of the most central social sustainability criteria, social justice, could not be applied in the appraisal, because – as a result of the interviews with the experts – it became clear that degrees of Social Justice can not be judged from the information generated in the scenario modelling. For example, an operationalisation of social justice could be the affordability of energy; however, information was not available to make a solid estimation of energy prices. To make robust statements on prices and affordability in 2020, assumptions on concrete policy measures and subsidy schemes are necessary, which was far beyond the scope of the empirical effort presented here. For that reason the indictor was eliminated from the assessment. Nevertheless, the criterion was included in the stakeholder ranking exercise and is therefore part of the discussion on the importance of sustainability criteria for more sustainable energy systems.

Naturally, there are also economic reasons in favour of installing renewable energy technologies in general. (Volpi 2005) Many renewables have the structural economic advantage that the variable costs are very low. There might be manifest investment costs but usually the running of the renewable power or heat plant is decisively cheaper than fossil fuel power plants. (Jacobsson and Lauber 2005) Governmental subsidies schemes provide starting aid for technologies not fully ready for competitive markets[87]. The costs of renewable energy technologies do, however, vary. The overall picture according to the renewable energy scenarios at hand is that the two decentralised scenarios E and C are associated with higher costs per energy unit. This is not further surprising. Scenario C ranks lowest in the cost factor, i.e. it is associated with the highest costs, being characterised by small scale technologies with large infrastructure costs and photovoltaics as the key technology. Scenario D, the biomass strategy, is performing best according to the cost factor, whereas the scenarios with large scale technology (A and B) yield similar results (between 40,000 and 43,000 €/ TJ).

[87] Which indeed as been the same case at the outset of fossil-fuel technology, as well as nuclear power and large-scale hydro power. (Jacobsson and Lauber 2005)

The indicator 'Effect on the Public Budget' represents the macro economic costs dimension integrated in the sustainability appraisal. This indicator does not account for public revenue but only for public spending. Whereas the criterion 'Costs' addresses the microeconomic costs on the business level, the criterion 'Effect on the public budget' focuses on the public expenditures. Governmental subsidies are investments covered by taxes that allow for a certain time pilot technologies to develop in a niche until they are able to gain market competitiveness. [88] In consequence, mature, established technologies perform better then young niche technologies. In the scenario appraisal, a further assumption was influencing this indicator: the establishment of new institutions is associated with surging increases in the public budget. New institutions represent an additional policy effort and consequently an enhanced public budget spending. This is surely a strong oversimplification that does not take into account the fact that new institutions might be more efficient and less prone to e.g. organisational problems and conflicting spheres of interest. Nevertheless, this reasoning is an attempt to address the institutional change dimension in the appraisal also from an economic point of view.

The other prominent macroeconomic dimension, employment, is discussed widely in context of renewable energy technologies. In the year 2004 19,100 jobs were available in the renewable technology production sector in Austria, and an additional 13,600 jobs were created in servicing and running renewable energy technologies. (Haas et al. 2006) This is quite a substantial contribution to the Austrian labour market. Employment has a social and an economic side: specifically, for the employment of (part time) farmers and in general for the benefit of inhabitants of rural areas. Employment represents an important political, social and economic challenge that can be addressed by the establishment and expansion of renewable energy systems. Among the renewable energy scenarios the greatest effect on employment is attributed to scenario E, owing to the decentralised nature of the energy system. Generally speaking, decentralised technologies are more labour intensive per energy unit than centralised, large scale technologies. However, the specific quality of the generated jobs is not addressed in the appraisal, which is an important aspect, in particular with regard to gender issues (Abbasi and Abbasi 2000, Clancy et al. 2004). Looking at it from a labour market perspective, though, there

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[88] The economic gains due to renewable energy technologies are substantial in Austria but not included in this appraisal. Recent studies show that the production of renewable energy technologies created a business volume of € 1,461 Mio Euro in Austria in 2004. The study accounts for direct effects (technology production), indirect effects (intermediate products, such as semiconductor industry in Austria) and secondary effects (due to increased incomes). (Haas et al. 2006)

exist more important and also more efficient employment policy tools that operate towards full employment than there is for management of energy transitions.

The spider web diagrams clearly show the overall sustainability profile of the scenarios. A comparison of the scenarios in the area size show significant differences, and the favourable scenarios (E and C) are well indicated. However, the diagram also shows that the scenarios have top performance in certain sustainability appraisal criteria. E.g. scenario D, which is obviously not performing very well overall, is the best according to the 'Costs' criterion and certain Water quality indicators (inorganic acids, AOX).

Trade offs and synergies

Detailed analyses of the impact matrix that tested the overall robustness of the results revealed inherent structures and offered a better understanding of the distinct results on the final scenario ranking. An analysis was performed that aimed at examining which criteria are supportive of or in conflict to each other, information that allows detailed analysis of trade-offs and synergies within the sustainability dimensions.

The GAIA plane visualises the discrimination direction of the 17 sustainability appraisal criteria. The plates provide two types of information: the direction of each indicator, and the length of its vector. Whereas the direction offers relative information - similar directions indicate supportive structures (synergies), opposite directions indicate conflicting structures (trade-offs), and the length indicates the discriminative power of the indicator for the overall ranking. (Bana e Costa 1990, Geldermann and Zhang 2001) The most discriminative criteria in this case study are (a) Phosphor Water Emissions, (b) Biological and (c) Chemical Oxygen Demand, (d) Noise, and (e) Security of Supply. Also rather strongly discriminative are the criteria (f) Effect on Public Budget, (g) Quality of Landscape, and (h) Regional Self Determinacy. The criteria (a), (b), and, (c) represent quantitative criteria, whereas all the others are qualitatively appraised criteria. A detailed investigation showed that those criteria that are characterised by a large range of the individual scenario results are the most discriminative criteria. In other words, criteria that have a high relative standard deviation (standard deviation divided by the mean of the results) are more influential on the final scenario ranking than criteria with a low standard deviation. The investigations showed, however, that the length of the vector is very sensitive to minor changes of the preference functions resulting in weakness. Therefore, the length of the GAIA vectors is not considered a reliable proxy in this case study for the identification of highly influential criteria. However one methodological insight is gained: despite the Water Quality indictors, which already showed poor data reliability, all the other highly discriminative criteria are qualitative criteria. This fact raises the question of whether the quantitative and qualitative criteria are treated differently in the GAIA interpretation, due to the different characteristics of the data. A possible explanation might be that there is a tendency for qualitative criteria, the full appraisal range was used by the experts, in order to put more differential weight to the individual scenarios, whereas for the quantitative the range of results is the outcome of a quantitative modelling exercise and that can, at least in principle, generate very similar results for each scenario.

On the contrary, the relative information of the positioning of the appraisal criteria towards each other is experienced as a valuable asset to the GAIA visualisation. The overall picture reveals that the environmental, social, technological, and economic criteria cover quite a large range. In particular the environmental dimension covers a very large range and is least homogeneous. A few criteria seem to point in opposing directions, for example the indicator 'Cumulated Material Effort' which indicates a more economic-dominated direction and 'Employment' which leans in the direction of social sustainability criteria (see Figure 41).

The environmental dimension covers the widest range in the plane, spreading across three quarters of the full circle. Most indicators are in supportive or neutral positions towards each other, but there are conflicts within the dimension. The indicators 'Cumulative Material Effort' and 'SO_2 equivalents' seem to be in conflicting positions. This shows that SO_2 emissions are not linearly linked to the amount of material used, but that certain technologies use processes that are related to especially high sulphur emissions. The environmental dimension strongly overlaps with the social and technological criteria range.

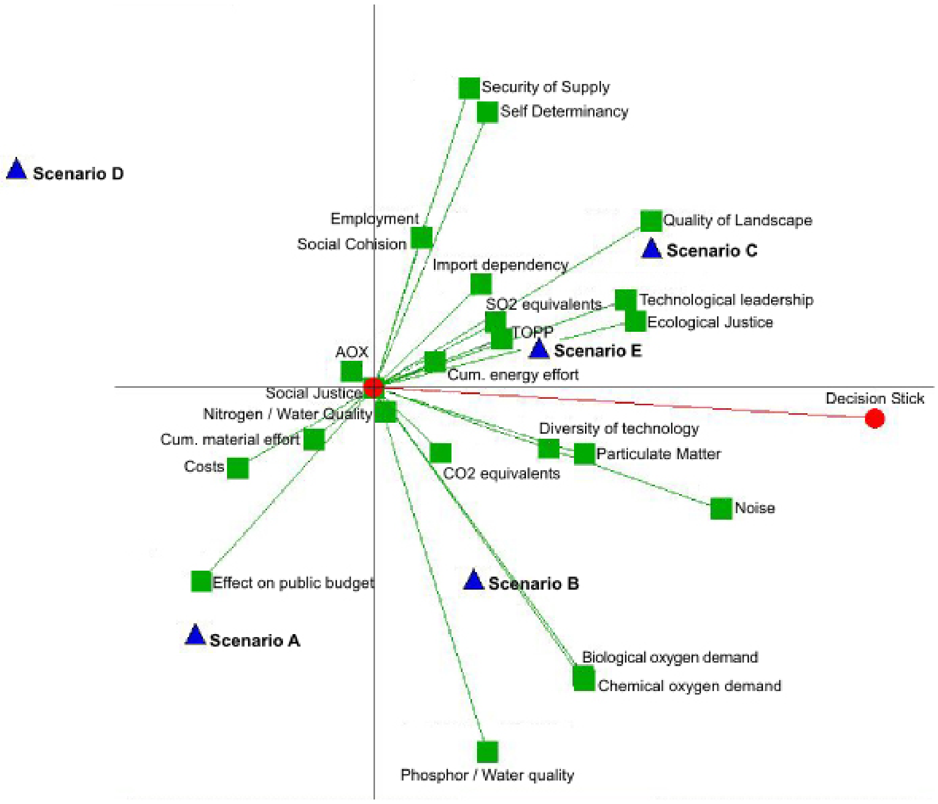

Figure 41. Visualisation by GAIA of the overall impact matrix representing the sustainability criteria impacts across the five scenarios

The social dimension covers an area of 90° and is in this sense very compact. None of the social criteria are in a conflicting position to each other. Remarkably, there is much overlap of technological criteria, such as Security of Supply, Import Dependency, and Technological Leadership. Also striking is the economic criterion ‘Employment’ which is in a supporting position to many social criteria and even completely overlaps the social criterion ‘Social Cohesion’. In contrast, the other economic criteria are in conflicting positions with the social criteria. The economic dimension is represented by merely three criteria which cover a rather large range of 160°. This clearly indicates that they are in conflict with each other. The criteria ‘Costs and Effect on Public Spending’ stands in contrast to the criteria ‘Employment’, which indicates that technologies that are minimising micro- and macro economic costs are not necessarily creating additional jobs. Moreover, the economic criteria are in opposition to most of the social and technological criteria as well as to some of the environmental indicators as well. As mentioned, one exception is ‘Cumulative Material Effort’, which is closely related to the economic criteria ‘Costs’ and ‘Effect on Public Budget’. The technological criteria spread across an area of 90° , similar to the social criteria. The GAIA plane presents the technological criteria in a supporting or neutral position towards the social criteria and environmental criteria and is in direct conflict to Costs and Effect on Public Budget.

Stakeholder weightings of the criteria

The operationalisation of the indicators allows for a standardized evaluation of the different scenarios, and provides the basis for the multi criteria analysis. In order to take the legitimate differences into account regarding the importance of the indicators in the MCA, the individual weight of each of the 17 criteria was determined by the stakeholders in individual interviews. The resulting average weights and their associated standard deviations can be regarded as a cross-section through the social preferences according to different goals related to more sustainable energy systems.

On average, the highest relative weights were put on three criteria (arithmetic mean of all 16 stakeholder weightings): Climate Change (9.74%), Rational Use of Resources (7.51 %) and (at the same level) Security of Supply (7.51%), almost doubling their relative weight compared to an equal weighing. The box plot (Figure 41. in the Discussion chapter) reveals that apparently there is a broad consensus within the stakeholders that positive climate change properties are a major goal for future sustainable energy systems. This finding is corroborated by the fact that Climate Change weightings by the stakeholders also have the lowest standard deviation. In contrast, a large standard deviation indicates that the criterion Rational Use of Resources is associated with a high ambiguity with regard to this target in future sustainable energy systems.

Surprisingly, no economic criteria are ranked within the top three. The highest ranked economic criterion is Costs (rank 4 with an average weight of 7.04%), followed by Employment (rank 6, 6.4%) and Effect on Public Budget (rank 11, 5.39%). Unusual about the criterion Effect on Public Budget is that is has the highest standard deviation, which indicates that stakeholders have very ambiguous opinions on the importance of public investments for more sustainable energy systems.

The lowest average weights are put on the following three criteria (in increasing order): Quality of Landscape (3.29%), Noise (3.42%), and Ecological Justice (4.47%). This ranking is shared by the majority of the stakeholders, as the low standard deviations point out, with exception of the criterion Quality of Landscape. Strikingly, the "local" issues such as Quality of Landscape and Noise, but also Regional Self Determinacy (rank 13 out of 17) are weighted very low. This might be due to the institutional level of this study, which included only national stakeholders. A parallel study undertaken on the local level reveals a completely different weighting structure: Quality of Landscape and Noise have a much more prominent position in the preference structure Omann et al. forthcoming

Similarities between stakeholder weightings

According to the cluster analysis of the stakeholder weightings, four stakeholder groups are significantly more similar to each other than to the rest of the stakeholders (see Table 32. in the Results chapter). However, it is difficult to interpret the emerging cluster of stakeholders. The four groups are rather heterogeneous and no clear picture is apparent. However, some clusters show a tendency towards a certain position (direction of thought and action). The first cluster is basically a group of small niche actors comprised of two NGOs (Euro Solar, WWF) and the research unit Centre for Social Innovation. Their major role seems to be a protection of niches. In the second cluster, two representatives for small hydro power and wind power are grouped together with the Federal Ministry for Transport, Innovation and Technology (BMVIT) and the Consumer Interest Council (VKI). This seems to be a group of more established niche energy players, representing an agency than aims to expand successful niches and gain efficiency. The third group is comprised of only two stakeholders: the Federal Ministry of Agriculture, Forestry, Environment, and, Water Management (BMLFUW), the Environment section, and the Renewable Energy Representative (AEE). Both are strongly supportive of renewables and play the role of renewable energy advocates.

The last stakeholder cluster is heterogeneous, but has a tendency to administration functions with has on the overall the highest regime affiliation. Belonging to this stakeholder cluster are the Chamber for Labour (AK), the Austrian Business Council for Sustainable Development (ABCSD), Global 2000, the Chamber of Agriculture, and the Representative of State Owned Forest. The environmental NGO Global 2000 is an exception to this overall pattern.

This result is contrary to the expectations one might have. Surprisingly, the clusters are ambiguous. The expected similarities of the weighting scheme that would group e.g. private businesses, administrative institutions, environmental NGOs, etc. together, are basically not present.

MCA ranking of the renewable energy scenario

When comparing the 16 final scenario rankings, it is surprising to find that of the mathematical possibility of 120 rankings (according to the faculty of 5, 5!), only 4 different rankings emerge (see Table 15. in Results chapter). The final results show an unambiguous general pattern along the 16 different stakeholder scenario rankings, with scenario E “Large Impact in Small Scale Use” and scenario C “Investment into the Future” in a top position (top cluster). Scenario B

"Extension of Competitive Advantage" in an intermediate position and scenarios A "Fast and Known" and D "Extensive Use of Biomass" ranked low (bottom cluster). The distance between the scenario E and C and between scenario A and D is in most cases very small. Apparently, the individual weight sets of the stakeholders act only upon the sequence within the top cluster of scenario E and C and within the bottom cluster of scenario A and D.

In the majority of cases, the top ranked scenario is scenario E "Large Impact in Small Scale Use", i.e. the most decentralised renewable energy system among all the scenarios. Even though the emission efficiency and cost efficiency of small scale technologies is structurally below average (see Sensitivity analysis), this was counterbalanced by the advantages of decentralised energy systems, such as the strong employment effect and higher security of supply (Haas et al. 2006), but also the often neglected effects such as positive impacts on social cohesion, diversity of technologies, or regional self-determinacy. Nevertheless, the result is surprising because decentralised energy systems represent niche technologies that are not fully recognised in energy policy. One reason for this relates to the immanent challenges in respect to grid management in decentralized energy systems, issues that were regarded by the stakeholders as merely technical and organisational challenges that would be met in the course of technological development. Scenario C, "Investment into the Future", the innovation driven R&D strategy, is always in the top cluster with scenario E and also top ranked in 4 stakeholder scenario rankings.

Similarly surprising is the fact that scenario D "Extensive use of biomass" is most often ranked on the last position (12 out of 16 times). In that respect, it has to be pointed out again that scenario D represents a centralised biomass scenario with a large fraction of primary biomass input (30 PJ/a) and a high share of direct electricity generation from solid biomass. It should be noted at this point that this form of biomass utilization is not subsidized anymore since the amendment of the feed-in tariffs in the Green Electricity Ordinance in Austria in the year 2010. (BMWFJ 2010) Therefore, this result should not be interpreted as a general indication of poor performance of bioenergy utilisation. In all five renewable energy scenarios biomass is employed for energy generation. The result rather points to the sustainability issues related to specific processes of biomass utilisation, issues that apparently deserve more emphasis in the discussion of sustainable potential of biomass in Austria. Scenario A, "Fast and Known", is also ranked low in the MCA. Whereas the scenario B "Extension of Competitive Advantage" is ranked on the intermediate position 16 out of 16 rankings. This is a surprisingly robust scenario.

Both scenarios in the top cluster represent decentralised energy systems that rely on the establishment of new institutions. This fact can be interpreted as an indication of the fundamental changes that are required of stakeholders' perceptions in order to bring about a transition towards more sustainable energy systems.

The scenario rankings of the stakeholders are so similar that obviously the overall influence of the weights on the final ranking is not very strong. Therefore, it can be concluded that the main ranking structure is very robust and primarily determined by the technical scoring processes summarised in the impact matrix. A similar finding is also described in Salo and Punkka (2005), who developed a method that is able to handle incomplete preference information in hierarchical weighting models. The weights on the criteria do influence the scenario ranking only in cases where scenarios rank closely together. Within the top and bottom scenario clusters, scenario positions are very sensitive and switch position in accordance to the complex interplay of indicator results and weighting estimates.

The dominant influence of the impact matrix on the scenario rankings in this case study can be demonstrated in the following spider web diagrams (Figure 42). For each renewable energy scenario the performance of the individual scenarios based on each indicator is accounted for on a five-notch scale. The influence of the weighting sets are not accounted for. The best performance in the impact matrix is ranked highest with 5. The spider web diagrams are a simplified presentation with all the impacts indexed. The size of the resulting area indicates – in general terms - the overall performance of the scenarios according to the impact matrix. Scenarios C and E have the largest area spanned across the indicators, whereas scenarios D and A clearly have a smaller area. Scenario B is in a middle position. The comparison of the specific form of the coloured area allows the similarities and differences of the characteristics of the scenarios to be comprehended.

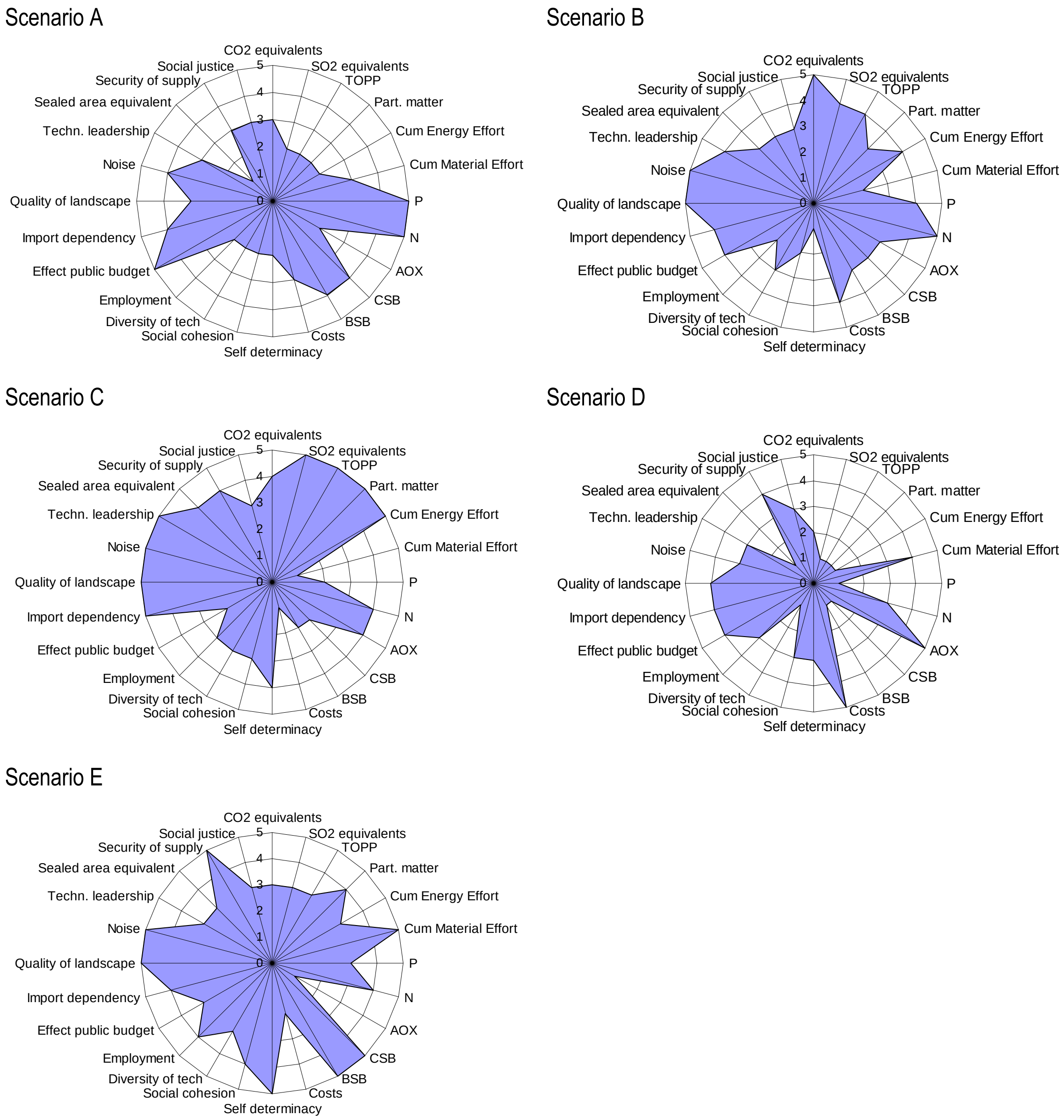

Figure 42. Spider web diagrams of the five scenarios. Each spoke represents a sustainability indicator, the performance of each indicator is accounted for on a five-notch scale (5… best, 0… worst).

Figure 42 suggests that apparently superior performance of scenario C and E is already a feature of the performance scores, even before weighting are taken into account, helping to explain the prevalence of this finding under all weighted perspectives. Some analysis of sensitivities to pessimistic and optimistic assumptions in the technical scoring process, would allow better exploration of the extent of this 'hard-wiring' of performance patterns in a particular set of scores.

Therefore the stakeholder clustering according to the weighting exercise and the groupings according to the scenario rankings are only partly congruent (see Table 18). Apparently, similarities in the weighting sets do not necessarily result in an identical scenario ranking.

		Weighting Cluster 1	Weighting Cluster 2	Weighting Cluster 3	Weighting Cluster 4	Weighting No cluster
MCA	ranking type 1		3, 13, 11	4, 7	2, 6, 10	16
MCA	ranking type 2		14		12	8
MCA	ranking type 3	9, 15			5	
MCA	ranking type 4	1				

Table 18. Comparison of weighting clusters and ranking results. The numbers in the cells refer to the 16 individual stakeholders in each cluster. For discussion see text.

This leads to the conclusion that the transportation of social preferences via the translation of criteria rankings in weights, based on the SIMOS method (see Method section), has only limited effects on the scenario ranking in the MCA. Not even the closest related stakeholders according to their weighting patterns arrive at an identical ranking of scenarios (for example, the stakeholder pairs 1 and 9, which are the closest pair across all clustering methods).

One reason for this discrepancy could be a methodological artefact of the cluster analysis. Although stakeholders 1, the Centre for Social Innovation, and 9, Euro Solar, are the most similar stakeholders with regard to their weighting scheme, an in-depth analysis reveals that nevertheless their weightings differ substantially, enough to lead to a distinct scenario ranking. This fact is illustrated in Figure 43. Whereas for criteria such as Climate Change Properties, Rational Resource Use, Diversity of Technologies and Social Cohesion a high agreement prevails (close to the 45° line), the two stakeholders disagree considerably about the importance of the effects on public budget, quality of landscape, social justice and employment. This, of course, reflects their different perceptions and positions as a social oriented research institute and a more economically oriented producer of solar energy.

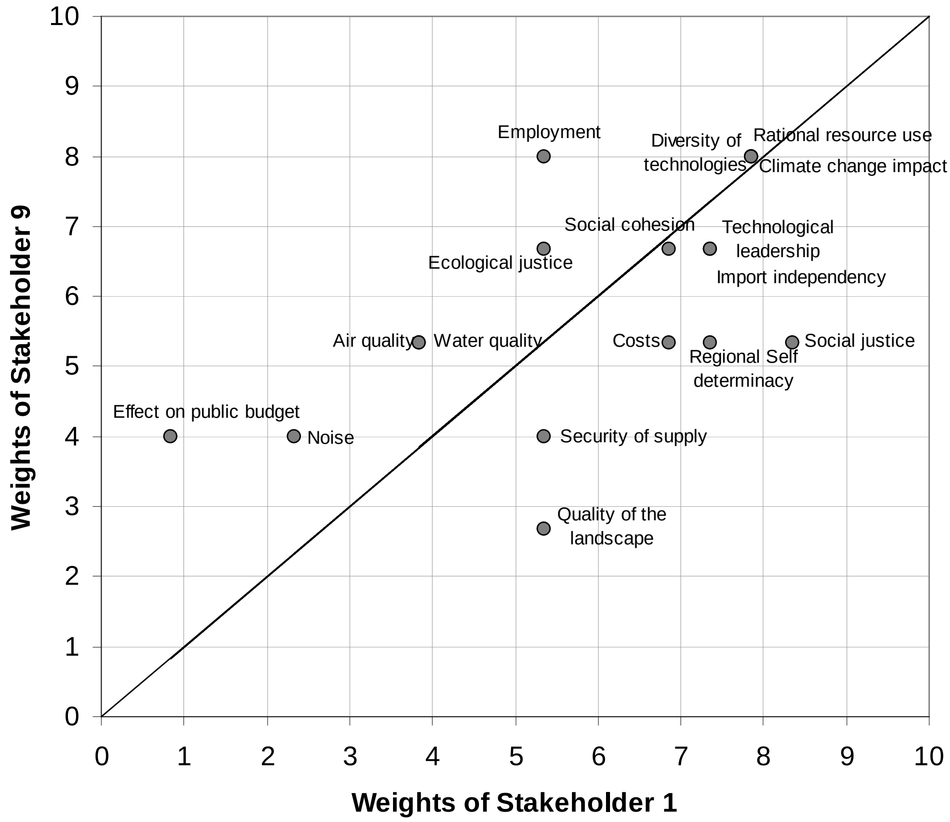

Figure 43. Comparison of the weighting schemes of stakeholders 1 and 9, the most similar stakeholders according to the cluster analysis. Each dot represents a sustainability criterion, the x-y position in the coordinate system is determined by the corresponding weight of Stakeholder 1 (x axis) and 9 (y axis). The 45° line indicates hypothetical 100% agreement.

However, methodological biases could also be responsible for the determining influence of the impact matrix and the surprising discrepancy between clusters of weights and groups of scenario ranking. One possible methodological intricacy could relate to the relatively high number of criteria. Due to their high number, low weights for each of the indicators are determined by the SIMOS method, as the sum of all weights adds up to 100. Consequently, when more indicators are weighted, the differences in their weights become smaller. There might come a time when the order of magnitude in weight differences is too small to be effective when compared to the differences within the impact matrix. This might have been an additional effect in this case study. However, no cases are documented in the literature (to the knowledge of the author) where a possible implication of the number of criteria is discussed. Obviously, further methodological work is needed to elaborate on this issue. In order to learn more about the effects of the weighting on the ranking results, various sensitivity analyses were performed in this study. The results of these analyses are discussed in the following chapter.

Discussion of the sensitivity analyses on weightings

As a starting point for the first sensitivity analysis, the weights of all criteria were set equal, resulting in a relative weight of each indicator of 5.8% (100 divided by 17). This allowed investigation of the overall effect of stakeholder weightings by providing an un-weighted control ranking. This resulted in the following rank of scenarios: E – C – B – A – D. Apparently, this is identical to the most frequent ranking resulting from the stakeholder weighting exercise, which indicates that the ranking is surprisingly robust. The main difference between the equal weights ranking compared to the individually weighted rankings is the distinct distance between scenarios A and D. The main explanation here is that scenario D is performing especially well in terms of economic criteria, and therefore its ranking depends strongly on the weight of this dimension. This indicates that most stakeholders rank economic criteria strongly, well above average. However, this is also the result of a methodological artefact: applying equal weights, the number of criteria becomes crucial, as discussed above. Since the economic dimension is represented by only three criteria, those scenarios with above-average performance in economic terms are ranked low, such as scenario D.

Another finding is that the scale on which the equal weight scenarios are ranked is higher (± 0.25) than in the average stakeholder rankings. The scale is represented by the range of the net flow (Φ). Net flows are an indication of the distance between highest and lowest scenario. A large net flow can indicate that the scenarios are relatively diverse, whereas a small net flow is an indication for greater similarity between the scenarios. In the hypothetical no-weight setting, differences between the scenarios are pronounced. In other words, the weightings schemes of the stakeholders actually bring the scenarios closer together. This is an indication that at least some of the criteria with a high discriminatory power for the ranking are weighted very low by the stakeholders. This can be seen in the example with the water quality indicators, which are considered less important by the stakeholders.

In a second sensitivity analysis, a disproportionately large weight, 70%, is put on one of the four sustainability appraisal dimensions. This approach allows for insights as to whether the scenario's performance is typical for a single sustainability dimension. Furthermore, it allows for investigation into the robustness of the final rankings by modulating the weights of the criteria in an extreme way.

In cases where the social sustainability dimension is emphasised (increasing the weight of this dimension to 70%), scenario E "Large impact in small scale use" is ranked first throughout all stakeholder rankings and scenario A "Fast and Known", the most centralised scenario, is ranked lowest in a robust manner. An overall increased net flow indicates that the scenarios are more differential in this sensitivity analysis. In the case where the weight of the economic dimension is increased drastically, the overall effect is a clear improvement of the ranking of scenario D. The relative weight of economic dimension has to be increased beyond 70% in order for scenario D to receive top ranking. In such an extreme case, scenario C is ranked worse, and drops to the last rank. In this case, there is a tendency towards smaller net flows. Putting the dominating weight on the environmental criteria exposes a less distinct sequence of scenarios when compared to dominating weights being placed on social criteria. But there are still general features of the changes: scenario D changes to the last position and the performance of scenario C advances, moving to the top of all the stakeholder rankings. In general, the distances between scenarios C, E, and B become smaller and a top cluster evolves. The range of net flows is a slightly larger but basically stable. When weighting the technological appraisal dimension very high, the ranking changes in the sense that scenario C ranks first and no other systematic changes of the rankings appear. The range of net flows becomes larger in this case, indicating that the scenarios are more differentiated from this perspective.

To summarise, the extreme weight shifts between the sustainability dimensions show a distinct and plausible reaction in the scenario rankings. The sensitivity analysis leads to the conclusion that scenario E can be seen as particularly favourable for social objectives, whereas scenario C relates particularly to ecological-technical targets. Scenario D is favoured by economic target settings, and is in clear opposition to ecologically dominated aims. From a social perspective, scenario A is highly unfavourable, whereas scenario B is constantly in an intermediate position. The actuality that in the Austrian renewable energy policy, a direction is followed that is close to scenario D in the case study presented here might lead to the conclusion that the basic preferences of the present energy policy lies obviously on the economic dimension, probably indeed at a weighting of at least 70%, and all the other criteria share the remaining 30%. This, of course, is not an optimistic premise for achieving a transition towards a more sustainable energy systems.

When a cluster analysis is applied to the weighting matrix, certain clusters of criteria can be identified that have equal weight structurally. For example the environmental criteria Air Quality and Water Quality are often weighted equally, which might indicate that stakeholders don’t make a distinction between those two environmental media in their preference scheme. Furthermore, Noise and Quality of Landscape are both weighted very low, which shows the relative disinterest of the national stakeholder in these local social issues. This stands in contrast to studies pointing to the intrusion on the quality of landscape as a major issue in the discourse on e.g. wind turbines. (Pedersen and Waye 2004)

Discussion of the sensitivity analysis on preference functions

The variations of preference functions allow methodological insights regarding the effect of the preference functions on the final scenario ranking result. In particular, the use of preference functions to address data uncertainty raises questions as to what kind of information is transported into the preference functions.

The first sensitivity analysis of the preference functions (SA1 PF_Usual) excels by very low data uncertainty and assumes therefore high data resolution. This means that even small differences in the scenario impact data make a great difference for the preference. There are no indifference thresholds. The rankings appear on the largest net flow range, which is somehow expected. Furthermore, the sensitivity analysis exhibits the most profound changes of the scenario sequences when compared to overall sensitivity analysis. Scenario A ranks worse in this modulation of the preference functions. Scenario D performs less badly. This can be explained by the relativisation of the bad performance in the environmental criteria. Without any indifference thresholds, the usually second-worst ranking of scenario A in performance terms is also fully accounted for. Overall, the assumption of low data uncertainty has no major effect on the final ranking other than the effect of the ranking of scenario A and D discussed above.

The second sensitivity analysis (SA 2 PF_Higher) is characterised by the basic assumption of high data uncertainty and therefore low data resolution. The most articulate effects are the small net flow and the least number of parallel rankings. Scenario E receives top ranking even more often. Scenario E performs best in regards to social and some technological (Security of Supply) and economic (Employment) criteria. These criteria seem to be less affected by higher indifference thresholds. Scenario D performs worst in this sensitivity analysis. The opposite effect to that in SA 1 can be monitored.

Common features of the change of scenario rankings due to the modulations of the preference functions in SA 3 PF_Level lead to an improved ranking of scenario E. Throughout 15 out of 16 stakeholder rankings, scenario E receives top ranking, which is even stronger than the SA 2 PF_Higher (14 out of 16 rankings). The introduction of indifference thresholds to the qualitative criteria seems to improve the ranking of scenario E. The change of the range of net flows is negligible but leads to slightly higher ranges of net flows. The negative discrimination of scenario A (11 out of 16 rankings on last rang) in this sensitivity analysis stands in contrast to the effect of sensitivity analysis 2. This also shows that the ranking of scenario D is influenced by thresholds of the quantitative indicators (which are mainly the environmental indicators). Greater uncertainty with respect to the qualitative criteria does not affect scenario D.

When comparing the overall effect of the three sensitivity analyses, it is obvious that SA 1 PF_Usual has the most severe effect on the ranking when taking the number of sequence changes into account. Summarising SA PF_Higher and SA PF_Usual do show contrasting effects on the rankings as would be expected when considering the range of net flow and the opposing effect on the first and last rank. The overall effect of preference functions on the result seems moderate. The sensitivity analyses show changes of the complete and the partial ranking of the scenarios. However, those changes mainly concern the first and last scenario cluster, which are already very closely together.

An innovative way of addressing uncertainty has been applied in this case study. The incorporation of uncertainty via the preference functions has been proven successful: it is a plausible way of incorporating uncertainty in the analysis. in the sense that, on the one hand, it appears as a coherent understanding of the indifference threshold from a methodological point of view and, on the other hand, it was an effective way of communicating the rather abstract concept of indifference threshold in an expert workshop and therefore in general enabled even more participatory activities. Another way to integrate uncertainty is to use fuzzy numbers. This approach would have been an interesting methodological addition and has been used successfully with other PROMETHEE applications (e.g. Goumas and Lygerou 2000, Fern et al. 2005) but was not possible in this study.

Reflections on the participatory process

This chapter presents reflections on the participatory process and the stakeholder involvement during the case study. Observations and appraisals of the highly interactive, social process, its design, structure and outcomes, will be summarized.

The outcomes of participatory processes vitally depend upon the commitment of the stakeholders. In other word, the outcomes are a result of the way they are engaged, inspired and encouraged to communicate their motivations and ways of thinking in the discussions. Participatory research processes and results are in general – and also in this case – affected by the context in which they take place. In particular the implicit culture of discussion and decision making, and the assembled perspectives of the stakeholders are among the most prominent influencing variables. Furthermore, the sample of stakeholders has a decisive influence on the outcomes which is controllable only to a certain extent in the research design, such as e.g. the refusal to participate of certain interest groups, the lack of resources to send representatives etc. Ensuing, the empirical results from the here presented Austrian case study can not straightforwardly be translated to situations and preferences in other countries or settings.

The scenario development process relied strongly on the energy stakeholders that were very engaged in defining the scenarios and active in adapting the scenario parameters. Compared to other participatory scenario-building techniques (as e.g. for the Southeast England according to personal communication with Stagl), the scenario-building process presented here was structured by scenario proposals. Whereas the main scenario storylines were accepted surprisingly well by the stakeholders, suggesting only minor changes, the scenario parameters had to be changed quite drastically during the scenario development. In contrast to observations made in other project contexts (Bohunovsky et al. 2007), the predefinition of scenarios did not discourage stakeholders from giving input according to the own expertise and to suggest concrete changes. The stakeholder process merely resulted in the merging of two storylines into one scenario (scenario A “Fast and Known”). Eventually, the stakeholders agreed to calculate energy profiles for five scenarios.

With regard to the scenario parameters, stakeholders surprisingly focussed on the time-frame aspect of energy planning. Despite its fundamentality, this assumption is not made explicit in the discussions; rather it is an implicit assumption of the discussants. The underlying time frame is a critical factor for energy strategies. For example, with a short-term time frame, such as those common in economic decisions, it is not sensible to invest in expensive pilot technologies which are not yet fully developed and thus still inefficient. On the other hand, long-term perspectives do not aim to maximise immediate profits. The conflict between long-term ambitions and short-term issues is well recognised in integrated assessment. (Polatidis et al. 2003). For a more thorough discussion see (the general discussion of scale in the literature Meadowcroft 2002, Jerome Chave 2003, Giampietro 2004, Rotmans 2006). Typically, energy planning is characterised by long-term perspectives, due to the large investment volumes (for example in infrastructure) which require long-term planning (Grübler 1998). This is also denoted in the “lock-in” phenomenon. (Unruh 2000) It can be assumed that in order to achieve structural changes of more sustainable energy systems, long-term perspectives are required: ecological changes and changes of resource availability and quality that occur during the next 50-100 years must be taken into account.

The participatory process clearly demonstrated that people with very different time frames are involved in the decision-making processes related to energy policy. This fact explains at least partly some of the fundamental disagreements between stakeholders on whether certain technologies are valued reasonable or favourable. In order to cope with these conflicting positions, assumptions on the time horizon were made explicitly in a scenario parameter and allowed for shorter-term and for longer -term strategies. However, the integration of the time frame in the modelling exercise was intricate because all scenarios were set for the base year 2020. The time horizon was integrated only indirectly in the technology profiles. The long-term perspective is characterised by an ambitious increase in photovoltaic and wood gas technologies. Remarkably, the scenario appraisal results reveal that the two scenarios with long-term time frames, scenario C “Investment into the future” and scenario E “Large impact in a small-scale use”, are ranked highest in a very robust way (see below). The scenario parameter ‘time frame’ represents an example, where the scenario narrative is transformed in a consistent factor influencing the respective set of key technologies.

The participatory development of the energy scenario was built on a two-stage process. At first, exploratory scenarios outlined the most interesting scenario storylines and scenario parameters. In the second stage, a selection of the most relevant scenarios was made by the stakeholders to model forecasting scenarios. The modelling was based on existing energy studies for Austria (see Methods). Finally, the modelling results were discussed and scrutinised in a stakeholder workshop.

This scenario developing approach allowed, on the one hand, the use of scenarios as vehicles for the stakeholder communication regarding favourable and/or threatening renewable energy futures; and, on the other hand, it provided the possibility to appraise and compare the resulting scenarios and their impacts with respect to existing scenario work and in accordance with present energy policy aims.

The quantitative modelling of the scenarios and the scenario impacts followed the features of the qualitative storylines as best as possible. This was one of the challenges when developing the two-stage scenario development process. It worked well for certain parameters and turned out to be rather intricate with other aspects of the narratives. This can best be illustrated at the parameter degree of decentralisation. The technological aspect of the decentralisation could be achieved by a respective share of the newly installed renewables' capacity assuming small-scale technologies such as small-scale wind turbines and biomass heating systems for single households. However, it was not possible to integrate the more fundamental changes that are still intimately associated with decentralization developments, such as the emergence of decentralised decision modes and decentralised ownership. The integration of the scenario parameter 'efficiency' worked particularly well in the biomass sector, which is one emphasis of the scenarios: the more systems efficiency was attributed to a scenario by the stakeholders in the narrative, the more co-generation power plants and utilisation of biomass residues were accounted for in the quantitative modelling.

Yet it showed in the narrative part of the scenarios that certain descriptive parameters turn up which are not necessarily compatible with quantitative scenario modelling, such as the need for new institutions. However, this parameter demonstrates well that the qualitative part of the scenarios bears key information for the appraisal of the qualitative sustainability criteria. Energy scenarios consisting merely of technology compilations don't allow for an appraisal of social, and, as in this specific case, technological sustainability criteria.

In conclusion, the combination of qualitative story lines and quantitative modelled parts was found to be very fruitful in terms of the stakeholder communication process and necessary as a prerequisite to appraise qualitative social and technological sustainability criteria. To translate qualitative scenario parameters into more concrete areas of conflict allowed different possible futures to be pictured and therefore discussed. The experience showed that this kind of interactive, visionary scenario process in rather heterogeneous groups is only possible with comprehensive narratives and thus confirms argumentations such as Berkhout and Hertin 2002, Konrad et al. 2004a, McDowall and Eames 2007. The quantitative modelling in the second stage allows a comparison with other studies and concrete policy aims.

Also, the selection of indicators was undertaken during the stakeholder process (based on telephone interviews and at the first workshop). In this process, three additional criteria were proposed by the stakeholders: (1) effect on public budget, (2) electromagnetic radiation, and, (3) noise. Whereas it was straightforward to incorporate the indicators 'Effect on public budget' and 'noise' in the set of appraisal criteria, it was difficult to operationalising the indicator 'electromagnetic radiation' as a health issue, because its health impacts are still contested and the scientific basis is ambivalent, which prevented the formulation of appropriate algorithms.

The specification of the indicators (i.e. definition of concrete indicators and data for assessments), however, was based on expert knowledge and not performed during the stakeholder participation process, so as not to distract stakeholder attention from criteria definition, and, scenario design and development.

Due to the extensive list of indicators and the tendency of stakeholders to model impacts quantitatively whenever the data availability is adequate, the appraisal phase (see overview in Figure 9 and Method chapter) was very demanding. Originally, it was planned to undertake several expert interviews for appraising the qualitative criteria. This could not be realised. It demonstrated quite clearly that the integration of multi-dimensional criteria, on the one hand, and the overall claim to drive complexity beyond the modelling of technological compilations, on the other hand, is highly resource-intensive. The best possible solution in this context was to conduct two expert interviews regarding the qualitative criteria.

The experience of the participatory process showed that the strict division between stakeholder inputs and (academia) expert inputs, which made sense at the beginning of the case study, was not as easily carried out as anticipated. In many cases, the boundaries were blurred. With some of the stakeholders, one had the impression that they are driven by strategy and policy. This was also the case for certain experts who were positioned as real advocates for certain technologies or certain types of energy systems. By contrast, the stakeholders who participated were very receptive to new cogent arguments. Other sustainability appraisal techniques such as multi-criteria mapping (Stirling and Mayer 2001) do not make this differentiation and the impacts are appraised in the stakeholder workshops, which seems a valuable alternative approach. However, for the discussion in the workshops it proved constructive that all participants had explicit interests.

Conclusions

An attempt will be made here to respond to the research questions posed in the Introduction. Could they be answered, and in what ways have they been answered in the course of this research process?

The first question refers to the efforts to generate an adequate conceptual framework for the analysis of transitions towards more sustainable energy systems. How can a systemic perspective on sustainable development as society-nature interaction contribute to an enhanced understanding of transitions towards more sustainable energy systems? What, in particular, can be gained by regarding natural systems and their dynamics as endogenous factors?

From the existing literature, it may be concluded that an earlier and simpler approach to addressing technologies one by one has largely been replaced by more complex, systemic notions such as large technical systems (Hughes 1987) or socio-technical systems (Geels 2002). The notion of socio-technical systems includes both the supply and the demand side of technology, its production as well as its utilisation, and addresses the role of institutions and actors on various levels. The Dutch transition management approach, for example (Kemp et al. 2005, Rotmans and Loorbach 2008, and others), combines this perspective with concepts of systems transformation based on evolutionary economics. This approach provides insight into how changes in technological niches may, if successful (or if favoured by changes in "landscape", the highest scale level in this perspective), affect the next higher level of technological regimes and eventually lead to transitions towards a more sustainable energy systems.

This model of the multi-level perspective on socio-technical energy systems is already fairly complex: it encompasses a large number of social and economic relations and is not narrowly "technological". With nature, though, it deals only as an exogenous force that may affect the "landscape level" and thus make a difference for probabilities of niche successes. In this model of socio-technical systems there is no direct causal link between energy technologies and (changes in) natural systems, nor is there a feedback loop between such changes and the success or failure of technologies or even technology regimes.

Under the general premise of approaching more sustainable development, in this case a transition to more sustainable energy systems, natural systems cannot be summarised at the landscape level. The feedback loops between society and nature and back to society again have to guide or even instruct the technological transition.

Historical accounts of energy systems and their transformations (how they depended upon and impacted upon social relations as well as upon natural systems (Sieferle 1997, Sieferle 2001, 2003), have inspired exploration of even more complex models which make an attempt to endogenise natural systems into the model dynamics rather than treat nature as exogenous. The most important feedback effect of energy technologies can be seen in detrimental changes in natural systems, namely the impact of carbon emissions on the climate. Here, the atmospheric gas composition is not just exogenous to the functioning of the socioeconomic and socio-technical systems, but – in both directions – causally interrelated. For the empirical research design, such interrelations are highly relevant, as change or even (natural) catastrophes in natural systems play a major role in social discourse and influence (and often tip) stakeholders' risk perception and preferences for technologies. At the same time, the model should remain sufficiently complex and functionally independent from the social systems so that it can guide research efforts including the discourse and stakeholder analysis. The society-nature interactions model developed by the Viennese school of social ecology (Fischer-Kowalski 1997, Fischer-Kowalski and Weisz 1999, Haberl et al. 2004a, and others) manages to fulfil these requirements.

If these models provide answers explaining what is gained by extending the conceptual model to include society-nature-interaction, there is also a legitimate question regarding the trade offs. What are drawbacks of such an increase in conceptual complexity? The most important loss seems to be a loss of sense of (or illusion of) control. If the conceptual model portrays two complex systems which interact with one another, then autopoietic (or autocatalytic) dynamics may be expected to dominate and intentional "management" of sustainable energy transitions appears even more difficult. This is a severe trade off, but according to the findings it is one that is difficult to avoid. This poses a formidable challenge when researching transition management.

The second group of research questions refers to the availability and adequacy of methods: How can future options of energy systems be appraised given such complexities and uncertainties? Do the methodological approaches of scenario building and multi-criteria appraisal (MCA) with stakeholder participation provide a 'toolbox' adequate for exploring sustainable development of the energy system?

In the methodological Section it is argued on a general level why these methods qualify for an exploration of sustainable energy system options. Multi-criteria appraisals take into account the multiplicity of legitimate perspectives and are even able to handle contradictory sustainability criteria, and eventually helping to reduce complexity. The involvement of stakeholders (in this case: stakeholders that have a strong influence on actual decision making and stakeholders that are most directly affected by such decisions) in the participatory process appears almost inevitable in a situation where expert systems as well as decision makers feel potentially overwhelmed by complexity and uncertainties. Such a situation calls for mode 2 science where experts and lay persons collaborate closely on problem definition and interpretation of the results. The choice of scenarios as a unit of analysis and appraisal (rather than single energy technologies) was judged to be the most appropriate level for a discourse about the sustainability of options.

The methodological procedure entailed development of five energy scenarios for Austria in 2020. There was a particular focus on renewables formulated in both quantitative and qualitative terms. In a first step, scenario narratives had to be structured by qualitative scenario parameters related to the time horizon, degree of innovation, infrastructural and institutional change. Then, technology profiles were calculated, enabling to estimate key parameters such as renewable energy supply of heat and electricity in PJ, CO_2 emissions in tons, share of renewables in % and to develop an impact matrix. This matrix displayed sustainability impacts in a transparent manner and was open to scrutiny from all parties involved in the appraisal process. Exploring the impact matrix also facilitated the building up of preferences about criteria. In the final stage of the appraisal process, the information from the impact matrix and criteria weights were used to calculate a ranking of the scenarios. In this process, it became clear that participatory scenario building was indeed a good choice of method. It acknowledged the multi-dimensionality related to a sustainable transition, and it invited narratives that enabled stakeholders to be visionary and to build possible futures containing their ideas, experiences and perspectives. This study confirmed that it is generally easier for stakeholders to deal with narratives rather than with purely quantitative information. Furthermore, the scenarios proved to be a highly effective communication tool that structured the exchange with other stakeholders and with experts. The challenges facing this method package relate to the processes of first opening up, then structuring, and, finally, closing down complexity.

In this thesis, a combination of scenario analysis with a participatory MCA was developed in order to take the complexities of the relevant socio-economic and biophysical systems as well as the uncertainties of long-term impacts into account. Based on the conceptual framework of society-nature interaction, multi-dimensional data and information was collected and structured along key criteria of sustainability, and eventually aggregated in order to derive pointed, univocal outcomes (rankings of scenarios). Could, by this integrated assessment procedure, a new methodology be developed that is suitable for a scientifically sound, robust and politically useful sustainability appraisal of strategies for increasing the use of renewable energy?

According to the insights gained from the Austrian case study, this methodology can successfully be applied in practice, and the conceptual framework developed in this thesis allowed deriving a methodology that allows to tackle the three challenges of transition management: The involvement of stakeholders in an intensive, discussion-oriented participatory processes (focus groups) allowed to take the multidimensional nature of sustainability into account. A scenario approach was developed, jointly with the stakeholders, in order to bring this multidimensionality together with the many uncertainties related to future developments, and to make complex interrelations between different drives, constraints and impacts perceptible. The MCA was successfully applied for the transparent structuring and aggregation of this complex information to derive robust rankings of scenarios.

Thus, in can be concluded that the combination of MCA, scenario analysis, and a participatory stakeholder process is promising. However, such an approach is – in terms of design and implementation – a challenging methodological option. A substantial effort is required for scenario building and the modelling of impacts. Assessing scenarios (rather than single technology options in the form of renewable energy pathways with an MCA, and applying a participatory MCA instead of simpler assessment tools or descriptive assessments) is resource-intensive. Moreover, gathering a sufficient number of relevant stakeholders for the workshops, and reassembling the same stakeholders again for a second round, remains a difficult issue. However, the findings emphasise that the results effectively capture the context of technology deployment and demonstrate a more robust and broader-based decision (simulation) process which addresses uncertainties, acknowledges multiple legitimate perspectives, and encourages social learning.

This study incorporates both elements 'opening up' and – quite emphatically in processes like scoring, aggregation and clustering – also 'closing down'. By revealing the implications of different assumptions and conditions, by e.g. identifying diverse scenarios and their drivers and the multidimensional impacts, the appraisal process is 'opened up' for policy makers. Whereas the aggregation result of the MCA takes the form of what might be called 'unitary and prescriptive' policy advice highlighting preferable courses of action representing therefore 'closing down' elements. This has potentially the advantage of conveying practical implications and clear justification for decision making. (Stirling, 2005)

Finally, the third group of research questions needs to be addressed, questions pertaining to the substantive findings of the empirical study. Which future energy systems and technologies show up in the Austrian sustainable energy discourse as represented by the stakeholders involved in the study? How do these energy systems and technologies perform according to the multi-dimensional sustainability criteria?

When applying a combined decision-aid tool in the real life situation of a research process with stakeholders, the results can be surprising. Scenarios E (‘‘Large Impact in Small-Scale Use’’, focussed on decentralized energy systems) and C (‘‘Investments into the Future’’, with a focus on long term R&D investment) were consistently ranked highest. Scenario B (‘‘Extension of Competitive Advantage’’ with a focus on benefiting from technology export) is in all cases in the middle position, and scenarios A (‘‘Fast and Known’’, the accelerated BAU-scenario) and D (‘‘Extensive Use of Biomass’’) were always ranked lowest. This outcome is in marked contrast to renewable energy promotion policies currently implemented in Austria that favour increased use of biomass for energy purposes, a policy that was also recently re-stimulated by the Biomass Action Plan of the EU. In Austrian official policies, deliberative institutional change towards more decentralised energy supply systems (as favoured by scenario E) has so far received very little attention.

The weighting schemes of the different criteria by the individual stakeholders did not change the general ranking pattern. This is surprising since the stakeholders – with the exception of climate change which is constantly ranked among the most important criteria – disagreed considerably over their ranking of sustainability criteria. In effect, the stakeholders apparently favoured the emergence and expansion of niche technology bundles over the continuation of regime technologies, regardless of the criteria.

However, this result warrants a caveat. It appears that the participatory methodology evoked rather more personal than “institutional” opinions. This is indicated by the fact that clustering did not place members of similar institutions together, as would be expected when acting in their institutional roles. In contrast, the participatory setting seems to encourage stakeholders to take personal positions rather than the strategic positions of their home institution. The robustness of the ranking results indicates that personal consensus among the experts and stakeholders prevails regarding fundamental changes that are required for a sustainable energy transition. The position of institutional or organizational settings is not adequately evoked and represented by these methods. An interesting methodological challenge would be to develop techniques that allow both personal and institutional logics to be addressed.

In fields such as ecological economics, sustainability science, and science and technology studies, a collective understanding of the need to combine analytical and participatory methods has been developed over the last few years. It is commonly acknowledged that such an approach has great potential to help policy-makers to scrutinise scenarios and stakeholder preferences in a robust, transparent and democratic process, to explicitly address complexity and uncertainty, and to foster social learning. However, the conditions are still unclear as to which public and stakeholder engagement and which quality criteria for the implementation of participatory exercises are most effective. Within the current institutional framework of representative democracies, there is considerable tension between public and stakeholder participation and legislatively delegated authority. By introducing public participation into the procedures of administrative agencies (which must be accountable to democratically elected officials), public lines of decision-making are sometimes crossed. When developing decision-making aids to foster sustainable development, participatory techniques must play a crucial role. Key methodological and institutional questions need to be addressed in this regard.

The usefulness to policy makers of the participatory multi-criteria appraisal methodology followed here can be manifold. On the one hand the study design allows exploring conditioning assumptions and sensitivities in detail and allows social learning and reflecting the consequences of the own and of other stakeholders' preferences. This might be useful to learn about new arguments and the specific conflicts of interest. On the other hand the methodology allows 'closing down' a wide range of complex information in a rather transparent way and arriving to an aggregated ranking result, a key requirement for policy makers. Although time- and resource intensive, such a systematic combination of the involvement of many perspectives and interests with a pointed, outcome oriented process can be fruitful in the light of the fundamental challenges transition management is facing.

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Appendix

Table A. 1. Comprehensive list of the relevant 31 Austrian key energy stakeholders identified in the stakeholder analysis and invited to participate.

Invited Stakeholder (German names)	Participation
Bundesministerium für auswärtige Angelegenheiten	
Bundesministerium für Finanzen	
Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft	X
Bundesministerium für Verkehr, Innovation und Technologie	X
Bundesministerium für Wirtschaft und Arbeit	
Wirtschaftskammer Österreich	X
Präsidentenkonferenz der Landwirtschaftskammern Österreichs	X
Bundeskammer für Arbeiter und Angestellte	X
Österreichischer Bauernbund	
Energie-Control GmbH	
Verein für Konsumenteninformation	X
Greenpeace Österreich	
WWF Österreich	X
Global 2000	X
Arbeitsgemeinschaft Erneuerbare Energie- Niederösterreich-Wien	X
Industriellen Vereinigung	X
Austrian Business Council for Sustainable Development	X
Österreichische Bundesforste AG	X
Oberösterreichische Landesregierung	
Oberösterreichischer Energiesparverband	
Oekostrom AG für Energieerzeugung und -handel	
Austrian Power Vertriebs GmbH	X
Kelag Konzern	
Steweag	
Eurosolar Austria	X
Österreichischer Biomasse Verband	
Interessengemeinschaft Windkraft Österreich	X
Bundesverband Photovoltaik Österreich	
Kleinwasserkraft Österreich	X
Wien Energie GmbH	X
Zentrum für Soziale Innovation	X

Figure A. 1. The six scenarios developed in the exploratory scenario phase for discussion with the stakeholders

Scenario A: “Fast and inexpensive” (13)

Total energy demand ⇧	**Share of renewable energy ⇧**	**Power**	**big, central capacities**
Total energy demand ⇩	Share of renewable energy ⇩	Heat	small, decentral capacities

Scenario B: “Extent the existing competitive advantage” (12)

Total energy demand ⇧	Share of renewable energy ⇧	Power	big, central capacities
Total energy demand ⇩	**Share of renewable energy ⇩**	**Heat**	**small, decentral capacities**

Scenario C: “Investment into the future” (2)

Total energy demand ⇧	Share of renewable energy ⇧	**Power**	big, central capacities
Total energy demand ⇩	**Share of renewable energy ⇩**	Heat	**small, decentral capacities**

Scenario D: “Biomass on a large scale” (5)

Total energy demand ⇧	**Share of renewable energy ⇧**	**Power**	**big, central capacities**
Total energy demand ⇩	Share of renewable energy ⇩	Heat	small, decentral capacities

Scenario E: “Big effects on small scales” (16)

Total energy demand ⇧	**Share of renewable energy ⇧**	Power	big, central capacities
Total energy demand ⇩	Share of renewable energy ⇩	**Heat**	**small, decentral capacities**

Scenario F: “Strengthen the known” (7)

Total energy demand ⇧	**Share of renewable energy ⇧**	Power	**big, central capacities**
Total energy demand ⇩	Share of renewable energy ⇩	**Heat**	small, decentral capacities

Table A. 2. Technology types and respective GEMIS technology identifyer

Technology type	GEMIS technology identifier
Hydro power	Wasser-KW-klein
Wind park	Wind-KW-600-Standort1870 - A
Wind park	Wind-KW-1800-Standort 1650 - A
Photo voltaic	Solar-PV-Mod-multi-med-A 50m²
Photo voltaic	Solar-PV-multi-Rahmen+rack-D
Solar thermal power	SolarKollektor-industriell
Biogas cogeneration-small-primary biomass	Biogas-Feuchtgut-BHKW-GM 500-OxKat/brutto
Biogas cogeneration-small-secondary biomass	Biogas-Gülle-BHKW-GM 500-OxKat/brutto
Biogas- large- primary biogas	Fabrik\Biogas-zentral-50km
Biogas line entry	Aufbereitung\Biogas-mix-R+S-Einspeisung-klein
Wood gas cogeneration-secondary biomass	Holzgas-FB-Altholz-A1/2-BHKW-GM-OxKAT-2010/brutto# kwk
Wood gas cogeneration- primary biomass	Holzgas-FB-KUP-Pappel-BHKW-GM-OxKAT-2010/brutto#kwk
Wood gas cogeneration- primary biomass	Holzgas-dZWS-KUP-Pappel-GuD-HKW-klein-2010/brutto# kwk
Wood gas electricity	Holzgas-dZWS-Altholz-A1/2-GuD-KW-klein-2010# nur strom
Biomass electricity- primary biomass	Holz-KW-DT-A
Biomass cogeneration-secondary biomass	Holz-HS-KUP-Pappel-HKW-DM-SNCR-2010/brutto
Biomass cogeneration-primary biomass	Holz-Altholz A1/2-HKW-DM-SNCR/brutto
Biomass heat large- secondary biomass	Holz-HS-Heizwerk-groß-A
Biomass heat large- primary biomass	Holz-HS-Waldholz-Heizwerk-1 MW
Biomass heat small- primary biomass	Holz-HS-KUP-Pappel-Heizung-10 kW-2010
Biomass heat small-secondary biomass	Holz-HS-Hzg-neu-A
Biomass heat small- primary biomass	Holz-Pellet-Hzg-neu-A
Biomass heat small- primary biomass	Holz-Stück-Hzg-neu-A
Biomass heat small- primary secondary	Holz-HS-Heizwerk-klein-A
Sewage cogeneration- large	Klärgas-BHKW-GM 1000-OxKat/brutto
Sewage cogeneration- small	Klärgas-BHKW-GM 200-OxKat/brutto
Geothermal plants heat	Geothermie-HW-D
Geothermal plants power	Geothermie-KW-ORC-D
Heat pumps	El-Wärmepumpe-Sole-A ist

Table A. 3. Additional renewable energy capacity in GWh until 2020 for scenarios A-E

Increase in (GWh) Technology	Output	SCENARIOS (2 0 2 0) A	"B	C"	D"	"E
Hydro Power	*electricity*					
Small hydro power (< 10 MW)	*electricity*	1,950	2,350	1,950	1,950	1,950
Large hydro power (> 10 MW)	*electricity*					
Wind parks	*electricity*	3,964	3,964	2,074	1,844	3,083
Wind parks, small	*electricity*	*622*	*622*	*380*	*306*	*645*
Wind parks, large	*electricity*	*3,342*	*3,342*	*1,694*	*1,538*	*2,438*
Photovoltaic (only roofs and facades)	*electricity*	6	6	2,032	6	508
Solar thermal heating	*heat*	3,774	3,774	1,374	3,774	3,774
Solar thermal, small	*heat*	*2,046*	*2,046*	*869*	*2,160*	*2,728*
Solar thermal, large	*heat*	*1,728*	*1,728*	*505*	*1,614*	*1,046*
Biogas- cogeneration	*electricity*	124	124	350	1,094	124
Biogas-*cogeneration*	*heat*	76	76	213	665	76
Biogas-cogeneration, agricultural	*electricity*	*46*	*46*	*47*	*376*	*46*
"	*heat*	*28*	*28*	*29*	*228*	*28*
	sum Biogas small	**66**	**66**	**218**	**616**	**88**
Primary		*36*	*33*	*87*	*400*	*31*
Secondary		*30*	*33*	*131*	*216*	*57*
Biogas-cogeneration	*electricity*	*78*	*79*	*77*	*719*	*79*
"	*heat*	*48*	*48*	*47*	*437*	*48*
	sum Biogas small	**134**	**134**	**115**	**572**	**112**
Primary		*74*	*67*	*46*	*372*	*39*
Secondary		*60*	*67*	*69*	*200*	*73*
Biogas Line Entry				230	572	
Biomass, *cogeneration*	*electricity*	2,735	2,113	915	2,735	2,424
Biomass, *cogeneration*	*heat*	3,009	2,324	1,007	3,009	2,666
Wood gas, *large, cogeneration*	***sum***	***1,477***	***1,141***	***596***	***1,477***	***1,309***
Wood gas, large cogeneration	*electricity*	*704*	*544*	*284*	*704*	*624*
Wood gas, large, cogeneration	*heat*	*774*	*598*	*312*	*774*	*686*
Biomass combustion, *cogeneration*	***sum***	***4,266***	***3,296***	***1,326***	***4,266***	***3,781***
Biomass combustion, cogeneration	*electricity*	*2,031*	*1,569*	*631*	*2,031*	*1,800*
Biomass combustion, cogeneration	*heat*	*2,235*	*1,726*	*694*	*2,235*	*1,981*
Prim		*2,154*	*1,483*	*451*	*2,624*	*1,078*
Sec		*2,112*	*1,813*	*875*	*1,642*	*2,703*
Biomass Electricity	*electricity*	200	275	450	1,700	200
Wood gas, large electricity secondary biomass	*electricity*	*100*	*100*	*350*	*800*	*100*
Biomass combustion, large, only electr., prim. biomass	*electricity*	*100*	*175*	*100*	*900*	*100*

Table A.3. continued

Increase in (GWh) Technology	Output	SCENARIOS (2 0 2 0) A	"B	C"	D"	"E
Biomass combustion, *only heat*	*heat*	10,385	8,770	4,957	17,421	9,702
Biomass-District heating	***sum***	***7,269***	***5,262***	***3,470***	***12,195***	***3,881***
Biomass-Nah- district heating Prim	*heat*	*7,020*	*5,014*	*3,226*	*11,834*	*3,619*
Biomass-Nah- district heating Sec		*249*	*248*	*244*	*361*	*262*
Wood pellets+ Wood chips	*heat*	***3,115***	***3,508***	***1,487***	***5,226***	***5,821***
Pellets + Wood chips Prim		*2,804*	*3,157*	*892*	*3,920*	*2,911*
Pellets + Wood chips Sec		*312*	*351*	*595*	*1,307*	*2,911*
Sewage gas, cogeneration	*electricity*	121	61	61	61	61
	heat	261	161	161	161	161
	sum	*382*	*222*	*222*	*222*	*222*
Sewage gas, small		*172*	*100*	*117*	*105*	*133*
Sewage, large		*210*	*122*	*105*	*117*	*89*
Geothermal power	*electricity*	11	61	61	11	11
Geothermal power	*heat*	686	1,746	1,746	686	686
Heat pumps	*heat*	221	221	221	221	751
Total additional electricity		9,111	8,954	7,893	9,401	8,362
Total additional heat		18,411	17,072	9,679	25,937	17,816

Table A. 4. Overview of the qualitative description of scenarios A--E

Characteristic	Scenario A "Fast and Known"	Scenario B "Extension of Competitive Advantage"	Scenario C "Investments into the Future"	Scenario D "Extensive Use of Biomass"	Scenario E "Large Impact in Small-Scale Use"
Size classes	++	++	-	+	----
Decision making and ownership structure	Large plants enable swift capacity expansion.	Medium to small plants with good export potentials are pushed. Centralised decision structures.	Synergies (system efficiency) due to local resource use and production structures results in a more decentralised use of technologies.	Trend towards large-scale technologies and more centralised decision-making structures.	Decentralised technologies with decentralised decision-making and ownership structures.
Key technologies	• Biomass (heat and CHP) • Wind power • Solar thermal energy • Sewage gas	• Biomass for individual households • Biomass CHP for communities • Small hydro power • Wind power (rotor production) • Solar thermal energy • Geothermal energy	• Photovoltaics (primarily on rooftops and facades) • Feed-in of biogas • Geothermal energy	• Biomass (esp. CHP) (biomass fuels also stem from plantations and imports) • Biomass district heating • Biogas (esp. CHP) • Solar thermal	• Biomass systems in private households and in communities (CHP, district heating) • Wind power • Biogas in private household and biogas CHP systems • Solar thermal • Heat pumps • Photovoltaics
Primary materials (+) vs. residue (-) in the biomass sector	+ Homogeneous structure of the primary materials constitutes a comparative advantage relative to residues.	0 (neutral) Export strategies are in the foreground. Use of residue is rather unimportant.	-- Long-term orientation, exploitation of synergies results in increased use of residue.	+++ Accelerated use of primary resources.	--- Full exploitation of the potentials of cascadic resource use by deployment of residues.
Time frame	---- Short-term.	-- Merely short-term economically viable time frame.	++++ Very long-term thinking. Development of technologies that are not yet very important today. Synergies.	- Rather short-term, as biomass energy plantations in the longer run jeopardise food production and weaken ecological buffer systems.	++ Long term, since new social structures on the regional level have to be created and responsibilities regionally rooted/established.
New institutions	-- In order to be able to act swiftly, reliance is on existing institutions.	-- No or only few new institutions, as the main focus is on export promotion, rather than on the domestic production system.	++ In order to promote long-term system efficiency, new institutions are required.	+ Changes in the tasks of the agricultural and forestry institutions.	+++ Production system subject to significant change, new institutions are required.
Summary	Large plants Very short-termism Few new institutions	Large plants High technical efficiency Few new institutions	High system efficiency Very long-termism New institutions	Biomass energy plantations (SRC) New institutions	Small plants Extensive use of residue New institutions

Note: The '+' and '-' signs indicate how important the various characteristics are in the respective scenarios ('0' indicates the neutrality).

Table A. 5. Impact matrix of the Austrian case study

	unit	**Scenario A**	**Scenario B**	**Scenario C**	**Scenario D**	**Scenario E**
Climate change properties						
CO_2 equivalents	*t/TJ*	18	16	17	21	18
Air quality						
SO_2 equivalents	*kg/TJ*	276	236	179	289	265
TOPP	*kg/TJ*	359	312	240	399	353
Particulate matter	*kg/TJ*	94	78	69	124	72
Rational use of resources						
Cumulated energy effort	*GJ/TJ*	2,365	2,099	1,822	2,444	2,274
Cumulated Material Effort	*kg/TJ*	81,441	83,182	105,203	78,311	75,468
Water quality						
Phosphorus	*mg/TJ*	30	31	56	77	33
Nitrogen	*g/TJ*	4	4	5	6	5
AOX	*mg/TJ*	25	24	22	20	33
CSB	*kg/TJ*	33	36	51	92	31
BSB	*g/TJ*	967	1,040	1,467	2,598	899
Costs						
Constant & variable costs	*E3 €/TJ*	43	41	51	40	46
Regional self-determinacy	*qualitative*	rather low	low	rather high	medium	high
Social cohesion	*qualitative*	rather low	rather low	medium	medium	rather high
Diversity of technologies	*qualitative*	rather low	medium	medium	low	medium
Employment	*qualitative*	rather low	rather low	medium	medium	rather high
Effect on public spending	*qualitative*	low	rather low	rather high	rather low	medium
Import independency	*qualitative*	medium	medium	low	medium	medium
Quality of landscape	*qualitative*	low	high	high	medium	high
Noise	*qualitative*	medium	low	low	high	low
Social justice	*qualitative*	medium	medium	medium	medium	medium
Technological advantage	*qualitative*	low	medium	high	low	low
Ecological justice	*qualitative*	low	medium	rather high	low	medium
Security of supply	*qualitative*	low	low	medium	medium	high

Table A. 6. Rankings of the sustainability appraisal criteria of the energy stakeholders in personal interviews (I= interviewee)

	criteria	I 1	I 2	I 3	I 4	I 5	I 6	I 7	I 8	I 9	I 10	I 11	I 12	I 13	I 14	I 15	I 16
1	Air quality	10	4	3	2	6	2	4	5	3	6	1	3	1	4	5	6
2	Climate change impact	2	1	1	1	1	1	1	2	1	1	1	1	1	1	1	3
3	Costs	4	2	5	7	1	1	6	3	3	2	2	1	6	11	4	1
4	Diversity of technologies	2	4	3	5	5	2	6	3	1	6	8	4	4	15	3	3
5	Ecological justice	7	5	4	8	7	5	2	6	2	6	6	4	1	10	1	7
6	Effect on public budget	16	2	7	7	2	2	7	6	4	3	7	2	6	9	4	4
7	Electromagnetic radiation	13	6	5	10	7	7	7	6	4	8	8	4	1	19	6	6
8	Employment	7	3	5	4	3	1	3	6	1	5	4	2	2	8	2	5
9	Import independency	3	3	8	7	4	3	7	2	2	4	5	3	4	3	1	4
10	Noise	13	5	3	9	6	4	7	6	4	7	4	3	1	18	6	6
11	Quality of the landscape	7	5	4	9	6	4	7	5	5	11	6	4	1	14	5	6
12	Rational resource use	2	1	1	1	5	2	1	2	1	5	5	3	5	12	5	1
13	Regional self determinacy	3	2	3	6	7	4	5	6	3	4	7	2	4	7	2	7
14	Risk of irreversible investment	3	4	3	10	6	5	7	6	5	8	2	4	6	16	3	8
15	Security of supply	7	2	1	5	4	1	6	1	4	8	3	1	2	2	4	1
16	Social cohesion	4	2	5	6	7	2	2	6	2	9	3	4	2	6	6	7
17	Social justice	1	4	4	10	2	1	2	3	3	6	3	1	2	5	2	7
18	Technological leadership	3	3	6	8	3	2	5	6	2	7	8	2	5	13	3	3
19	Water quality	10	4	3	3	6	2	3	5	3	6	1	3	1	4	1	6

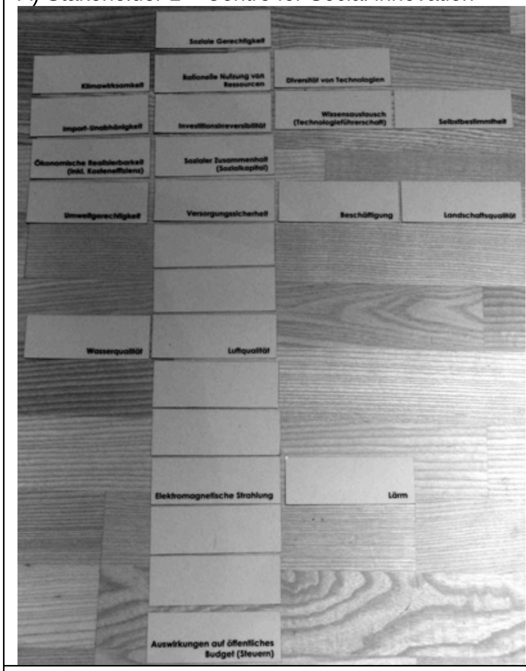
Table A. 7. Weighting of the appraisal criteria, which are transformed with the SIMOS method from the individual stakeholder ranking of criteria (I = interviewee);

	I 1	I 2	I 3	I 4	I 5	I 6	I 7	I 8	I 9	I 10	I 11	I 12	I 13	I 14	I 15	I 16
1	3,85	3,83	6,94	10,59	3,01	6,35	6,51	3,77	5,33	5,56	10,13	4,64	7,77	8,29	3,13	3,13
2	7,86	8,14	9,35	11,83	12,05	7,94	11,83	12,74	8,00	10,11	10,13	9,93	7,77	9,98	9,38	8,75
3	6,86	6,71	4,54	4,34	12,05	7,94	2,96	9,75	5,33	9,20	8,86	9,93	2,59	4,36	4,69	12,50
4	7,86	3,83	6,94	6,84	4,82	6,35	2,96	9,75	8,00	5,56	1,27	1,99	4,66	2,12	6,25	8,75
5	5,35	2,40	5,74	3,09	1,20	1,59	10,06	0,79	6,67	5,56	3,80	1,99	7,77	4,93	9,38	1,25
6	0,84	18,56	2,14	4,34	10,24	6,35	1,18	0,79	4,00	8,29	2,53	7,28	2,59	5,49	4,69	6,88
7*																
8	5,35	5,27	4,54	8,09	8,43	7,94	8,28	0,79	8,00	6,47	6,33	7,28	6,74	6,05	7,81	5,00
9	7,36	5,27	0,93	4,34	6,63	4,76	1,18	12,74	6,67	7,38	5,06	4,64	4,66	8,85	9,38	6,88
10	2,34	2,40	6,94	1,84	3,01	3,17	1,18	0,79	4,00	4,65	6,33	4,64	7,77	1,00	1,56	3,13
11	5,35	2,40	5,74	1,84	3,01	3,17	1,18	3,77	2,67	1,01	3,80	1,99	7,77	2,68	3,13	3,13
12	7,86	8,14	9,35	11,83	4,82	6,35	11,83	12,74	8,00	6,47	5,06	4,64	3,63	3,80	3,13	12,50
13	7,36	6,71	6,94	5,59	1,20	3,17	4,73	0,79	5,33	7,38	2,53	7,28	4,66	6,61	7,81	1,25
14*																
15	5,35	6,71	9,35	6,84	6,63	7,94	2,96	15,72	4,00	3,74	7,59	9,93	6,74	9,41	4,69	12,50
16	6,86	6,71	4,54	5,59	1,20	6,35	10,06	0,79	6,67	2,83	7,59	1,99	6,74	7,17	1,56	1,25
17	8,36	3,83	5,74	0,59	10,24	7,94	10,06	9,75	5,33	5,56	7,59	9,93	6,74	7,73	7,81	1,25
18	7,36	5,27	3,34	3,09	8,43	6,35	4,73	0,79	6,67	4,65	1,27	7,28	3,63	3,24	6,25	8,75
19	3,85	3,83	6,9	9,34	3,01	6,35	8,28	3,77	5,33	5,56	10,13	4,64	7,77	8,29	9,38	3,13

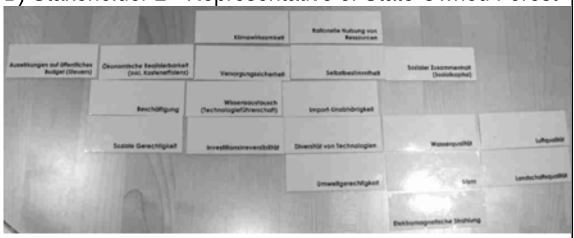
* Criteria 7 “Electromagnetic radiation” and 14 “Risk of irreversible investment” have not been further investigated and are therefore not included in the weighting calculations.

Figure A. 2. Stakeholder rankings of the sustainability criteria (images)

A) Stakeholder 1 – Centre for Social innovation



B) Stakeholder 2 - Representative of State Owned Forest



C) Stakeholder 3 - Federal Ministry of Traffic, Innovation and Technology

D) Stakeholder 4 - Federal Ministry of Agriculture, Forestry, Environment, and, Water Management

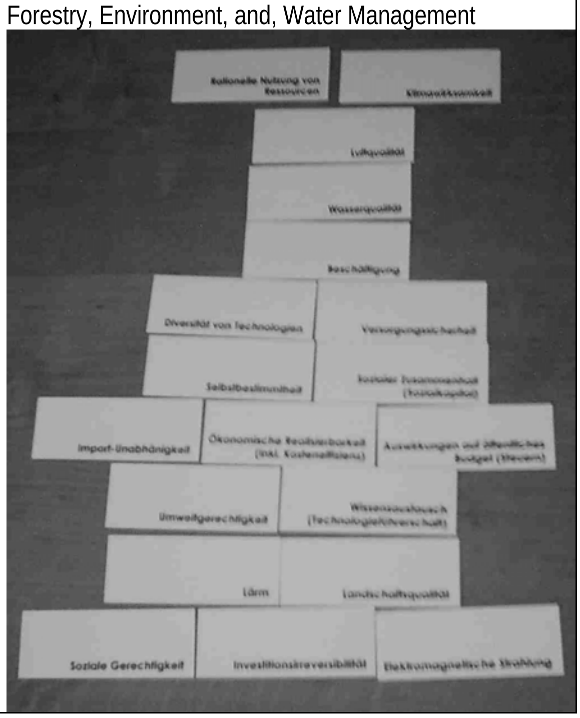


Figure A.2. continued

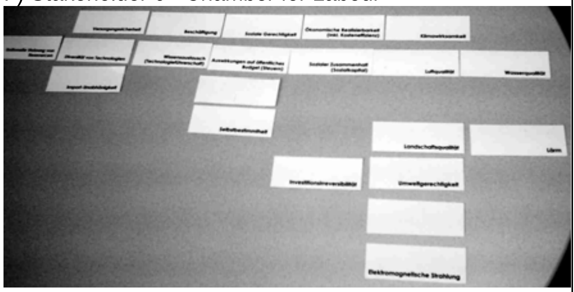
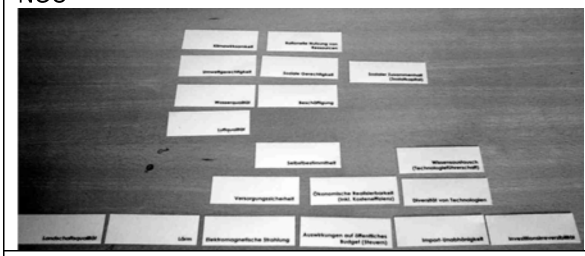
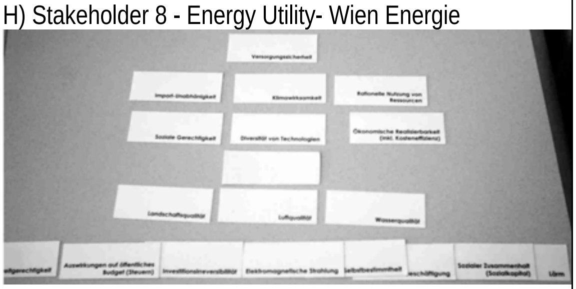
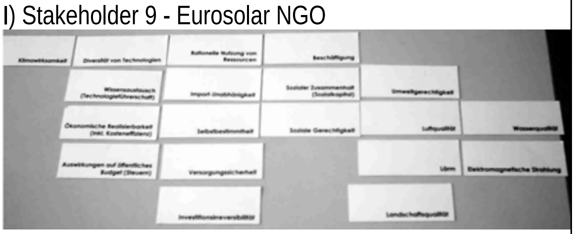
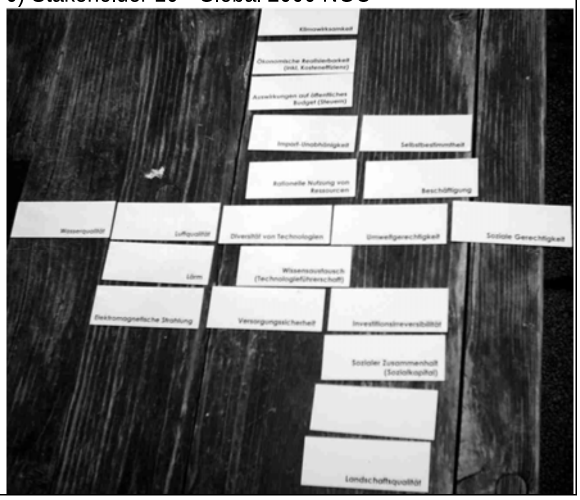
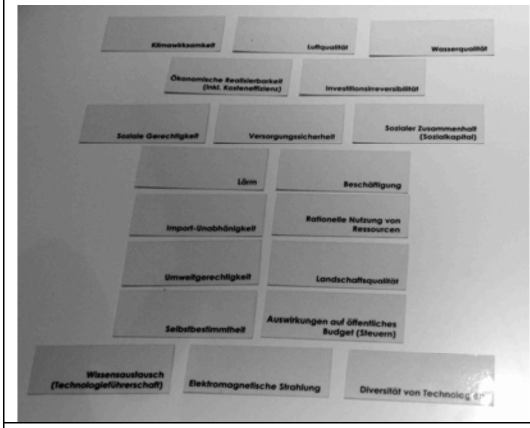
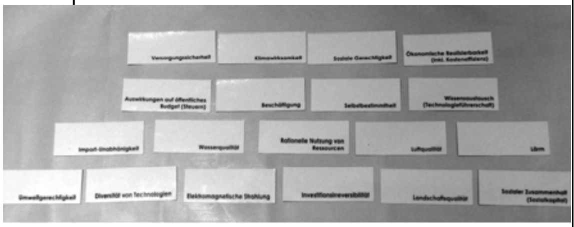
E) Stakeholder 5 - Chamber for Agriculture 	F) Stakeholder 6 - Chamber for Labour 
G) Stakeholder 7 - Renewable Energy Association AEE, NGO 	H) Stakeholder 8 - Energy Utility- Wien Energie 
I) Stakeholder 9 - Eurosolar NGO 	J) Stakeholder 10 - Global 2000 NGO 

Figure A.2. continued

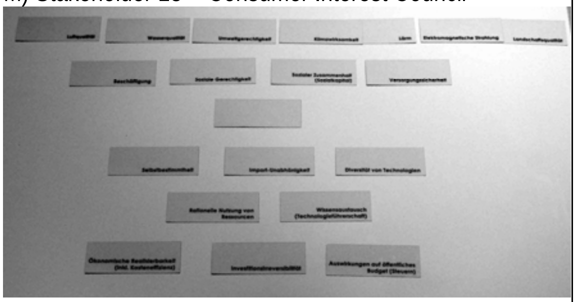
K) Stakeholder 11 - Representative for Small Hydro Power



L) Stakeholder 12 - Business Council for Sustainable Development



M) Stakeholder 13 - Consumer Interest Council



N) Stakeholder 14 - Representative for Wind Power

O) Stakeholder 15 - WWF NGO

P) Stakeholder 16 - Industrialists' Association

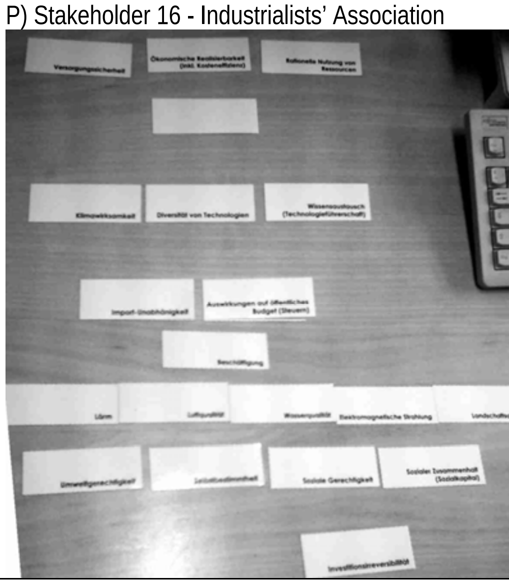


Figure A. 3. Dendrogram of a hierarchical cluster analysis of the stakeholders according to their ranking of the sustainability appraisal criteria (method 2: nearest neighbour, complete linkage)

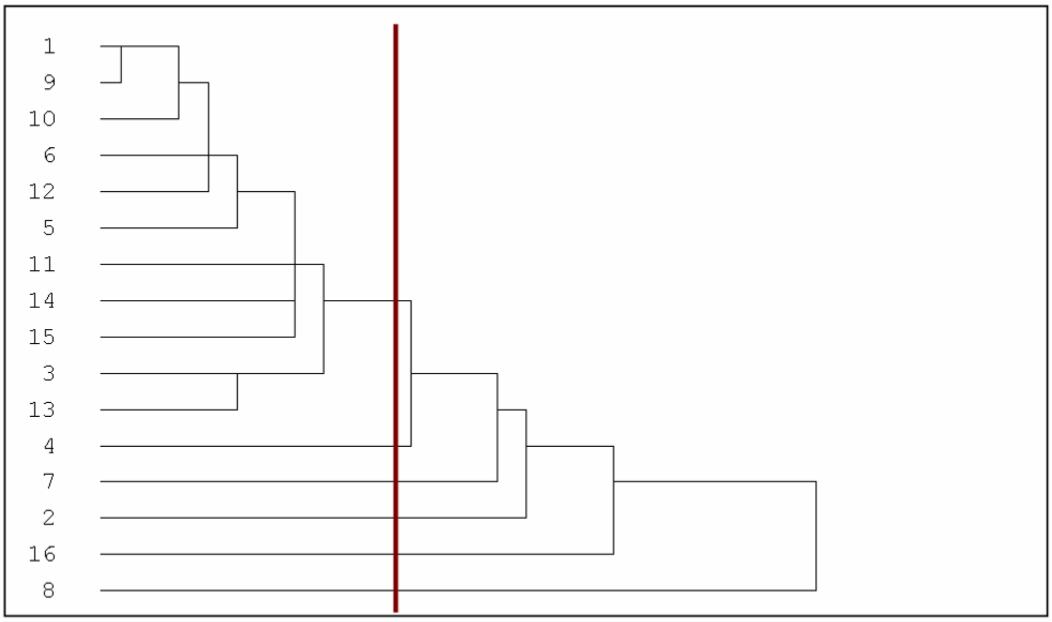
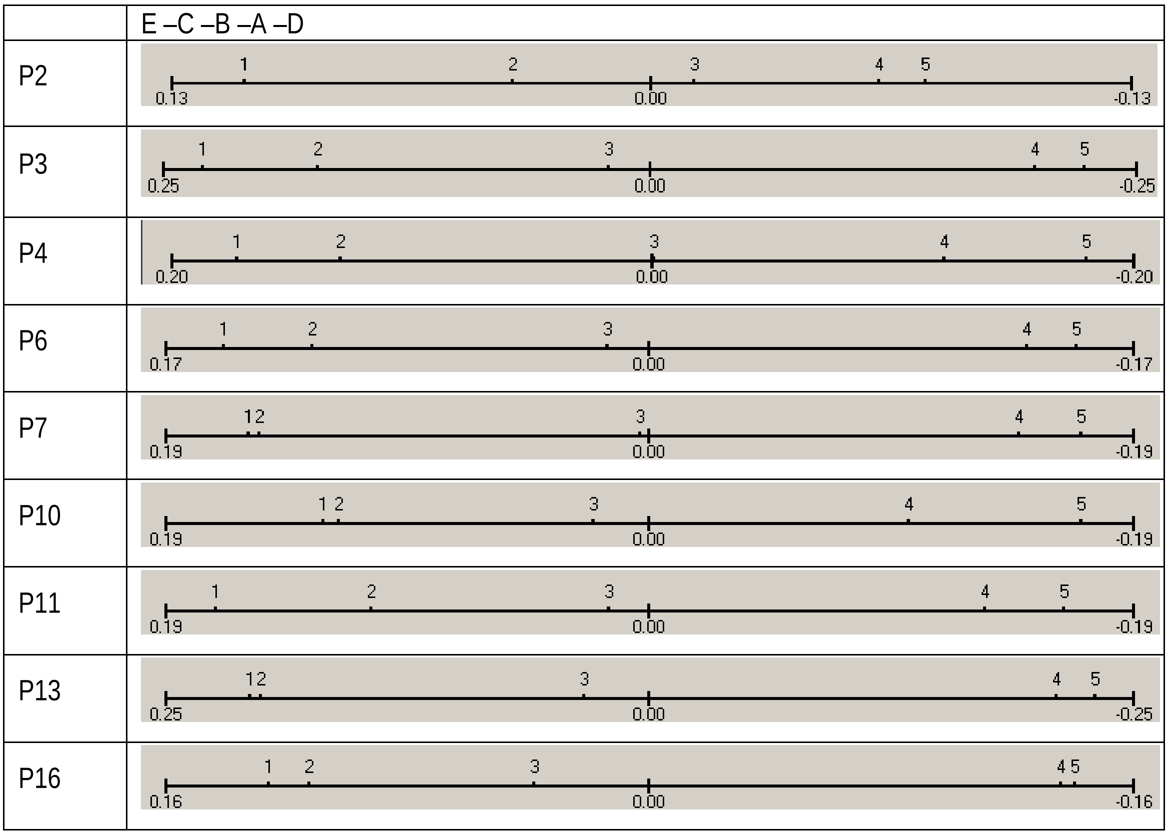
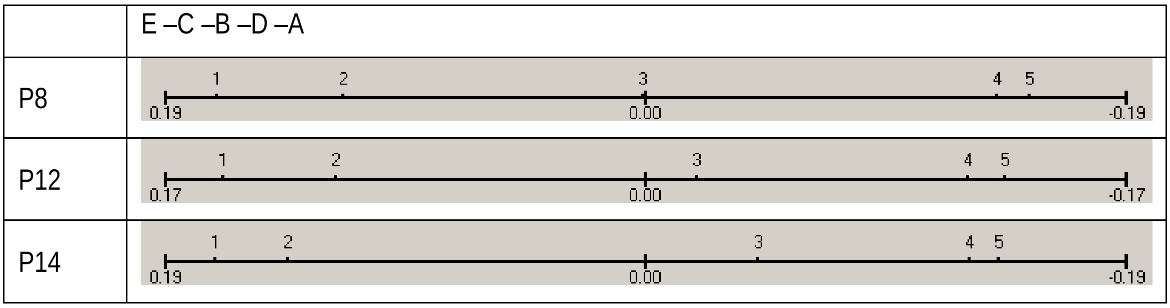


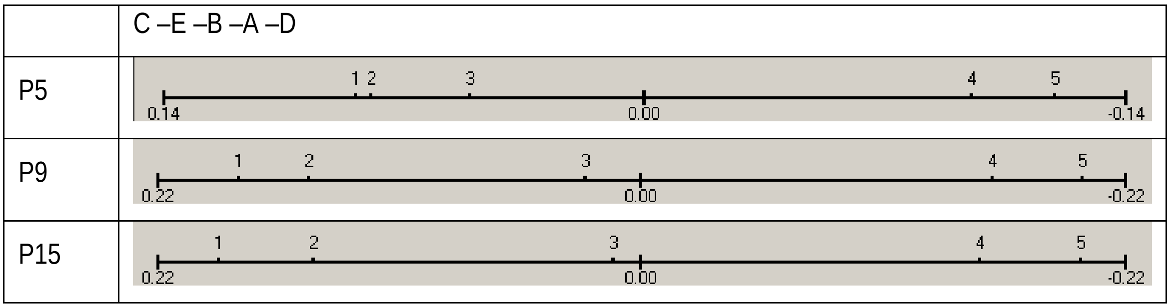
Table A. 8. Mean net flow of stakeholder rankings according to scenarios A to E.

	Scenario A	Senario B	Scenario C	Scenario D	Scenario E
P1	0.15	0.19	-0.01	-0.19	-0.15
P2	0.11	0.04	-0.01	-0.06	-0.07
P3	0.23	0.17	0.02	-0.2	-0.22
P4	0.18	0.13	0	-0.12	-0.18
P5	0.08	0.08	0.05	-0.09	-0.12
P6	0.15	0.12	0.01	-0.13	-0.15
P7	0.15	0.15	0	-0.14	-0.17
P8	0.17	0.12	0	-0.15	-0.14
P9	0.15	0.19	0.03	-0.16	-0.20
P10	0.13	0.12	0.02	-0.1	-0.17
P11	0.17	0.11	0.02	-0.13	-0.16
P12	0.15	0.11	-0.02	-0.13	-0.11
P13	0.21	0.2	0.03	-0.21	-0.23
P14	0.17	0.14	-0.04	-0.14	-0.13
P15	0.15	0.19	0.01	-0.15	-0.20
P16	0.13	0.12	0.04	-0.14	-0.14
mean	0.16	0.14	0.01	-0.14	-0.16
median	0.15	0.13	0.01	-0.14	-0.155
standard deviation	0.034	0.043	0.022	0.038	0.041

Figure A. 4. Stakeholder ranking groups according to the complete ranking







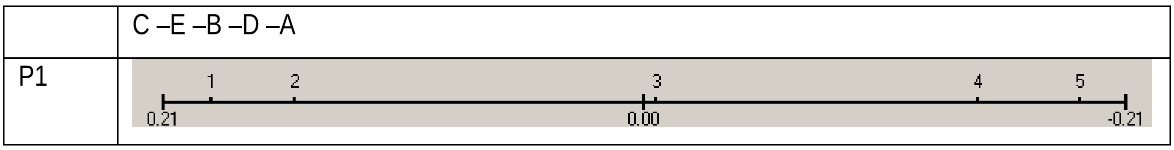


Figure A. 5. Partial scenario ranking of the most common complete scenario ranking E –C –B –A – D (group 1)

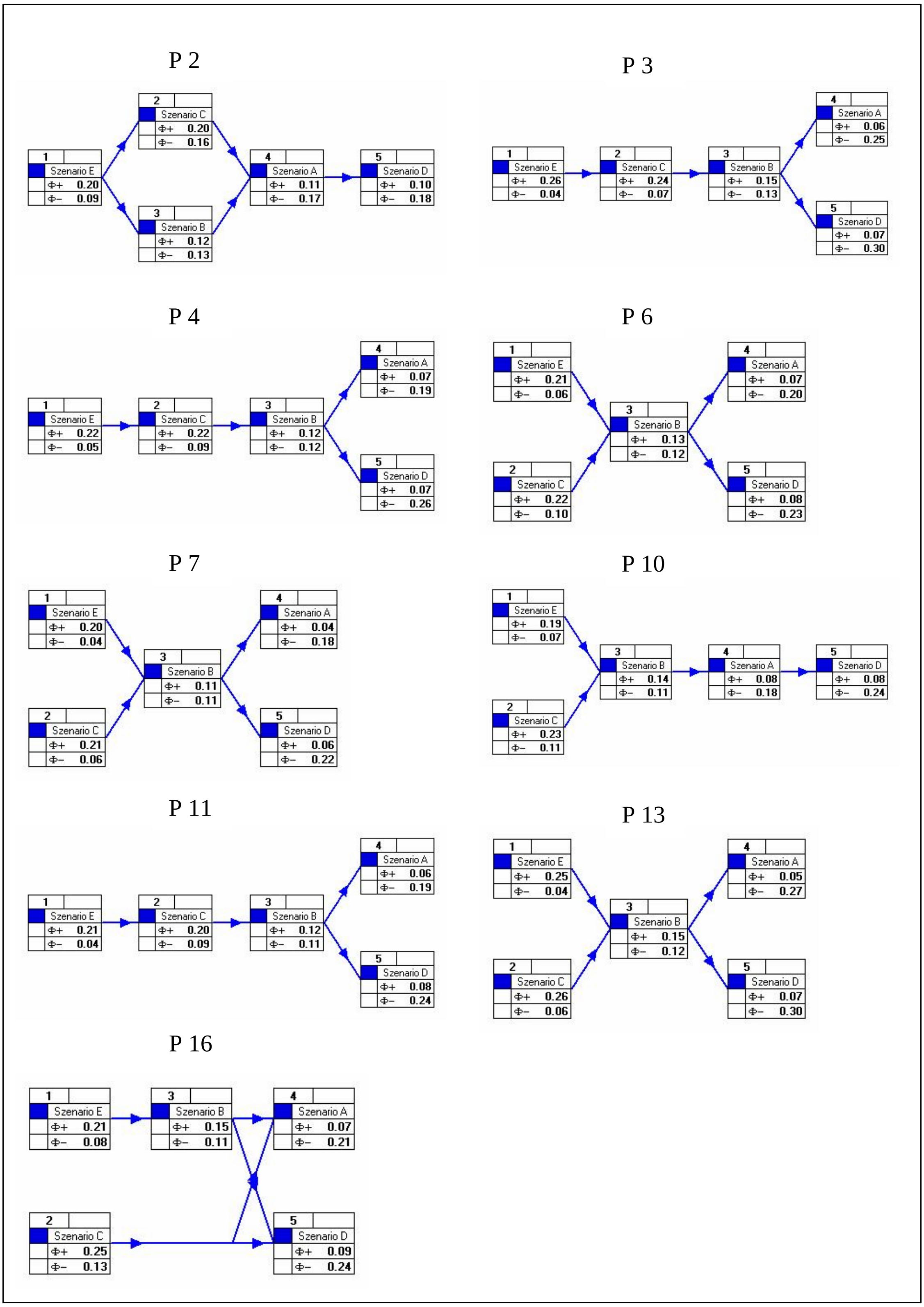


Figure A. 6. Partial scenario ranking of the three singular occurring complete scenario rankings C –E –B –A –D (group 2)

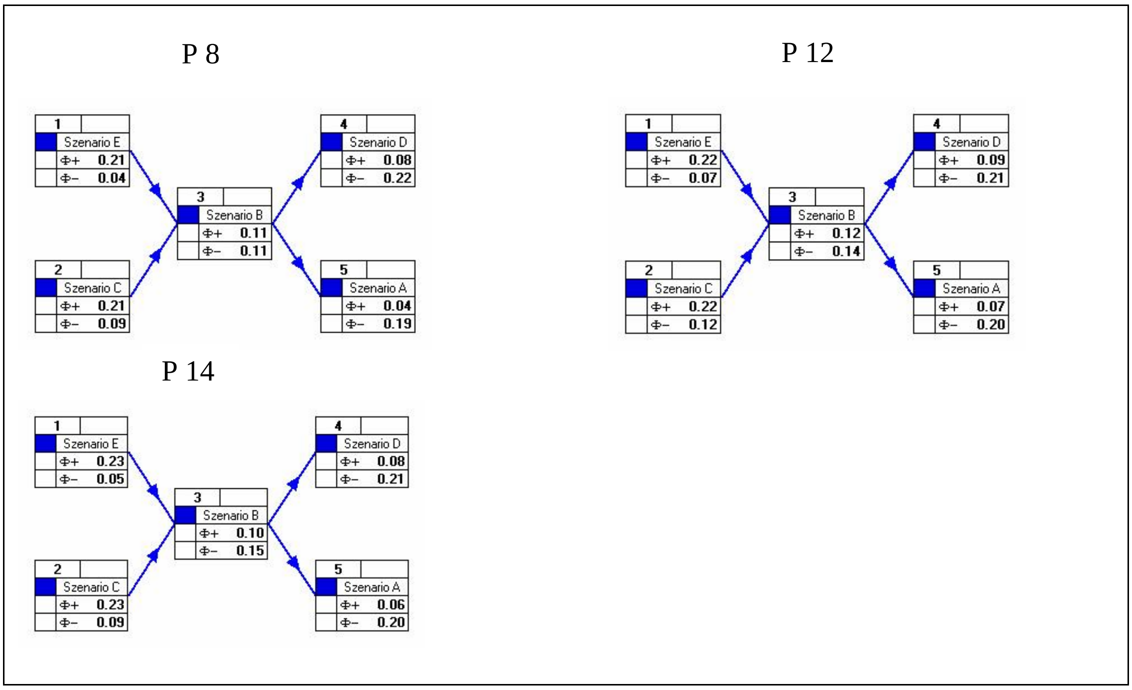


Figure A. 7. Partial scenario ranking of the second common complete scenario ranking E –C –B –D –A (group 3)

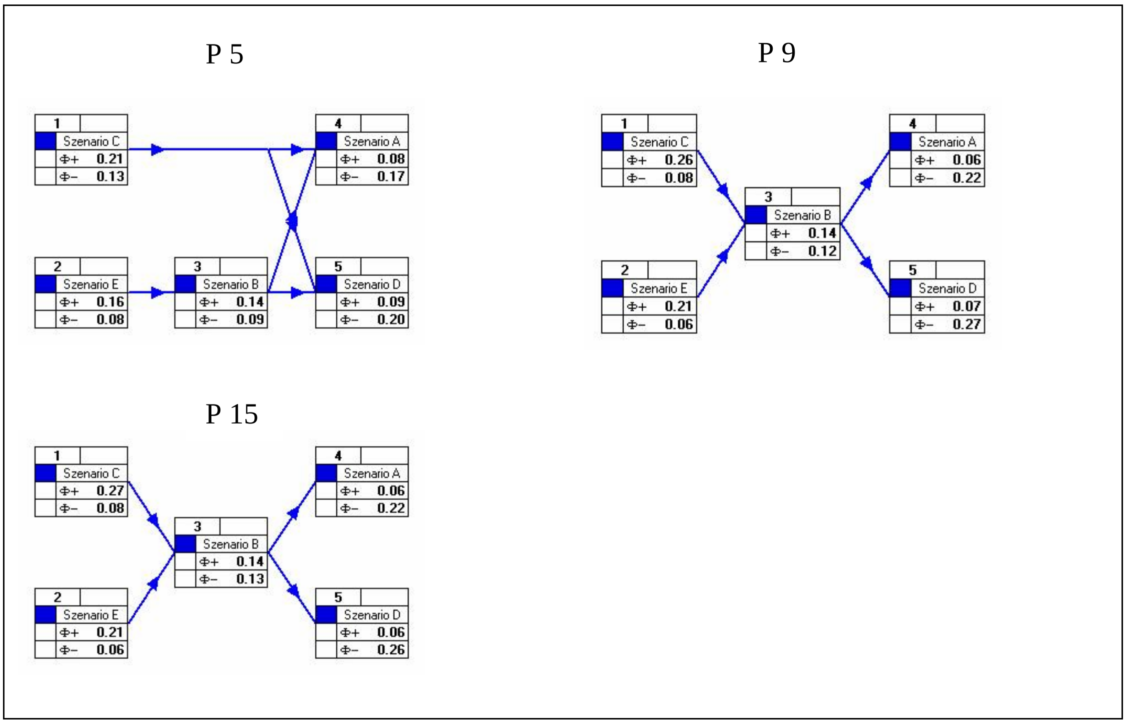


Figure A. 8. Partial scenario ranking of the three singular occurring complete scenario rankings C –E –B –D –A (group 4)

P 1

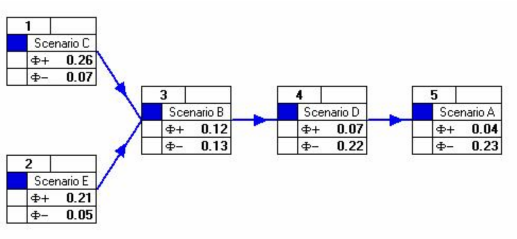
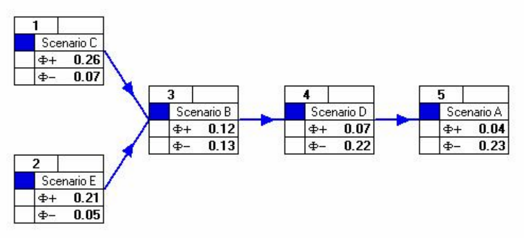
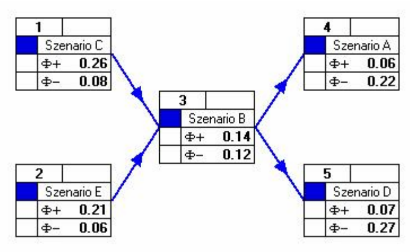


Figure A. 9. Similarities of stakeholder rankings according to weighting cluster - participants, 1, 9, and, 15 (Research Centre for Social Innovation; Euro Solar; WWF),

1 - Research Centre for Social Innovation



9 - Euro Solar



15 - WWF

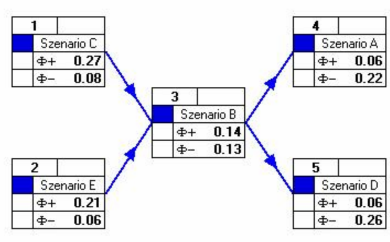
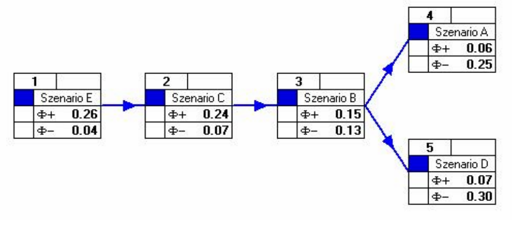
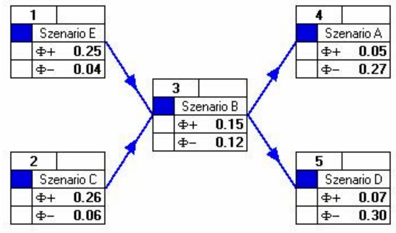


Figure A. 10. Similarities of stakeholder rankings according to weighting cluster - participant 3, 13, 11, and, 14 (Ministry of Infrastructure; Consumer Interest Council; Renewable Energy Representative, Small Hydro Power; Renewable Energy Representative, Wind Power)

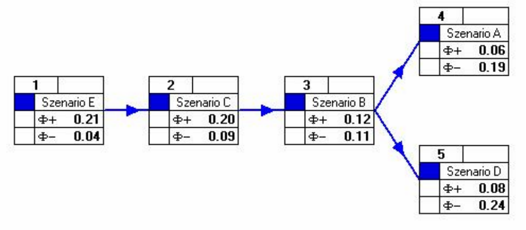
3 - Ministry of Infrastructure



13 - Consumer Interest Council



11 - Renewable Energy Representative, Small Hydro Power



14 - Renewable Energy Representative, Wind Power

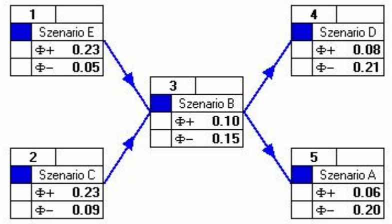
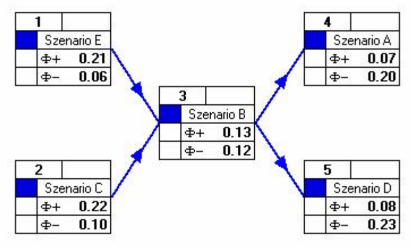
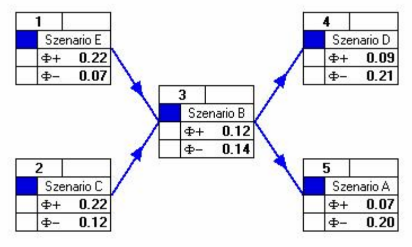


Figure A. 11. Similarities of stakeholder rankings according to weighting cluster - participant 6, 12, 10, 5, and, 2 (Chamber for Labour; Austrian Business Council for Sustainable Development; Global 2000; Chamber for Agriculture; Representative of State Owned Forest)

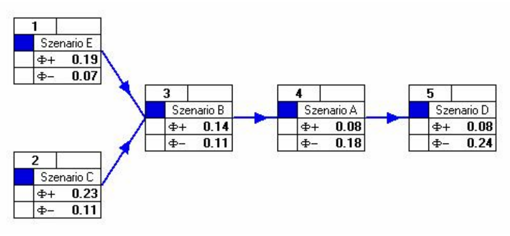
6 - Chamber for Labour



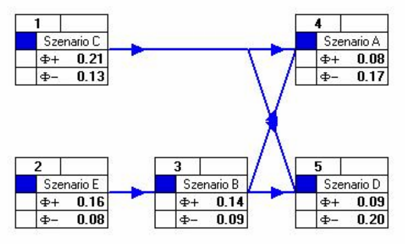
12 - Austrian Business Council for Sustainable Development



10 - Global 2000



5 - Chamber for Agriculture



2 - Representative of State Owned Forest

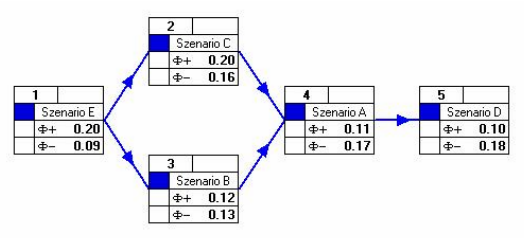
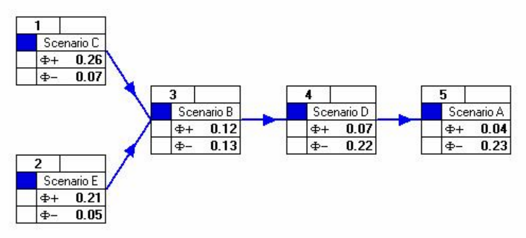


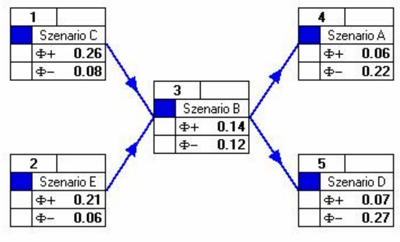
Figure A. 12. Groups of two stakeholders with similar rankings according to the cluster analysis. a) 1 (Research Centre for Social Innovation) and 9 (Euro Solar), b) 6 (Chamber of Labour) and 12 (Austrian Business Council for Sustainable Development), and c) 3 (Ministry of Infrastructures) and 13 (Consumer Interest Council)

a) 1 (Research Centre for Social Innovation) and 9 (Euro Solar)

1 - Research Centre for Social Innovation

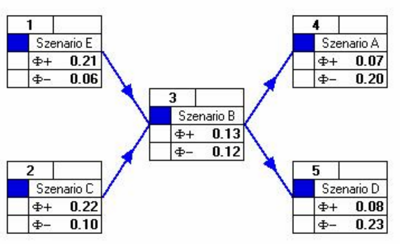


9 - Euro Solar

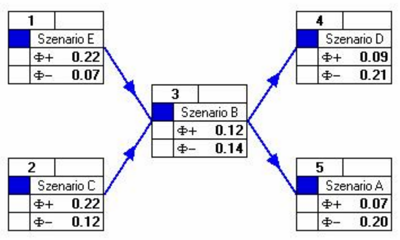


b) 6 (Chamber of Labour) and 12 (Austrian Business Council for Sustainable Development)

6 - Chamber for Labour

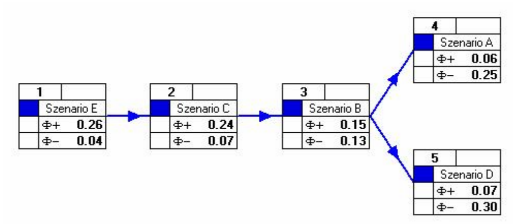


12 - Austrian Business Council for Sustainable Development



c) 3 (Ministry of Infrastructures) and 13 (Consumer Interest Council)

3 - Ministry of Infrastructure



13 - Consumer Interest Council

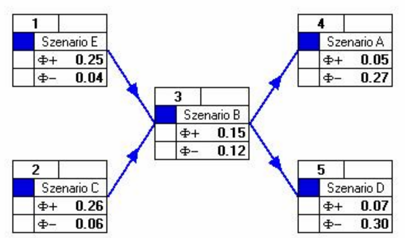


Table A. 9. Individual criteria preference functions for the standard and the sensitivity analysis SA1-3 PF.

Criteria- *Indicators*		Standard PF_0	SA 1 PF	SA 2 PF	SA 3 PF
1	Air Quality				
	SO_2 equivalents	Linear, 10%- 60%	Linear, 15%- 60%	Usual	Linear, 10%- 60%
	TOPP	Linear, 10%- 60%	Linear, 15%- 60%	Usual	Linear, 10%- 60%
	Particulate matter	Linear, 10%- 60%	Linear, 15%- 60%	Usual	Linear, 10%- 60%
2	Climate Change Properties				
	CO_2 equivalents	Linear, 6%- 60%	Linear, 10%- 60%,	Usual	Linear, 6%- 60%
3	Costs	Linear, 10%- 25%	Linear, 15%- 25%	Usual	Linear, 10%- 25%
4	Diversity of Technologies	V-Shape, 4	Linear, 1- 4	Usual	Level, 0.5- 1.5
5	Ecological justice				
	Sealed area equivalents	V-Shape, 4	Linear, 1- 4	Usual	Level, 0.5- 1.5
6	Effect on Public Budget	V-Shape, 4	Linear, 1- 4	Usual	Level, 0.5- 1.5
7	Employment	V-Shape, 4	Linear, 1- 4	Usual	Level, 0.5- 1.5
8	Import Dependency	V-Shape, 2	Linear, 1- 2	Usual	Level, 0.5- 1.5
9	Noise	V-Shape, 2	Linear, 1- 2	Usual	Level, 0.5- 1.5
10	Quality of the Landscape	V-Shape, 2	Linear, 1- 2	Usual	Level, 0.5- 1.5
11	Rational Use of Resource				
	Cumulated energy use	Linear, 10%- 60%	Linear, 20%- 60%	Usual	Linear, 10%- 60%
	Cumulated material use	Linear, 10%- 60%	Linear, 20%- 60%	Usual	Linear, 10%- 60%
12	Reg. Self determinacy	V-shape, 4	Linear, 1- 4	Usual	Level, 0.5- 1.5
13	Security of Supply	V-Shape, 2	Linear, 1- 2	Usual	Level, 0.5- 1.5
14	Social Cohesion	V-Shape, 4	Linear, 1- 4	Usual	Level, 0.5- 1.5
15	Social Justice	V-Shape, 4	Linear, 1- 4	Usual	Level, 0.5- 1.5
16	Technological Leadership	V-Shape, 2	Linear, 1- 2	Usual	Level, 0.5- 1.5
17	Water Quality				
	P	Linear, 30%- 60%	Linear, 40%- 60%	Usual	Linear, 30%- 60%
	N	Linear, 30%- 60%	Linear, 40%- 60%	Usual	Linear, 30%- 60%
	AOX	Linear, 30%- 60%	Linear, 40%- 60%	Usual	Linear, 30%- 60%
	CSB	Linear, 30%- 60%	Linear, 40%- 60%	Usual	Linear, 30%- 60%
	BSB	Linear, 30%- 60%	Linear, 40%- 60%	Usual	Linear, 30%- 60%