Coherent Energy and Environmental System Analysis

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Content

Foreword

This report presents a summary of results of the strategic research project "Coherent Energy and Environmental System Analysis" (CEESA) which was conducted in the period 2007-2011 and funded by the Danish Strategic Research Council together with the participating parties.

The project was interdisciplinary and involved more than 20 researchers from 7 different university departments or research institutions in Denmark. Moreover, the project was supported by an international advisory panel.

The results include further development and integration of existing tools and methodologies into coherent energy and environmental analysis tools as well as analyses of the design and implementation of future renewable energy systems.

For practical reasons, the work has been carried out as an interaction between five work packages, and a number of reports, papers and tools have been reported separately from each part of the project. A list of the separate work package reports is given at the end of this foreword while a complete list of all papers and reports can be found at the end of the report as well as at the following website: www.ceesa.dk.

This report provides a summary of the results of the different project parts in a coherent way by presenting tools and methodologies as well as analyses of the design and implementation of renewable energy systems – including both energy and environmental aspects.

The authors listed in the report represent those who have contributed directly as well as indirectly via the work of the different work packages. By nature this means that each individual author cannot be responsible for every detail of the different reports and papers of work packages conducted by others. Such responsibility relies on the specific authors of the sub-reports and papers. Moreover, individual participants may have personal views that differ from parts of the recommendations of this main report.

List of CEESA Background Reports:
Part 1: CEESA 100% Renewable Energy Scenarios towards 2050
Part 2: CEESA 100% Renewable Energy Transport Scenarios towards 2050
Part 3: Electric power systems for a transition to 100% Renewable Energy Systems in Denmark before 2050
Part 4: Policies for a Transition to 100% Renewable Energy Systems in Denmark before 2050
Part 5: Environmental Assessment of Renewable Energy Scenarios towards 2050

Henrik Lund, Project coordinator, October 2011

International Advisory Panel Statement

The world is faced with urgent and complex climate problems manifested by increasing global warming due to emission of greenhouse gases. A major part of the greenhouse gases come in the form of CO_2 from combustion of fossil fuels. So far, however, international negotiations aiming at commitments for reduction of greenhouse gas emissions from consumption of fossil fuels have not been successful – in spite of supplementary problems in relation to "Peak Oil".

On this background, there is a need for concrete analyses and examples that document the technological and social possibilities of phasing out fossil fuels in a way that is acceptable from a social and economic viewpoint. This applies in particular to industrial countries. The Danish CEESA project is a constructive example of such a case study.

The CEESA project illustrates that it is possible in Denmark to make a transition from an energy system dominated by fossil fuels to a supply system based completely on renewable energy with a dominating part of intermittent sources like wind and solar. The CEESA scenarios perform this transition before the year 2050 using mainly known technologies in combination with significant energy conservation. Without energy conservation, the transition will be much more difficult to realise.

The need for new systems thinking and new planning principles for energy investments is among the important observations in this scenario project. With dominant contributions from intermittent sources and limited amounts of biomass in relation to solutions of storage problems, it is necessary to integrate the electricity, heat and transport sectors much more than in traditional supply systems based on fossil fuels. The CEESA project shows how this can be done in an efficient and economical way.

The planning of the transition also requires longer time horizons than the commercial market can offer. As a consequence, it is proposed that the balance between the commercial market and societal planning is shifted to the advantage of societal planning to avoid short-sighted investments. It is an extra benefit of the proposed transition to a renewable energy system that it significantly improves the Danish energy supply security in relation to Peak Oil and the expected increasing oil price.

The CEESA project combines its technological scenarios with proposals for policy means supporting the implementation of the selected scenarios. This is an important combination for the further progress and realisation of the proposed transition to a 100 % renewable energy supply system. Without efficient policy means, this transition will not be realised in time. The report has special focus on policy instruments for reduction of energy consumption in the transport and household sectors and it is emphasised that the different supply and consumption sectors typically require different policy means.

On behalf of the International Advisory Panel, it is my pleasure to recommend the results of the CEESA project to policy makers both in Denmark and internationally.

Niels I. Meyer (Chairman), Technical University of Denmark, Lyngby, Denmark

Other members of the International Advisory Panel are:
Thomas B. Johansson, Lund University, Lund, Sweden
Mark Barrett, UCL Energy Institute, London, United Kingdom

Highlights

The output of the project can be divided into three main areas: Firstly, results related to the further development and integration of existing tools and methodologies into coherent energy and environmental analysis tools. Secondly, results related to the analysis of future sustainable energy systems. And finally, dissemination of the results.

The result of the CEESA project includes the following highlights:

Tools and Methodologies:

- Further development of several existing tools such as vehicle drive cycle analysis and energy systems analysis tools including implementation of abilities to analyse new biomass conversion technologies and combined hour balances of storage and exchange of bio(syn)gas as well as electricity and district heating.
- Development of a new CEESA transport scenario tool.
- A method for qualitative modelling of electricity system control structures and a tool for evaluating control resource use in scenario studies.
- Further development of the methodology basis for combining energy system analysis with life cycle assessment.

Modelling and Analyses:

- Development of biomass resource scenarios and review of potential biomass conversion technologies.
- Design and modelling of a transport scenario.
- Combined energy system and LCA analyses of a 100% renewable scenario including hour balances of bio(syn)gas production, storage and exchange (additional to balancing and exchange of electricity and district heating).
- Evaluation of electricity grid stabilisation with electric vehicles.
- Design of a policy and implementation strategy.

Dissemination:

- Establishment of a dialogue with potential beneficiaries and dissemination of tools and methodologies on an on-going basis including contributions to the Danish Society of Engineers Climate Action plan 2050 (2009), Heat Plan Denmark (2008 and 2010), EnergyTown Frederikshavn and Long-term vision for Aalborg Municipality (2010), among others.
- 5 PhD projects (One finalised and 4 expected to be finalised in 2012).
- 19 book chapters or journal papers.
- 25 conference proceedings and presentations.
- Input to proceeding strategic research projects, among others the “Zero emission buildings” research centre project.
- Analyses and report input to a national debate on export of wind power from the Danish energy system, “Danish Wind Power – Export and Costs” (2010).

Executive summary

This executive summary presents the main results of applying the tools and methodologies developed in the CEESA project to the design and implementation of 100% renewable energy systems in Denmark before 2050.

It is found that the transition from the present energy system dominated by fossil fuels to a system dominated by renewable energy sources requires significant changes in existing policies on both supply and demand sides. This is a change from polluting energy systems dependent on depleting inputs to energy systems that depend on non-depleting inputs and which are relatively abundant, non-polluting and intermittent.

In order to succeed, such change requires the system based on renewables to be supported by strong and efficient energy conservation. In Denmark, wind power and biomass are expected to be the two dominant resources in the short and medium term perspectives. In order to ease the pressure on wind and biomass resources, energy conservation becomes essential and so does the inclusion of contributions from additional sources such as solar and geothermal energy.

The change requires infrastructure where intermittent renewable energy sources can be managed in such a way that energy is available at the right time and in the right amount for the consumers. A main challenge for the transition planning is to obtain an efficient co-ordination between investments in the electricity, transportation, and heat sectors. The policy instruments include new systems of taxes, subsidies, tariffs, and other economic conditions in order to obtain an optimal effect.

One main problem is to assure an energy-efficient use of low-temperature sources from CHP, waste incineration, industrial surplus heat and geothermal energy. In this relation, a new generation of low-temperature district heating infrastructure becomes essential.

Another part of the main problems in a future energy system dominated by intermittent renewable sources (e.g. wind and solar energy) is the stability of the electric grid and the security of supply to electricity consumers. In this connection, biomass in different forms plays a central role as a storage element. However, biomass is also required in the transport sector and for high-temperature industrial process heat (transformed to a liquid fuel or to biogas) while the amount of Danish biomass, taking into account other uses of the land area, is rather limited. In this respect, it becomes important to use the existing natural gas grid including substantial gas storage capacity in order to distribute and store biogas and syngas in future renewable energy systems. The CEESA project presents a technical scenario towards 2050 that achieves the specified goal with emphasis on infrastructures of transport and electricity supply as well as district heating.

The CEESA scenario proposes that the best solution is to let electricity from wind power replace the demand for biomass where possible and to stabilise the grid by other means than biomass where relevant alternatives are available. These means include systematic use of heat pumps and heat storage, eventually combined with electric cars and gas grid storage. The proposed policy means are selected in accordance with these technological solutions.

The CEESA project has documented that it is possible to find technical solutions for a 100 % renewable energy system that meets the required conditions with a satisfactory societal economy. However a certain technological development becomes essential for the coming years. The project has also described a number of new policy instruments for implementing the renewable energy scenario.

A summary of some of the concrete considerations is given below.

Biomass potential

In the CEESA project, significant efforts have been put into identifying the biomass potential. It is emphasised that the potential is dependent on the future use of land area and future farming practices. Currently, a substantial amount of land is allocated to meat production. Consequently, three different scenarios have been analysed: a business-as-usual scenario, conversion to organic farming and enacting dietary changes in the Danish population.

For all three scenarios, resources have been estimated both in relation to primary production and in the form of processing waste. Primary resources include dedicated energy crops, wood from forests, parks and gardens; and straw, stalks or leaves from agricultural crops. Secondary biomass resources or biomass in the form of by-products and waste include manure from animal production, processing residues as mill residues, molasses, pulp, whey and wood residues.

The results show that in a business-as-usual scenario, the potential is approx. 180 PJ/year, while enacting dietary changes increases the biomass potential to approx. 200 PJ/year. A shift in forest management practices and cereal cultivars could increase the potential further. As a consequence, a target of 240 PJ/year by 2050 has been applied to the scenarios described in the following. Such potential represents the use of residual resources only.

A target of 240 PJ/year by 2050 implies a number of potential conflicts due to many different demands and expectations for ecosystems services. Meeting the target in a Danish context requires agricultural land otherwise allocated to food crop production to be converted to energy crop production, potentially reducing food and feed production. All crop residues must be harvested, potentially reducing the carbon pool in soils. A strategy towards increasing the amount of organic agriculture in Denmark will decrease the amount of domestically produced bioenergy available. Moreover, if biomass in a future non-fossil society has to cover the production of materials currently based on petro-chemical products, even more pressure will be put on the biomass sector. A way to reduce conflict potential is to reduce the demand for biomass for energy or to further develop agriculture and forestry in order to increase biomass production per unit of land.

More details are given in Background Report Part 1: "CEESA 100% Renewable Energy Scenarios towards 2050."

Life cycle analysis

To analyse the environmental consequences of the renewable energy systems as well as to assist in the design, a life cycle assessment (LCA) has been performed. Focus has been on the consequences of use of biomass resources. In addition, impacts related to crop changes in Denmark have been assessed and evaluated with respect to the importance to Danish energy production.

Different scenarios and solutions of 100% renewable energy have been analysed. The main findings of the LCA are that a consistent abatement of the greenhouse gases (GHGs) (about 66-80% depending on the scenario) can be achieved by implementing renewable energy systems. The main differences between different scenarios are related to the fuels in the transport sector.

As an input to the design of future renewable transport systems, the results of the LCA emphasise that the impacts associated with rapeseed cultivation are significantly higher than those associated with willow due to low yield in the rapeseed case. The analyses show that significant aspects of energy crops cultivation can completely offset the benefits of biofuels. This applies especially to the production of biodiesel.

Additional to the GHGs, a significant decrease of the acidification and its environmental impact was observed in general for 100% renewable solutions. This is mostly due to reduced emissions of SO_2 and NO_x from fossil fuel combustion in power plants.

Significant impacts of land use changes (principally indirect) underline that in today's system and given the present institutional set-up of international trade, major impacts related to land use changes can make the option of using fossil fuels for heavy transport preferable to the production and use of biodiesel-like fuels.

More details are given in Background Report Part 5: "Environmental Assessment of Renewable Energy Scenarios towards 2050"

Transport scenario

The CEESA project has put special emphasis on the development of scenarios for renewable energy in the transport sector. This complex sector poses a significant problem in renewable energy systems.

The project presents a model of the existing Danish transport sector as well as a projection towards 2050. International aviation, international sea, trucks, cars and other vehicles related to Danish passenger and freight transport are considered in the CEESA project. This provides a complete assessment of the requirements needed to implement renewable energy in the sector. The overall results indicate that direct electricity should be given priority over all biofuels in the transport sector and that co-electrolysers will need to be developed in the future to maintain a sustainable biofuel consumption.

The CEESA project describes three different 100% renewable energy transport scenarios which emphasise the urgency of strong investments in advanced public transport, in the development of more efficient electric vehicles, and in the development of co-electrolyser-based synthetic fuels, especially for aeroplanes and heavy-duty vehicles. This can also reduce the pressure on the biomass resource.

As part of this work, a number of detailed, generic and transparent analyses of current state-of-the-art battery electric vehicles have been conducted under realistic conditions. Such analyses show that the present technology has challenges to overcome before it can meet the general expectations as presented in most literature. Consequently, it should be stressed that the present technology needs further development in order to be able to fulfil the preconditions for the future scenarios.

Finally, it is also evident from the results that a 100% renewable energy transport sector can be achieved with lower costs than the business-as-usual reference which is forecasted for Denmark's transport system.

More details are given in Background Report Part 2: "CEESA 100% Renewable Energy Transport Scenarios towards 2050".

Technological development and renewable energy scenarios

The aim of the CEESA project has been to design a relevant scenario for transforming the present energy system based mainly on fossil fuels into a 100% renewable energy system by year 2050. The design of such scenario highly relies on the technologies which are assumed to be available within the chosen time horizon. To highlight this issue, the CEESA project has identified the following initial scenarios based on three different assumptions with regard to the available technologies:

> ***CEESA-2050 Conservative:*** *The conservative scenario is created using mostly known technologies and technologies which are available today. This scenario assumes that the current market can develop and improve existing technologies. In this scenario, the costs of undeveloped renewable energy technologies are high. Very little effort is made to push the technological development of new renewable energy technologies in Denmark or at a global level. However, the scenario does include certain energy efficiency improvements of existing technologies, such as improved electricity efficiencies of power plants, more efficient cars, trucks and planes, and better wind turbines. Moreover, the scenario assumes further technological developments of electric cars, hybrid vehicles, and bio-DME/methanol production technology (including biomass gasification technology).*

CEESA-2050 Ideal: In the ideal scenario, technologies which are still in the development phase are included on a larger scale. The costs of undeveloped renewable energy technologies are low, due to significant efforts to develop, demonstrate and create markets for new technologies. For example, the ideal scenario assumes that fuel cells are available for power plants, and biomass conversion technologies (such as gasification) are available for most biomass types and on different scales. Co-electrolysis is also developed and the transport sector moves further towards electrification compared to the conservative scenario.

CEESA-2050: *This scenario is a "realistic and recommendable" scenario based on a balanced assessment of realistic and achievable technology improvements. It is used to complete a number of more detailed analyses in the project, including the implementation strategy, as well as in a number of sensitivity analyses. Here, however, less co-electrolysis is used and a balance is implemented between bio-DME/methanol and syn-DME/methanol in the transport sector. This is the main CEESA scenario.*

The *Conservative* and *Ideal* scenarios are used to illustrate that different technological developments will have different effects on the extent of the use of biomass resources, as well as the requirements for flexibility and smart energy system solutions. In all scenarios, energy savings and direct electricity consumption are given a high priority. In the CEESA scenarios, the *smart energy system* integration is crucial. The scenarios rely on a holistic *smart energy system* including the use of: heat storages and district heating with CHP plants and large heat pumps, new electricity demands from large heat pumps and electric vehicles as storage options, electrolysers and liquid fuel for the transport sector, enabling storage as liquids as well as the use of gas storage.

Such *smart energy systems* enable a flexible and efficient integration of large amounts of fluctuating electricity production from wind turbines and photovoltaics. The gas grids and liquid fuels allows long-term storage, while the electric vehicles and heat pumps allows shorter term storage and flexibility.

All the above three technology scenarios are designed in a way in which renewable energy sources, such as wind power and PV, have been prioritized, taking into account the technological development in the scenarios and the total costs of the system. Moreover, they are all based on decreases in the demand for electricity and heat as well as medium increases in transport demands. Consequently, none of the scenarios can be implemented without an active energy and transport policy. However, sensitivity analyses are conducted in terms of both a high energy demand scenario as well as the unsuccessful implementation of energy saving measures. These analyses point in the direction of higher costs, higher biomass consumption and/or a higher demand for more wind turbines.

In the *conservative* technology scenario, wave power, photo voltaic and fuel cell power plants are not included and emphasis is put on bio-DME/Methanol and on direct electricity consumption in the transport sector. The electrolysers are based on known technology in this scenario. Smart energy systems and cross-sector system integration is required between the electricity system, district heating sectors as well as into the transport system and gas grid in all scenarios. The integration into the transport system and gas grids is, however, not as extensive in the *conservative* scenario as in the *ideal* scenario. In the *ideal* scenario, wave power, photo voltaic, fuel cell power plants, and a number of other technologies are used to their full potential, while, in the *recommendable* scenario, the technologies are assumed to be developed to a degree in which they can make a substantial contribution. For all technologies, sensitivity analyses are made in which they are replaced with existing technologies. The primary energy consumption for 2050 of the three scenarios and the reference energy system is compared in Figure 1 below. Compared to the reference energy system, all the scenarios are able to reduce the primary energy supply to a level of approximately 500 PJ. There are however large differences between the structure of this primary energy supply.

In the *conservative* technology scenario, a 100% renewable energy system is possible with a total biomass consumption of 331 PJ. The *ideal* technology scenario can decrease this consumption to 206 PJ of biomass. In the CEESA 2050 *recommendable* scenario, the biomass consumption is 237 PJ and thus 30 PJ higher than in the *ideal* and 96 PJ lower than in the *conservative* scenario. In all three scenarios, hour-by-hour energy system analyses have been used to increase the amount of wind turbines to an amount ensuring that the unused electricity consumption, also referred to as excess electricity, is lower than 0.5 TWh (1,8PJ). These analyses also ensure that the heat supply and gas supply is balanced. The importance of that is visible in the differences in the installed wind power capacities in the three 100% renewable energy scenarios, i.e., the *ideal* scenario is able to utilise more wind power than the *conservative* scenario.

The recommended CEESA scenario

The current primary energy supply in Denmark (fuel consumption and renewable energy production of electricity and heat for households, transport and industry) is approximately 850 PJ, taking into account the boundary conditions applied to transport in this study, in which all transport is accounted for, i.e., national/international demands and both passengers and freight. If new initiatives are not taken, the energy consumption is expected to decrease marginally until 2020, but then increase gradually until 2050 to about 970 PJ. The reference energy systems follow the projections from the Danish Energy Authority from 2010 until 2030, and the same methodology has then been applied here to create a 2050 reference energy system. The measures of savings, transport as well as renewable energy and system integration between the electricity, heat, transport and gas sectors can reduce the primary energy supply to 669 PJ in CEESA 2020; 564 PJ in CEESA 2030; 519 PJ in 2040, and 473 PJ in CEESA 2050, respectively.

At the same time, the share of renewable energy from wind turbines, photovoltaic, solar thermal, and wave energy, as well as biomass will be increased. The share of renewable energy in the recommended energy system increases from about 20 % in 2010 to 42 % in 2020 and to about 65 % in 2030. If the oil and gas consumption in refineries and for the extraction of oil in the North Sea is excluded, 73 % is the share of renewable energy in the 2030 energy system. Coal is phased out before 2030. In 2050, the entire Danish energy system (incl. transport) is based on 100 % renewable energy. The primary energy supply is illustrated in Figure 2. More details are given in Background Report Part I: "CEESA 100% Renewable Energy Scenarios towards 2050"

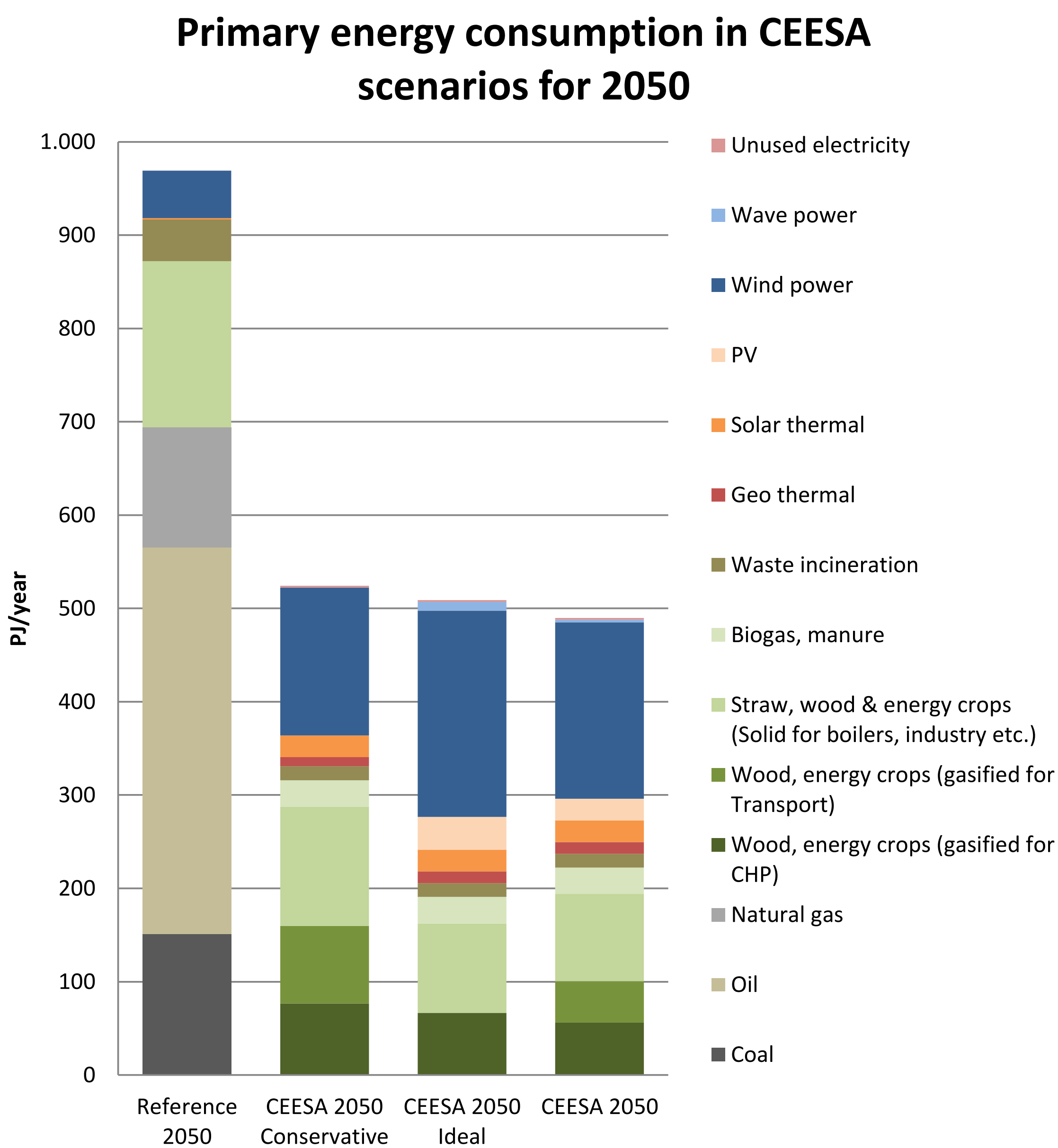

Figure 1: Primary energy supply in the 2050 reference energy system and the three CEESA 100% renewable energy scenarios.

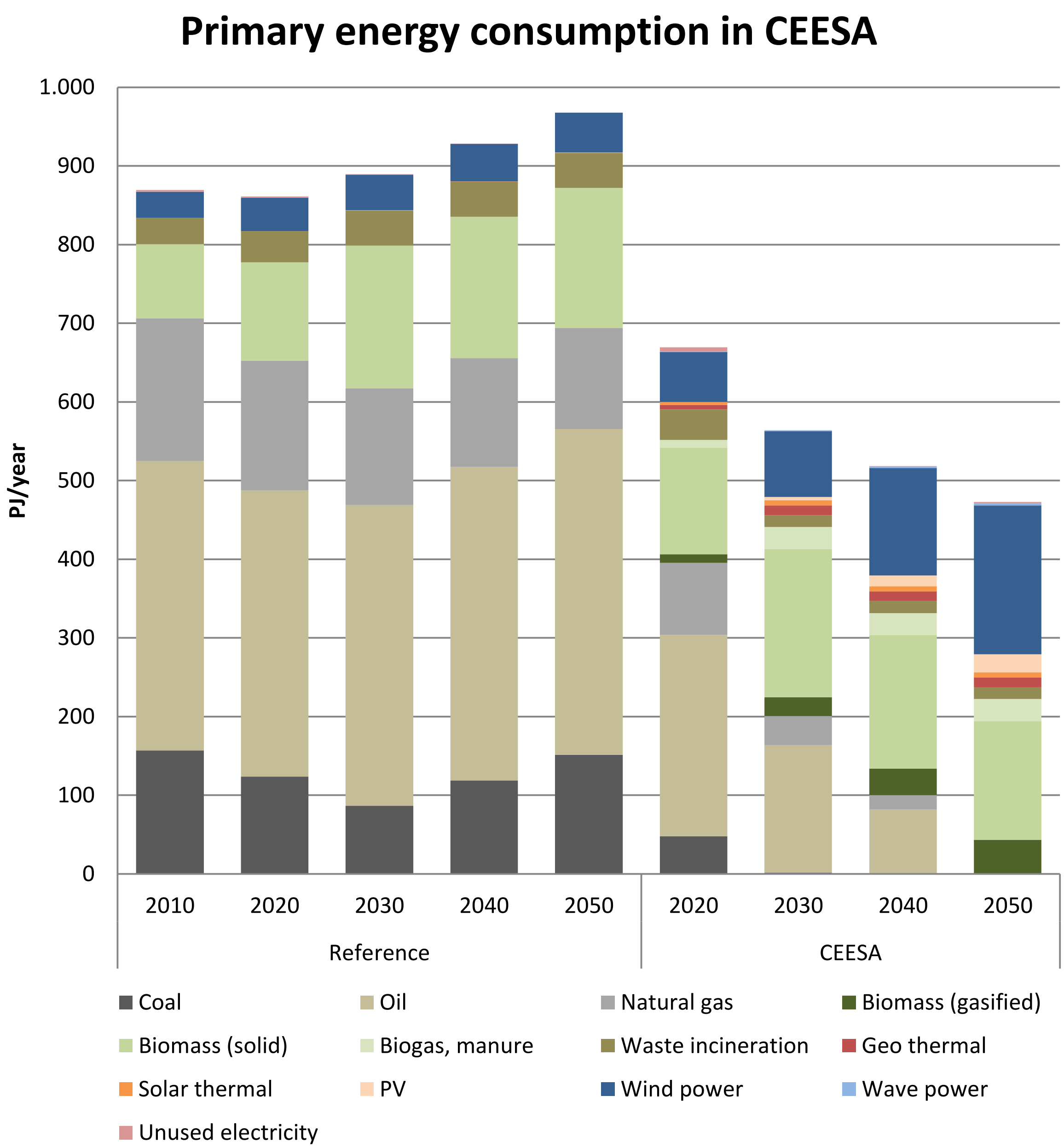

Figure 2: Primary Energy Supply in CEESA.

Future power systems

Special attention has been given to qualifying the hourly-based scenario analyses of future energy systems by investigating the short-term situation of the electricity system and relating the scenario findings to the design of future control structures. The analyses were manifested in two main parts. In the first part, analyses of electric vehicle (EV) based battery storages to support large-scale integration of wind power in Denmark were in focus.

The second part included methodology development for evaluation, analysis and selection of future control strategies for different power system structures.

Electricity generated from wind power forms a significant fraction in all scenarios, ranging from 50% to 200% of the projected conventional electricity demand which will dramatically increase the need for system balancing in response to prediction errors and short-term fluctuations. Electricity systems in operation today have been proven capable of integrating about 20% fluctuating generation. The means offered in the CEESA scenario include a largely increased availability of controllable electricity consumption units by integration with other energy sectors and 'cheap' demand-side storage, supplying sufficient reserves on the hourly level.

For future power system operation, some of today's notions, such as "peak demand" or "base load generation", become less meaningful and thus need to be revised. A general *paradigm of flexibility* will be supported by probabilistic notions of balancing capacity. For the *design* of operation strategies, a more explicitly function-oriented and formal modelling approach is described. In particular, the fundamental role of synchronous generators in power system operation will need to be reconsidered. With regard to *evaluation*, a more explicitly risk-oriented modelling approach enables an informed selection of future power system operation strategies.

The design of new control structures is an incremental, experimental development. It is therefore important to further develop simulation platforms that enable the evaluation of operation strategies in the context of future power systems scenarios.

More details are given in Background Report Part 3: "Electric power systems for a transition to 100% renewable energy systems in Denmark before 2050."

Policy instruments for implementation of a transition to 100% renewable energy systems

A part of the CEESA project has been to define policies and market design in order to make a complete transition in Denmark from fossil fuels to renewable energy sources before 2050.

The policy instruments include new systems of taxes, subsidies, tariffs, and other economic conditions in order to obtain an optimal effect.

In addition, a number of institutional and regulatory changes are proposed. A central question in this connection is the balance between the role of the market and the role of societal planning and regulation. Considering the long lifetime of many energy plants and infrastructures, including buildings, it is concluded that the balance needs to be shifted to increase the role of long-term societal planning and regulation. A challenge for the transition planning is to obtain an efficient co-ordination between investments in the electricity, transportation and heat sectors.

A number of macro-economic barriers exist for the transition from fossil fuels to renewables e.g. in relation to market structures that support lock-in action for technologies based on fossil fuels. In Denmark, another barrier is the prevalence of high discount rates for the planning of future investments.

Some of the existing barriers can be removed (or reduced) by national changes of tariffs, taxes and other policies, and of the planning methodologies and priorities, while others may need changes at the EU level. These changes will require alternative political decisions at high levels in Denmark and the EU. However, the political mechanisms of the paths to these high-level decisions are not part of this report.

The CEESA proposals for policy instruments are based on a list of criteria where the highest priority is given to efficient fulfilment of the overall goal of the CEESA project: 100 % renewables in the Danish energy supply before 2050. Other criteria include consideration of economic efficiency, social balance in the policies, promotion of Danish employment and industrial production, and policies that support public involvement for energy conservation.

More details are given in Background Report Part 4: “Policies for a Transition to 100% Renewable Energy Systems in Denmark Before 2050”

1 Introduction

1.1 Research Project Aim and Focus

The main focus of this project has been

- to further develop and integrate existing tools and methodologies of environmental life cycle assessment and energy system and market analysis into coherent energy and environmental analysis tools.
- to apply such integrated tools and methodologies to the analysis of future sustainable energy systems with an emphasis on: 1) how to integrate the transport sector including considerations of limitations in biomass resources; 2) how to develop future power systems suitable for the integration of distributed renewable energy sources; and 3) how to develop efficient public regulation in an international market environment.

The hypothesis has been that the prioritisation between the use of different renewable energy and biomass resources has become of significant importance to the development of sustainable energy systems in countries such as Denmark. Consequently, the design and evaluation of energy systems cannot be done properly without comprehensive environmental assessment tools. To obtain a truly sustainable energy system, it is important to optimise not only individual sub-systems (e.g. the electricity distribution system, the transport system, the production system, etc.) but also the overall energy system. Most discussions about environmental aspects of energy production have so far focused on greenhouse gas emissions directly related to the production phase. It should, however, be emphasised that all phases, both upstream and downstream of the actual energy production (electricity, fuels, energy carriers), may significantly affect the overall environmental impacts. As a consequence, a number of indirectly related processes and impacts must be addressed as well.

Environmental aspects must be assessed at systems level, including all relevant sub-processes (e.g. biomass production, resource handling and upgrading, waste disposal, etc.) and derived processes (e.g. effects on crop markets, resource scarceness). Environmental impact modelling in a life cycle perspective provides a useful framework for such analyses in combination with a detailed technical knowledge of the systems and technologies involved.

The work process of the project is shown in Figure 1.1. The work has taken its point of departure in state-of-the-art energy system and LCA analyses of 100 per cent renewable energy systems followed by further developments of methodologies and tools within four sub-themes, ending up with coherent energy and environmental system analyses of the same systems.

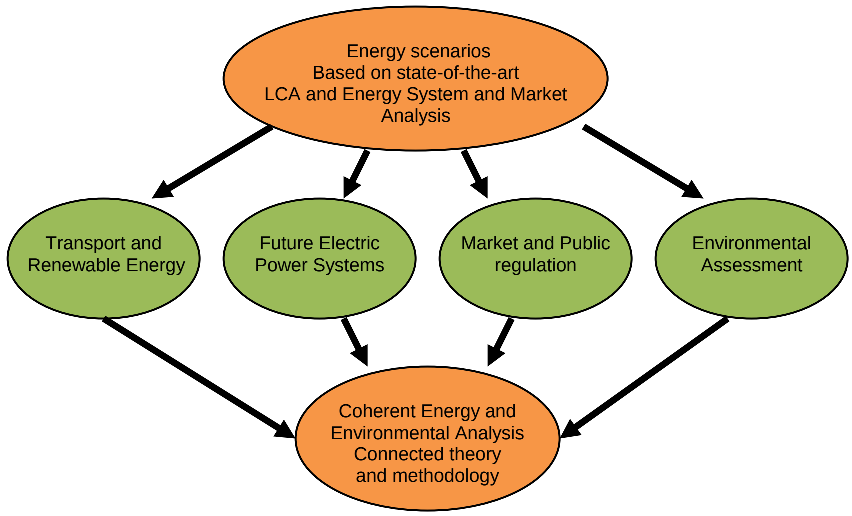

Figure 1.1: Under an overall range of scenarios, the work has been carried out within four sub-themes that were subsequently integrated and included in the development of tools and methodologies for a new generation of coherent energy and environmental analyses.

1.2 Initial State-of-the-art LCA and ESA analyses

In the initial phases of the CEESA project, existing energy system and LCA models were used to present state-of-the-art analyses of 100 per cent renewable energy scenarios for Denmark. The 100 per cent renewable energy scenario of the Danish Society of Engineers' (IDA) Energy Plan 2030 for Denmark, published in December 2006 one month before the beginning of the CEESA project, was used as a starting point for the analyses, and the following four scenarios with different use of biomass and different developments in demands were identified:

- The two 100 per cent renewable energy scenarios from the "IDA Energy Plan" published by the Danish Society of Engineers in December 2006 which ensured scenarios with high degrees of biomass versus high degrees of wind, and
- The two IDA scenarios were extended with two similar scenarios with higher energy demands. The energy demands of 2004 were chosen.

The state-of-the-art energy system analysis is published and documented in (Lund 2007, Lund and Mathiesen 2009 and Lund 2010). The following main conclusions can be highlighted:

A 100 per cent renewable energy supply based on domestic resources is physically possible, and the first step towards 2030 is feasible for Danish society. However, when reaching a high share of intermittent resources in combination with CHP and savings, the development of renewable energy strategies becomes a matter of introducing and adding flexible energy conversion and storage technologies and designing integrated energy system solutions.

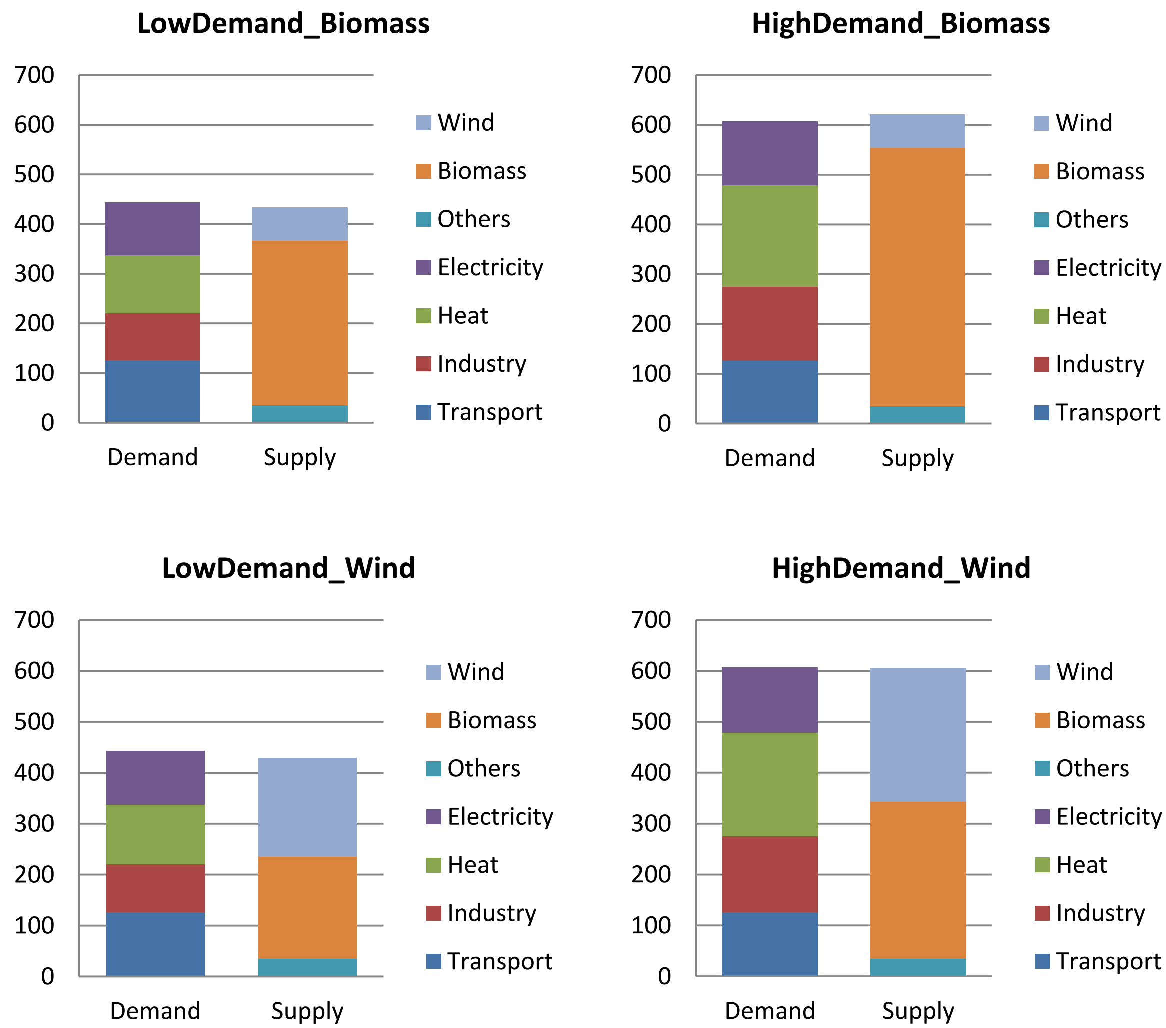

Figure 1.2: The four initial scenarios with different biomass resources and different energy demands were initially identified as a framework for the CEESA project.

An initial screening of the environmental aspects of three energy scenarios with various shares of biomass and wind power was carried out in a life cycle perspective. The initial state-of-the-art LCA was based on the EDIP methodology (EDIP: Environmental Declaration of Industrial Products) and carried out in the GaBi4 LCA software. Environmental impacts and consumption of non-renewable resources were included, while impacts on the working environment were excluded.

This initial LCA was not a full LCA modelling (e.g. consequences of land use changes were not included) but rather a screening intended to highlight important aspects which should be further addressed in the CEESA project. The LCA screening was based on output data from an energy system analysis of the abovementioned initial scenarios. Due to the comparative approach applied, the LCA screening covered only aspects in which the two scenarios differed from each other. In terms of primary energy supply, the scenarios differed only in their utilisation of biomass and wind power, while the use of other RES, such as solar thermal, wave power and photovoltaic, was identical. Regarding biomass utilisation, the only difference between the scenarios was the amount of biomass used for power and district heating. It was roughly assumed that the biomass feedstock used for this production was energy crops (willow), thus assuming that biomass residues/waste were utilised for other applications within the energy system (transport, industrial heat production, etc.). In Table 1.1, an overview is given of the scenario differences and the specific technologies assumed for the LCA screening.

Parameter	Unit	Biomass scenario	Wind scenario	Technology assumed	Scenario difference
Biomass for CHP/PP	TWh/y	42.8	6.9	SOFC plants using producer gas from two-staged biomass gasification	Operation, Biomass gasification capacity
Biomass used in boilers	TWh/y	2.8	2.5	Boiler based on wood chips (grate firing)	Operation
Offshore wind power capacity	MW	3000	12000	Offshore wind turbines	Capacity
Offshore wind power production	TWh/y	11.7	46.8		Operation
Electrolysis capacity (for grids 2 and 3)*	MW	0	10000	Electrolysis plants using reversed SOFC's	Capacity
Electrolysis operation (for grids 2 and 3)*	TWh/y	0	14.4		Operation
Hydrogen for CHP	TWh/y	0	8.8	SOFC plants using hydrogen	Operation
Hydrogen used in boilers	TWh/y	0	3.5	Boilers using hydrogen	Operation
Hydrogen storage (for grids 2 and 3)*	TWh/y	0	3.0	High pressurised tanks (glass fibre laminated steel tanks, 30 bar)	Capacity

Table 1.1: Overview of LCA screening scenarios and technologies (rounded numbers). Grids 2 and 3 are meant to represent district heating systems based on small and large CHP plants, respectively. CHP: Combined Heat and Power, PP: Power Production, SOFC: Solid Oxide Fuel Cell (planar cells assumed).

A large share of materials/inputs used in the scenarios was likely to be produced in countries outside Denmark. As such, the production of these inputs could not immediately be assumed to be based on renewable energy sources. In a life cycle perspective, upstream energy consumption (power, process heat and transport) traditionally contributes to a significant part of the environmental impacts of products/product systems. The impacts associated with energy consumption are highly dependent on the given energy production technology. However, it is highly uncertain which technologies will deliver the marginal power and heat production for the processes involved in the scenarios. The uncertainty was particularly high considering the time horizon for the 100 per cent RES scenarios (e.g. 2050). Based on the above considerations, upstream energy use was modelled separately and quantified in "energy units" serving as an indicator for impacts and resource consumption associated with energy use. This approach provided more transparent results better suited for later evaluation of sensitivity and scenario adjustments. Recycling was assumed for materials which are typically recycled, such as steel, iron, aluminium, lead and copper. However, material losses were still assumed to exist resulting in net waste generation. Apart from quantifying net waste generation in amounts, emissions from most landfill waste were also included.

According to the screening (See Fig. 1.3), more upstream energy was consumed in the wind scenario compared to the biomass scenario. The main part of the energy use in the wind scenario was related to manufacture of offshore wind turbine farms and hydrogen storage tanks, while energy crop production was the dominating energy consumer in the biomass scenario. In both scenarios, the main share of primary energy consumption took place during material production rather than during manufacture of components/plants or disposal processes.

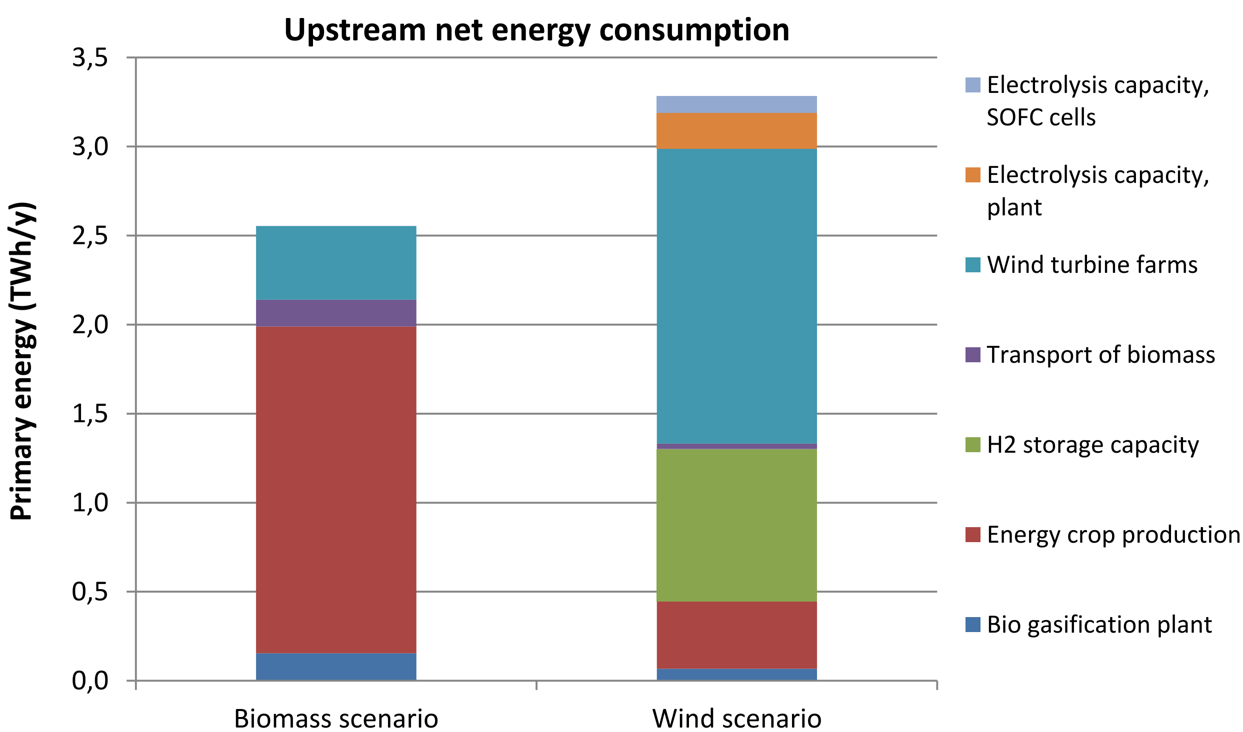

Figure 1.3: Upstream energy consumption result of LCA screening.

The wind scenario was characterised by larger waste generation; i.e. amounts of bulky waste, hazardous waste, slag and ashes. The higher amounts of waste were mainly generated from disposal of wind turbine farms, hydrogen storage tanks and electrolysis plants. On the other hand, the biomass scenario induced a larger contribution to nutrient enrichment, global warming, acidification and photochemical ozone formation compared to the wind scenario. Larger energy crop production and production of fertilisers in the biomass scenario were the main reason for the larger contribution to the first three of these impact categories. The main emissions contributing to these impacts were nitrate and phosphate leaching, nitrous oxide, ammonia, and nitrogen oxide emissions to air. Hydrocarbon emissions from SOFC plants based on biomass producer gas caused the larger contribution to photochemical ozone formation in the biomass scenario (See Figure 1.4)

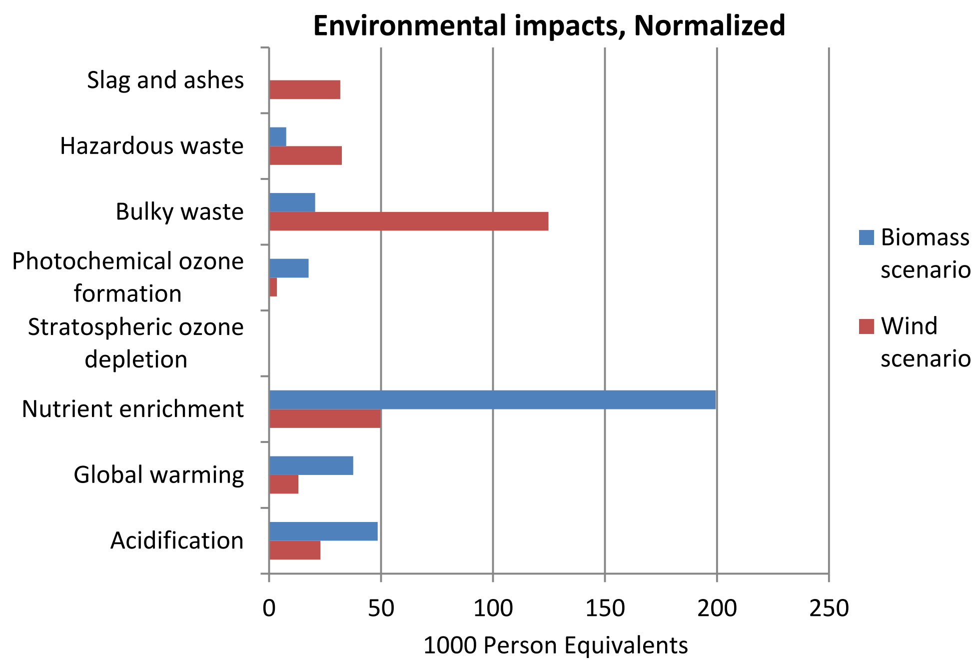

Figure 1.4: Environmental impacts (LCA screening)

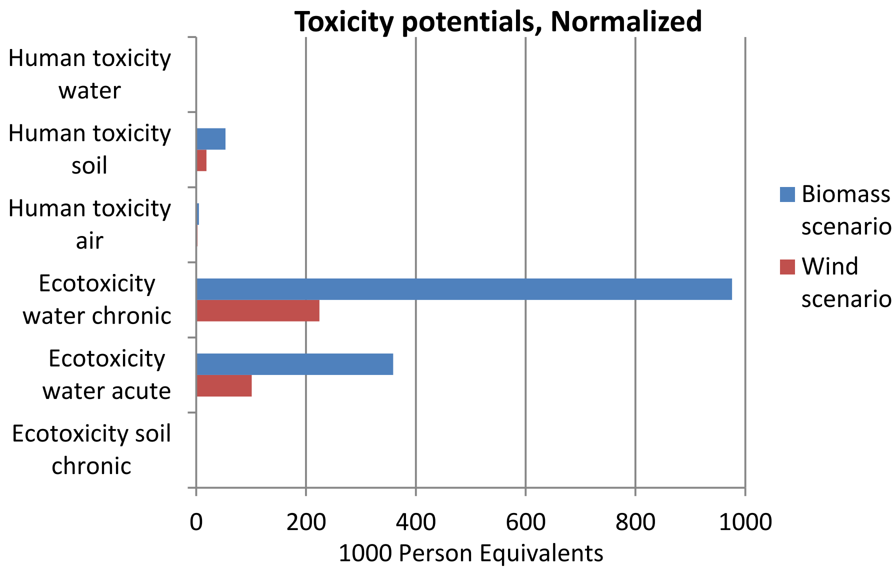

Figure 1.5: Toxicity potential (LCA screening)

With respect to toxicity impact potential (see Fig. 1.5), the biomass scenario caused significantly larger contributions to ecotoxicity. The reason was higher consumption of pesticides due to larger energy crop production.

In the biomass scenario, the main consumption of scarce material resources was associated with manufacture of offshore wind turbines and included metals, such as zinc, lead, iron, copper and aluminium. As more wind power was included in the wind scenario, scarcity of material resource was more pronounced here. The total material resource consumption in the wind scenario was approximately $1220 \cdot 10^3$ PR (Person Reserves) compared to $12 \cdot 10^3$ PR in the biomass scenario. The consumption of yttrium for ceramic materials in reversed SOFC's in the wind scenario was the dominating resource consumption ($1140 \cdot 10^3$ PR). Arable land resources and the environmental impacts related to changes in crop production (direct land use changes) and market related responses to the changes in crop production (indirect land use changes) represent very important contributions to the environmental impacts related to biomass based energy production. Use of arable land for biomass production was not quantified in the LCA screening, but development of the necessary methodological framework and LCA modelling of environmental impacts related to the changes in land use (as induced by the energy production) was included as a significant part of the LCA activities in the CEESA project.

1.3 Initial conclusions and project framework

The initial energy system analysis identified the following improvements of system flexibility as being essential to the conversion of the energy system into a 100 per cent renewable system: Firstly, relevant substitutions for oil products in the transport sector must be found. Given the limitations of biomass resources, solutions based on electricity become key technologies. Moreover, such technologies (direct electric vehicles as well as hydrogen or similar energy carriers produced fully or partly from electricity) increase the potential of including wind power in the ancillary services of maintaining the voltage and frequency of the electricity supply.

The next key point is to include small CHP plants in the regulation as well as adding heat pumps to the system. Such technologies are of particular importance since they provide the possibility of adapting to intermittent wind electricity while maintaining the high fuel efficiency of CHP. The third key point is to add electrolysers to the system and, at the same time, provide for a further inclusion of wind turbines in the voltage and frequency regulation of the electricity supply.

In the CEESA scenario, electric and hydrogen fuel cell vehicles are introduced into the entire transport sector. If such solution is replaced by biofuel-based transport technologies, the need for biomass resources is nearly doubled. Consequently, the project emphasises the importance of further developing electric vehicle technologies. Moreover, it indicates that biofuel transport technologies should be reserved for the areas of transport in which the electricity/hydrogen solution proves insufficient. Biomass resources should in general be prioritised for fuels and chemical feedstock in applications where carbon content, high energy density and fuel storage are most needed.

The project documents that Denmark can be converted into a supply of 100 per cent renewable energy consisting of 280 PJ/year biomass, 19 PJ solar thermal, 2,500 MW power from waves and PVs and 10,000 MW wind power. Moreover, the study shows how biomass resources can be replaced by more wind power and vice versa and points out that Denmark will have to consider to which degree it should rely mostly on biomass resources or on wind power. The solution based on biomass will involve the use of present farming areas, while the wind power solution will involve a significant share of hydrogen or similar energy carriers leading to certain fuel inefficiencies in the system design.

The LCA screening focused on the environmental impacts related to direct emissions and activities within the Danish energy and transport sectors. It was shown that the use of resources, in particular biomass resources, was contributing with the largest impacts overall. As a consequence, it was concluded that further development of the energy scenarios in the CEESA project should focus on minimising the use of biomass resources and preferably limit these to residual biomass resources.

Based on the LCA screening, the following aspects were deemed relevant for the project:

- Impacts from energy crop production are important; biomass consumption in the energy systems should therefore be as low as possible. The types of biomass resources (and related arable land resources) used for energy production may significantly affect the overall environmental impacts associated with the energy production.
- System boundaries and approaches for including impacts related to land use changes.

- Manufacture and disposal of offshore wind farms, hydrogen storage systems, electrolysis plants including reversed SOFC's may be important.
- Process data for individual energy technologies, e.g. efficiencies, emissions, etc.
- Assumptions about energy production and marginal technologies outside Denmark.
- Ensuring that all energy consumption related to Danish activities is included in the modelling.
- Inclusion of other relevant impacts, e.g., impacts on landscape and biodiversity.

2 Tools and Methodologies

In the following, the terminology "tool" is used for, e.g., energy system analysis computer tools such as EnergyPLAN, while the terminology "model" is used for the description of a certain energy system by use of the tool. The development of tools, models and methodologies of coherent energy and environmental analysis has included further development and integration of existing tools and methodologies as well as development of new tools. Moreover, models have been implemented into existing tools. The work of the CEESA project includes the following:

2.1 The EnergyPLAN tool

The EnergyPLAN energy system analysis is an existing tool which has been developed and expanded into its present version since 1999. In the beginning of the CEESA project, the tool was used to present state-of-the-art energy system analyses of 100 per cent renewable energy scenarios for Denmark. New options implemented in the tool, such as different transportation options and different individual heating options together with options to calculate total annual socio-economic costs, were tested and applied to an Energy Plan 2030 for Denmark in co-operation with the Danish Society of Engineers (IDA). Later on, in 2009, the tool was used to design the IDA Future Climate Plan and the CEESA scenarios. The different work packages have continuously developed descriptions on individual technologies and regulation strategies which have been implemented in the EnergyPLAN tool. The CEESA project has contributed with the following:

- New user interface and the establishment of a website where the model can be downloaded together with documentation and an online training programme.
- New facilities of waste-to-energy technologies in combination with geothermal and absorption heat pumps.
- New facilities to use COST data.
- A number of biomass conversion plants and their integration into heat and electricity supply including biogas, gasification, biodiesel and biopetrol (ethanol) plants.
- New facilities to conduct grid gas (natural gas and/or bio/syngas) balancing analyses including import/export and the use of gas storage and active regulation of gasification plants.
- Implementation of additional grid stabilisation options (see the section below about the grid stabilisation tool for further explanation).

The complete tool, including documentation, references and all contributions from the CEESA project, is made available on www.EnergyPLAN.eu.

2.2 The Balmorel Tool

The Balmorel tool is an existing tool which was originally developed within the framework of the Balmorel project hosted by the former Danish TSO ElkraftSystem. The original project (1999 - 2001) was financed by the Danish Energy Research Programme as well as by the institutions involved in the project and was aimed at the Baltic Sea region. The participants were research institutions from most countries in the region. The Balmorel tool has subsequently been developed and applied in various contexts and is not limited to the original focus region. The Balmorel tool is open source and is available on www.balmorel.com, where documentation and case studies may also be found. The tool is programmed in GAMS (General Algebraic Modelling System) and can be operated with or without user interface with direct access to the code. A GAMS license and a linear programming solver are required to operate the tool.

During the CEESA project, a method has been developed to convert the CEESA energy scenarios to the Balmorel structure, and a model of the IDA 2050 scenario with 100 per cent renewable energy has been created in Balmorel. The IDA 2050 was the starting point for the final CEESA scenario. For the surrounding countries, data from the Balmorel "Perspective" scenario from the project "Efficient district heating in the future energy system" have been used, where a 90% reduction in greenhouse gases in Denmark and the neighbouring countries is imposed. The structure and functionality of the "Perspective" model have been maintained with 21 district heating areas in Denmark and economic optimisation of investments and operation of energy production and transmission. To resemble the CEESA scenarios, a restriction has furthermore been added to ensure continuous use of waste over the year and a representation of the flexible demand of electric vehicles similar to the one applied to EnergyPLAN has been implemented.

Balmorel covers the Nordic area, including Denmark, Finland, Norway and Sweden, the northern part of Germany and the Baltic countries. Thus, the tool is developed with international trade of power as an integral part. Balmorel has been used to determine the long-term price of power and also to show the impact of international trade on the Danish energy system. Such long-term prices have been used to create input to the EnergyPLAN modelling of the CEESA scenarios.

2.3 The ADAM/EMMA Tool

The ADAM/EMMA models are an existing set of modelling tools which have been used as a baseline for forecasting long-term demand of energy in Denmark. ADAM is the macroeconomic tool used in Denmark by the Ministry of Finance for preparing the official forecasts for the Danish economy. EMMA is the interlinked energy demand tool that converts the economic forecasts to energy demand forecasts. The baseline developed in the CEESA project is based on the latest forecasts for economic growth published by the Ministry of Finance.

During the CEESA project, major developments of the ADAM/EMMA models have taken three directions:

- The interlink between the economic tool ADAM and the energy tool EMMA has been improved.
- A new model for transport has been developed.
- Tool equations, especially for energy intensive sectors, have been improved.

Currently, EMMA may be run either as a satellite tool to ADAM or the two tools may be run simultaneously. Running EMMA as a satellite tool ensures that official economic forecasts are not changed but are used as an exogenous input to the analysis. Running ADAM/EMMA simultaneously assures consistency between the two tools and macro-economic effects of changed energy consumption may be evaluated.

A new model for the energy consumption within transport has been developed and included in EMMA; this is done by dividing the demand for transport into transport of goods and transport of people. Transport of people is further divided into transport to and from work and transport in people's leisure time. Equations for the transport needs, level of substitution between collective and private transport and energy efficiencies are estimated on historical data. In addition, for transport of people a model analysing effects of introducing electric vehicles has been developed, the main issue being that electric vehicles are expensive, but when having an electric vehicle the marginal cost of using it is low. The main implication of electric vehicles is increased energy efficiency in transport; rebound effects and the substitution from public to private transport are present, but the aggregated effect is a considerable reduction in the energy consumption. The model and analysis were presented at the IAEE conference in Vilnius, August 26-28, 2010.

During the CEESA project, model equations have been re-estimated and especially equations for the energy intensive sectors have been improved. Over the last couple of years and especially during the financial crisis, energy intensive sectors have been reduced and model equations for these sectors have needed revision.

EMMA determines the individual industries' demand for electricity, other energy, and transport energy. Electricity is substituted by other energy for some industries, while other industries do not have the option of changing between these. For other energy, a certain degree of substitution is assumed for the industries between oil, coal, gas, district heating, and biomass, while exogenously fixed shares are used for the households. The ADAM and EMMA models have been used to create energy demand projections until 2050.

ADAM/EMMA are used by the Danish Energy Authority for projections of energy demand and the model, data and documentation may be downloaded from the website of the Danish Energy Authority:
http://www.ens.dk/daDK/Info/TalOgKort/Fremskrivninger/modeller/emma/Sider/Forside.aspx

2.4 Grid Stability: Methods and Models

The EnergyPLAN and Balmorel tools and models are based on deterministic hourly energy balances. While this suffices for most analyses on the level of resource requirements in energy systems, it is also required for the electricity system to remain stable and continuously balanced, also within the hour. Voltage and frequency stability is affected by the momentary conditions and both voltage and frequency need to remain within certain limits. Electricity generated from wind power forms a significant fraction in all scenarios, ranging from 50% to 200% of the projected conventional electricity demand, which will dramatically increase the need for system balancing in response to prediction errors and short-term fluctuations. Electricity systems in operation today have not been proven capable of integrating this amount of fluctuating generation and operational principles have to be adapted significantly. This implies that existing tools and methods for analysing electricity system operation are not designed to fulfil such requirements.

Therefore, it has been one of the project aims to develop tools and methodologies for assessing the impacts of scenarios established on an hourly scale using the EnergyPLAN model on the electricity system. The contributions of the CEESA project are divided into three parts, a quantitative analysis based on existing methods, a qualitative study of scenario requirements which led to the design of new modelling methods, and an adaptation of the EnergyPLAN tool to improve calculation of intra-hour fluctuations.

Existing models can be employed to quantify the incremental contribution individual new technologies can make to improve the system operation. Models of the first part of the work have been the following:

- Establishment of a case model in DIgSilent for the island of Bornholm for the frequency response analyses of scenarios defined in EnergyPLAN. The DIgSilent is an existing commercially available tool for electric analyses which already contains a global library with e.g. steam, gas, and wind turbine models. Other systems and components (battery storages, grid models for Bornholm, Lolland etc.) have been modelled separately using the tools available within the DIgSilent
- Analyses of electric vehicles' effect on the grid stability of the electricity system with the aim of establishing recommendations for the handling of the grid stabilising ability of electric vehicles in the EnergyPLAN tool

The analyses are presented in separate articles but as mentioned, the modelling software tool is a commercial product.

The second part of the work examined what additional factors need to be investigated in order to substantiate the technical feasibility of the CEESA scenarios, and how these factors could be studied. The main factors influencing the operation under high wind power penetration are the limited predictability, and the potentially large wind power fluctuations. The means offered in the scenarios include a largely increased availability of controllable electricity consumption units by integration with other energy sectors and cost-effective demand-side storage. Contributions aimed at modelling electricity system operation with these types of units as well as the representation of new control structures include:

- Extending grid models with a generalised energy buffer model. The theoretical concept of the so-called Power Nodes model is described in separate articles and its implementation is based on the numerical programming environment MATLAB.
- Adapting an existing functional modelling approach (Multilevel Flow Modelling (MFM)) and extending it to model the electricity system's control architecture.

The modelling methods of the second part of the work are going to be considered in future studies. Further, results of the modelling work in work package 3 lead to suggestions for future improvement of the EnergyPLAN tool.

Due to its nature, the EnergyPLAN tool relies on a simplified grid stability system rather than actual dynamic simulations. Generating technologies are split up into two general categories; technologies that may support grid stability and technologies that may not. For most of the technologies that may support grid stability, the user may additionally specify which share of the given stock of the given technology that may do so. Other technologies are by default assumed to be grid stabilising while yet others cannot support grid stability.

Supported by the analyses in the CEESA project, the EnergyPLAN tool has been expanded to allow additional technologies to assist in supporting grid stability. This includes electric vehicles, vehicle to grid and interconnections to outside areas. Waste CHP has also been included as a grid stabilising technology.

Electric vehicles as well as vehicle to grid are already employed on an hourly basis in the EnergyPLAN model to ensure the hourly balance between electricity production and demand. However, analyses have demonstrated that the technologies may also have a role to play in fast regulation and thus frequency stability. Similarly, interconnections are already used on an hourly basis to ensure the balance between electricity production and demand, but interconnections can and will also play a part in maintaining grid stability. EnergyPLAN has therefore been expanded with the ability to model a certain fraction of interconnection capacity as grid stabilising.

Depending on the general energy system configuration, this may have varying impacts on the performance of the energy system. If other grid stabilising technologies are scarce, the model can decrease the production that would otherwise have to be at condensing mode power plants solely for grid stability reasons. However, if technologies such as wind turbines or photovoltaic cells are employed in large scale, the impact is less and the grid stability criteria are more likely to already have been met if they are assumed grid stabilising. In actual applications, production would be less if units are grid stabilising as they would need to be curtailed to enable upward regulation; however, this has not been quantified. The simulation tools and models as well as documentation will be available at the CEESA website www.ceesa.dk.

2.5 The CEESA Transport Scenario Tool

The CEESA Transport Scenario tool is a national transport scenario modelling tool developed as part of work package 2 of the CEESA project. It consists of a single MS Excel spreadsheet providing the user with a quick, easy and detailed overview of the various inputs and outputs. The tool enables the creation of transport and energy demand scenarios related to the activities of Danish citizens, in Denmark or abroad, and goods consumed in Denmark towards 2050. The resulting transport and energy demand is available for 2010, 2020, 2030 and 2050. The tool contains detailed information with regard to transport and energy demands for passenger and freight transport, specific energy consumptions, coefficients of utilisation and the share of different fuels for a wide range of transport modes, including subdivisions of several transport modes according to transport distance and purpose (work and leisure). The tool makes it possible to vary the projections of the transport demand for different modes of transport, change vehicle-specific energy consumption, include a technology efficiency factor, change the coefficients of utilisation and to perform modal shifts between selected modes of transport for the periods of 2010-2020, 2020-2030, and 2030-2050. Furthermore, it is possible to introduce pre-selected new or future vehicle and fuel technologies. For optimum utility, the model requires that the user has detailed knowledge of the transport system, demand and energy projections, possibilities to improve efficiencies of technologies, and the possibility to implement modal shifts and new technologies. TransportPLAN as well as its supporting documentation is available on the CEESA website, www.ceesa.dk.

2.6 Vehicle Drive Cycle Design and Simulation Tool

A design and simulation tool of a current state-of-the-art battery electric vehicle (BEV) and a fuel cell hybrid electric vehicle (FCHEV) has been developed in Matlab/Simulink as part of the CEESA project. The methodology of the tool and model is a further improvement of the simulation model developed in the PhD project "Design of a Fuel Cell Hybrid Electric Vehicle Drive System", 2010, by Erik Schaltz.

The input to the vehicle model developed in the CEESA project is a given drive cycle, i.e. a time-speed curve. The simulation model designs the main components of the drive system, i.e. the drive train, electric machines, power electronics, battery, and fuel cell. The vehicles are designed to handle the maximum power end energy requirements due to the drive cycle input. The output of the simulation model is the consumed "fuel" of the vehicle, i.e. the grid energy of the BEV and hydrogen energy of the FCHEV, total vehicle mass, volume of drive system, and total vehicle cost. The cost calculation is a new feature compared with the simulation model developed in the PhD project. The simulation model consists of several sub-models, e.g. vehicle forces, electric machine, power electronics, battery, and fuel cell, which have a non-constant efficiency. The simulation tool and model as well as documentation will be available at the CEESA website www.ceesa.dk.

2.7 Life Cycle Assessment (LCA) Methodology

Existing life cycle modelling software is typically based on extensive databases containing information about emissions related to a long range of technologies and processes. Within an LCA, these data are used for modelling the potential environmental impacts related to specific systems of technologies and processes which comprise the modelled scenarios in question. The results of LCA modelling, however, depend heavily on the quality of technology data included in the assessment. Existing LCA databases typically rely either on general (average) data or data for specific technologies not appropriate for the scenarios in question. In order to meet the needs of supporting choices between alternative renewable energy systems, three aspects were found to be essential for the modelling of the systems: 1) identification of the technologies, processes and systems that are influenced by the decisions the LCA aims to support, including identification of the marginal technologies and supplies on the markets affected by the decision, 2) definition of system boundaries and scope of the modelling, and 3) identification of the environmental impact of these systems and processes. In the CEESA project, the development of advances in LCA methodology and modelling has mainly focused on two sub-systems:

- Crop/biomass production in Denmark and the consequences of changes in this.
- Energy production in Denmark, especially electricity production.

From the beginning of the project, it was acknowledged that the most significant environmental impacts related to crop/biomass based energy production do not derive from the biomass conversion technologies themselves but rather from the changes in crop production and land use supporting the biomass production system. Such changes include the direct environmental impacts of producing the energy crop (direct land use changes (dLUC)) as well as market related responses to the change in import/export relations due to the replacement of food/feed crops by energy crops (indirect land use changes (iLUC)). The identification of the involved marginal mineral fertiliser supplies is also of key importance to both dLUC and iLUC.

These mechanisms are complex, and there was an absence of both methodology and data at the beginning of the project. Thus, one of the main focus areas of the methodology development and data provision within the LCA work package has been to improve both methodology and database.

With respect to the LCA scenarios included in the CEESA project, it was necessary to evaluate and update existing energy technology data in order to properly model the future Danish energy systems suggested in the project. This was based on an extensive literature search and further implemented in the EnergyPLAN model.

LCA and Energy System Analysis (ESA) tools have not been integrated into a single tool as part of the project. The primary reason for this was to maintain the flexibility of current LCA software (system definition, process setup, and inventory databases). Rather than providing a simplified LCA tool to be integrated with ESA, it was chosen to further extend the LCA modelling using existing state-of-the-art LCA software (SimaPro) and base the LCA on modelling outputs from EnergyPLAN and Balmorel. This approach facilitated an integrated and coherent evaluation of the energy systems while at the same time allowing the use of the best available software for the modelling.

3 Modelling and Analyses

As explained in the introduction and illustrated in Fig. 1.1, the work has taken its point of departure in state-of-the art energy system and LCA analyses of 100 % renewable energy systems. On this basis, work has been organised in different work packages on an in-process basis and included in the development of tools and methodologies for coherent energy and environmental analyses as described in chapter 2 of this document. These tools have subsequently been applied to the analysis and further development of the above mentioned state-of-the-art scenarios leading to the results and scenarios documented in the report of work package 1, “CEESA 100% Renewable Energy Scenarios towards 2050”, which is summarised in the following.

3.1 Biomass resources and Conversion Technologies

In the CEESA project, significant efforts have been put into identifying the biomass potential. Such a potential depends on the current use of land area and farming practices, but also on future land use options. The biomass potential for energy and transport purposes has been estimated on the basis of Danish agriculture and forestry for a range of scenarios assuming a business-as-usual scenario, conversion to organic farming, enacting dietary changes in the Danish population, or applying more extreme forest exploitation The latter will on the one hand contribute significantly to Danish exports, and on the other hand limit the option of bioenergy self-reliance. The results show that a substantial amount of land is currently allocated to meat production. There are several biomass feedstocks that could be used for energy purposes, but at the same time, these primary production systems must still supply food, feed, and materials. If biomass has to cover the production of materials, which are currently based on petro-chemical products, and self-sufficiency is the goal, significant changes would have to be imposed on the agricultural sector.

In the CEESA project we have considered biomass resources from primary production as well as in the form of processing waste.

Biomass resources from primary production

As primary resources we consider dedicated energy crops, wood from forests, parks and gardens; and straw, stalks or leaves from agricultural crops. The resource potential is estimated as technical potential, i.e. resources that technically are available for use in society. From an economic point of view, individual resources may not be fully available.
Straw from cereals make up the largest part of the resource potential of primary production. We estimate a decrease in the resource potential from 135 PJ yr^{-1} in 2000 to 129 PJ yr^{-1} in 2050 (Fig. 3.1) mainly due to an expected conversion of agricultural area to other uses, e.g. infrastructure, dwellings, industrial sites and recreational areas as forests or golf courses.

Biomass from by-products and waste
As secondary biomass resources or biomass in the form of by-products and waste, we consider manure from animal production, processing residues as mill residues, molasses, pulp, whey and wood residues.

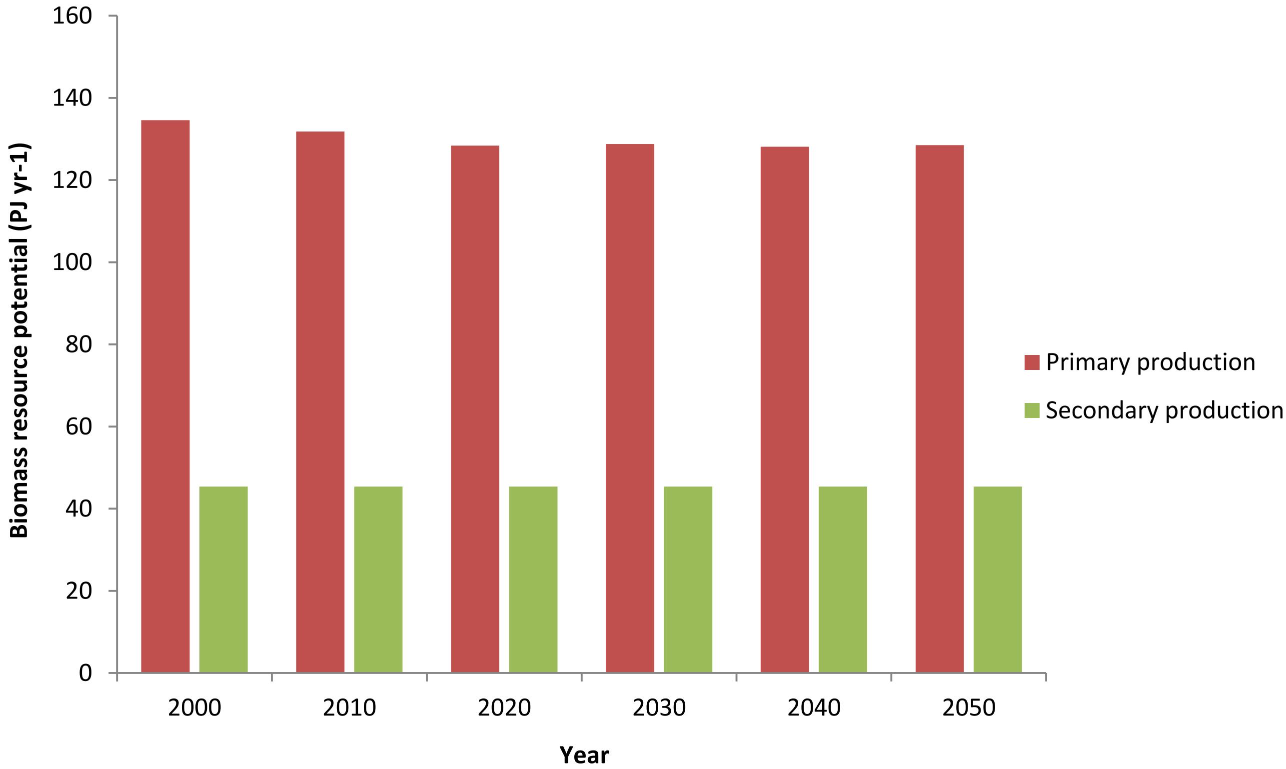

Figure 3.1: Biomass resource potential of primary and secondary production 2000-2050.

Resource availability
No biomass resource is truly residual. Every biomass resource or fraction has a function in the ecosystem or in the economy. It cannot be removed from the ecosystem or the economy without inducing some changes and requiring some counter action if status quo is to be maintained. A consequence hereof is that using biomass resources for energy will to a stronger or weaker degree impose a conflict between the current use of a resource and a future use for energy services. Particularly resource conflicts may be induced if resources currently used for feed is diverted into energy uses. This will be the case if the technical potential of straw or food industry residues as whey, brewer's grain or molasses is to be realised. Other resources are more readily available as e.g. the part of straw production currently left in the fields or unutilised forest increment. However, more readily available does not mean without conflict. Straw left in the field will in most cases increase the carbon

content of the soil and unutilised forest increment contributes to a build-up of standing wood in Danish forests, which is a goal in current forest policy.

Options of increasing biomass resources

Several options exist to change and preferably increase the amount of biomass resource. The CEESA project has explored a range of options as described in this section.

Organic farming

Denmark is a farming country; app. 63 % of the land surface is allocated to agriculture. Organic farming has increased its proportion of agriculture. Statistics from The Food and Agriculture Organisation of the United Nations on organic farming only go back to 2004, but in 2008 5.5 % of the agricultural area or 147,000 ha was certified as or in conversion to organic farming. As compared to conventional farming in Denmark, organic farming is characterised by a lower proportion of cereals and a higher proportion of grass and clover in the crop rotation. Crop yields in organic farming are in general lower that in conventional farming. Estimates for winter and spring cereals are yields 50-85 % of those achieved in conventional farming. Corresponding figures for rape seed is 67-75 % and pulses 69-85 %. Furthermore, organic livestock production requires some sort of bedding material. Assuming a complete conversion of Danish agriculture to organic farming, we find the straw potential to be zero. The biogas potential from animal manure is estimated to 6-16 PJ yr^{-1}. In general, conversion to organic farming will substantially reduce the amount of biomass resources.

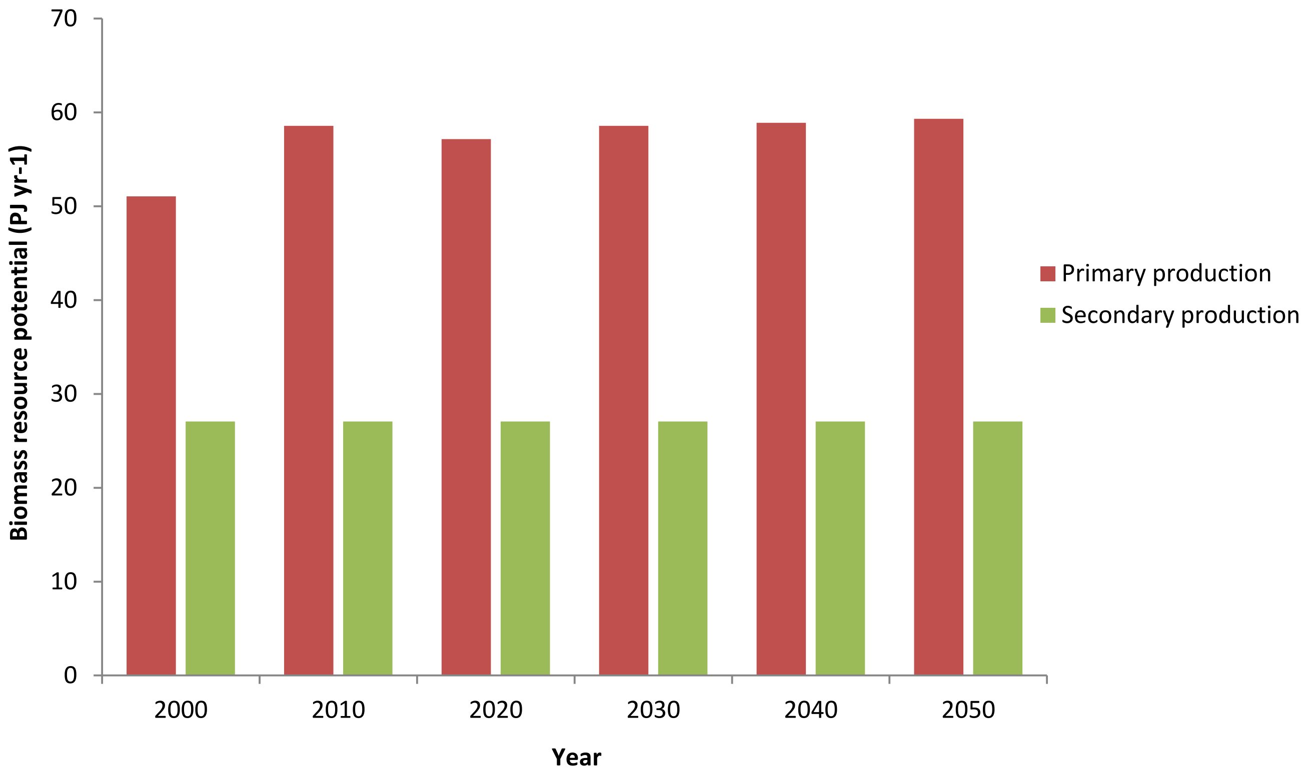

Figure 3.2: Biomass resource potential under the assumption that the entire agricultural sector in Denmark is converted to organic farming principles and is self-sufficient in feed.

Dietary changes

60 – 70 % of the Danish cereal production is used to feed animals for meat, dairy and egg production and 95-100 % of the Danish grasslands in rotation are used to produce coarse fodder to feed ruminants. The demand for livestock products thus requires significant areas of agricultural land. However, Danish livestock production does not only supply Danish consumption. Domestic consumption corresponds to ~30 % of domestic production of meat, dairy products and eggs with substantial variation between different food stuffs. For pork, Danish consumption corresponds to 15 % of production. For eggs, the figure is 137 %. The food intake of an average Dane does not follow general dietary recommendations. The average diet contains too much meat and too little cereal products, fruits, vegetables and fish. Adjusting the Danish diet towards dietary recommendations would reduce the land area needed for agriculture. Assuming that land released from agriculture is used for dedicated energy crops as willow, we find an additional biomass resource potential of 15-36 PJ yr^{-1}. Assuming an even more drastic change in diet to a lacto-ovo vegetarian diet could increase the biomass resource potential by 28-68 PJ yr^{-1}.

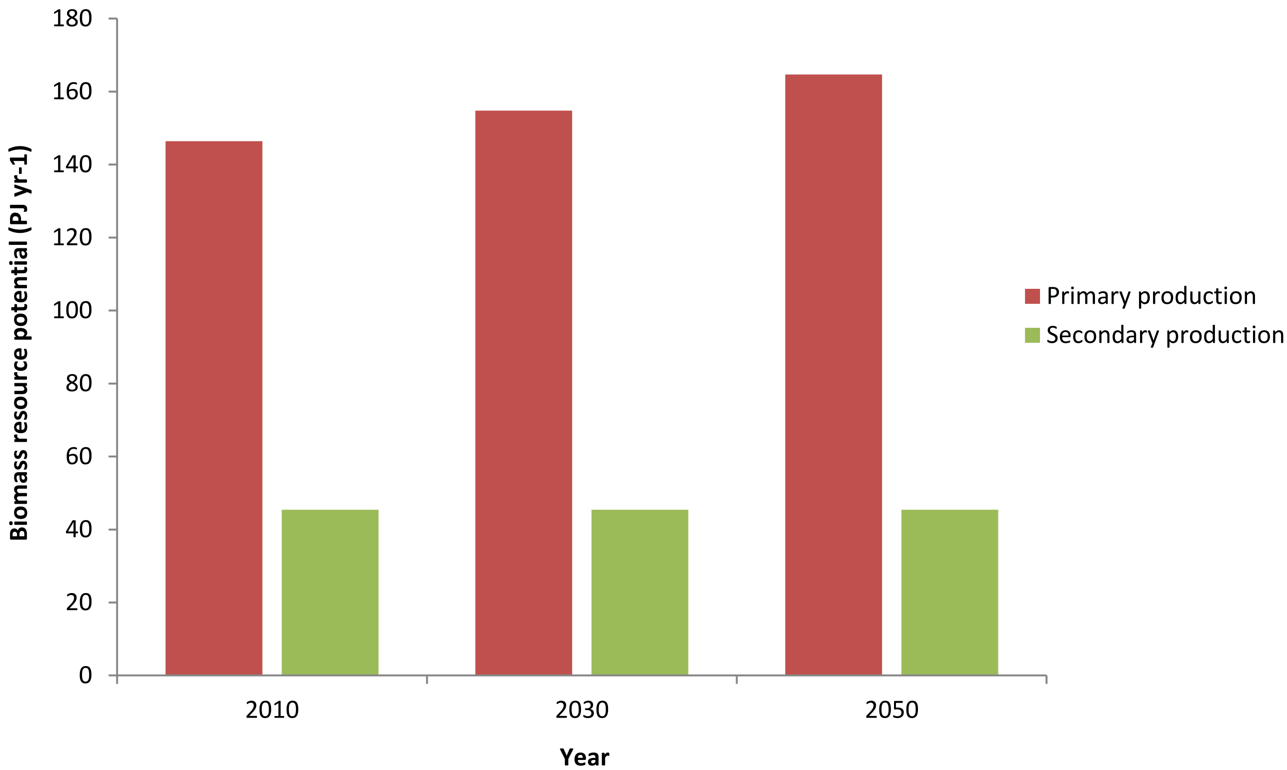

Figure 3.3: Biomass resource potential under the assumption that the entire Danish population adopts a diet recommended by Fødevareinstituttet (National Food Institute) containing less meat and more cereals, fruits, vegetables and sea food.

Forest management practices

A shift in forest management practices may increase the amount of biomass available for energy purposes through increased utilisation of biomass from early thinning and allocation of a larger part of harvested wood to energy purposes than to industry purposes. We find the potential of Danish forests to be 21.1 PJ in 2010-2019, 20.2 PJ in 2020-2029 and 19.7 PJ in 2030-2039 corresponding to an increase relative to the current potential of 16.7, 15.9 and 15.4 PJ yr^{-1} in 2010-2019, 2020-2029 and 2030-2039, respectively. Forestry offers other options to increase energy production than changing the allocation of wood. Exotic tree species as Sitka spruce (Picea sitchensis), Douglas fir (Pseudotsuga menziesii), Grand fir (Abies grandis) and poplars (Populus sp.) exhibit higher growth rates than most native species such as e.g. beech (Fagus sylvatica) and oak (Quercus sp.). A general shift towards these high productive species could increase the biomass potential. Such a shift is, however, to some degree in conflict with current forest policies described in "Det Nationale Skovprogram", which aim at increasing the coverage of native tree species.

Different cereal cultivars

Different wheat cultivars produce different amounts of straw. It has been shown for wheat that straw yields can be increased without compromising crop yields. We assume that straw yields can be increased by 20 % and that this can be achieved for cereals in general. The straw potential can thus be increased by 14-15 PJ yr^{-1}.

The global dimension

Denmark is not the only country concerned with the supply horizon of fossil resources and their potential impact on the global climate. Many countries consider biomass as one of the pillars in a future non-fossil energy system. At the same time, the global population is expected to reach 9 billion around 2050. As a consequence, increasing competition on biomass resources is expected and concern over the resource potential is growing. Probably the most accessible biomass resource is residues from agricultural crops. The annual global production of crop residues is estimated to 4.2 Gton (dry weight). Of this amount, 3.5 Gton comes from only six crops; barley, maize, rice, soy bean, sugar cane and wheat. Agricultural intensification, i.e. mechanisation, improved nutrient management, improved seed sources and better plant protection, can increase crop as well as residue production of these six crops. It is estimated that global residue production can be increased by 1.2 Gton yr^{-1} (dry weight). The potential for increased production is geographically very dispersed. Particularly southern Asia exhibits a huge potential of more than 250 Mton yr^{-1} of additional residue production.

3.2 Renewable Energy in Transport Scenarios

The research aim of this part of the project is to develop scenarios for renewable energy in the transport sector. The transport sector poses a significant problem in renewable energy systems since it has historically relied on liquid fuels (typically over 95% oil), the demand for transport is growing rapidly in recent decades, and the transport sector is characterised by a wide variety of modes and needs. It is therefore essential that the future transport system is assessed in detail so that it complements the needs of a 100% renewable energy system in Denmark.

The methodology used in CEESA to assess the Danish transport sector is outlined in Figure 3.4, while the resulting scenarios are displayed in Figure 3.5. To begin, a 2010 *reference* model of the existing Danish transport system was created based on existing transport demands, transport-energy demands, and technologies. This data was collected for 26 different modes of transport and where adequate data was available, these characteristics were further subdivided by trip length and type. Once the 2010 *reference* model was complete, a *reference* scenario for the years 2020 and 2030 was developed based on forecasts from the Danish Infrastructure Commission (Infrastrukturkommissionen). A *reference* scenario was also projected for the year 2050 based on a number of business-as-usual assumptions. Naturally, a significant amount of data was collected and a large number of calculations were required to make the 2010 *reference* model and the *reference* scenarios. Hence, a new spreadsheet Transport Energy Scenario Tool, which has been named TransportPLAN, was created during the CEESA project. Due to the wide range of data and outputs available in TransportPLAN, it can be used to assess a variety of different transport scenarios, which are also displayed in Figure 3.4. In CEESA, these outputs were used as inputs to the energy system analysis tool, EnergyPLAN, so the implications of various transport scenarios on the complete energy system could be assessed (which is the research aim of Part 1 of the project).

One key challenge encountered when developing the methodology was the definition of the transport boundary. In CEESA, the objective was to account for all transport demands associated with Denmark and hence the *reference* includes all passenger and freight demands, for both domestic and international transport. To do this, three distinct boundary conditions were defined and considered for each mode of transport assessed: national, transit, and international as displayed in Figure 3.6. In CEESA, 100% of the national transport demand and 100% of the Danish transit demand in other countries are included. The international transport demand was calculated by assuming that 50% of the demand was assigned to Denmark and 50% was assigned to the other country of origin. In this way, both countries share responsibility for the transport demand created between them. By using these boundary conditions for the transport sector, CEESA is not completely comparable to other publications. For example, the 'Energy Strategy 2050' report completed by the Danish Climate Commission did not include the international component of the transport demand and it did include the transit component of other counties in Denmark. As a result, the energy consumed by transport in 2050 is approximately 75 PJ (25%) higher in the CEESA *reference* than in the Danish Climate Commission's study. It should be noted that the principle of the boundary condition applied to both the energy and transport system is that, if all countries applied the same boundary condition, all consumptions would be accounted for and no elements would be counted twice.

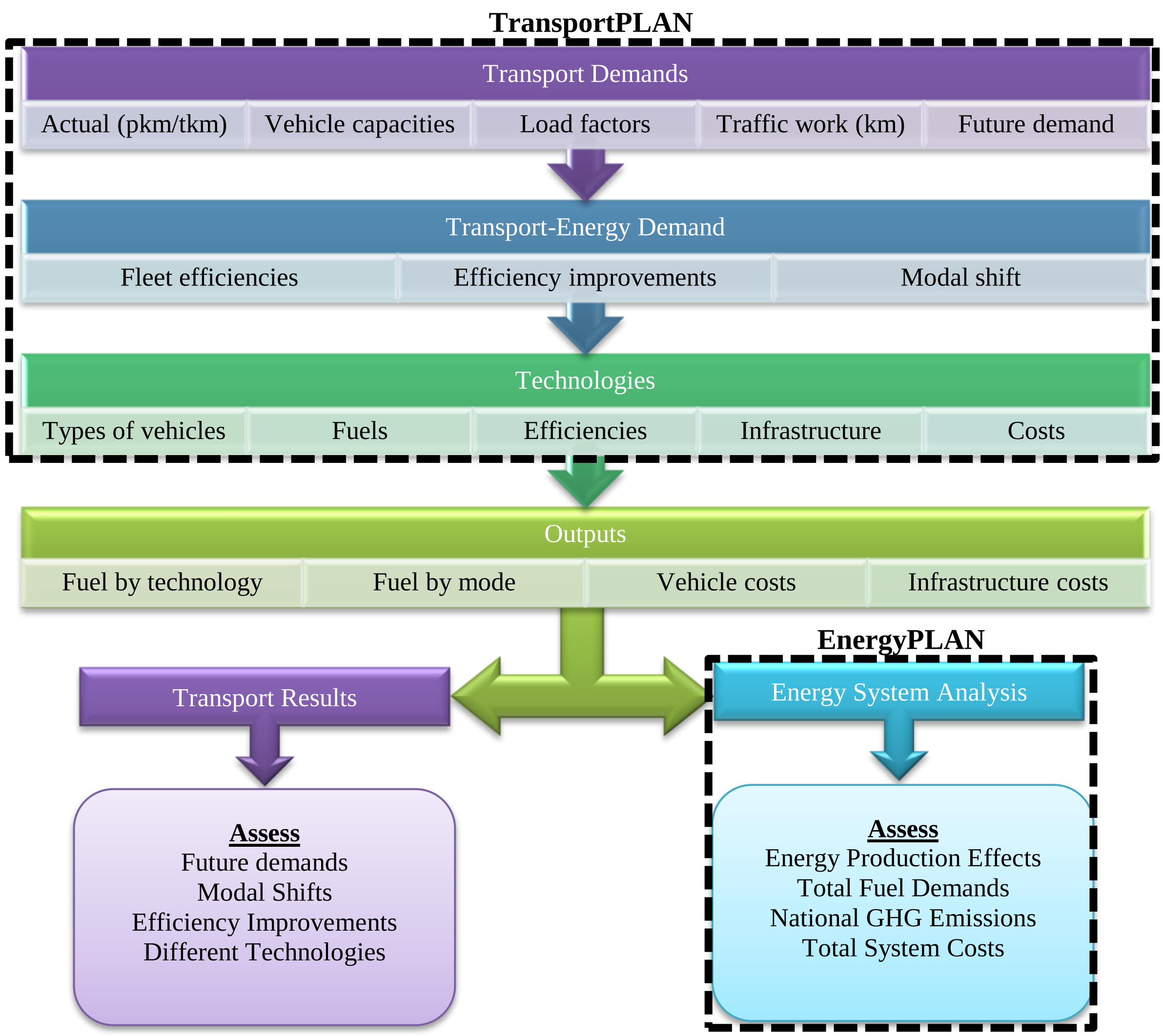

Figure 3.4: Methodology used to assess the transport sector in the CEESA project.

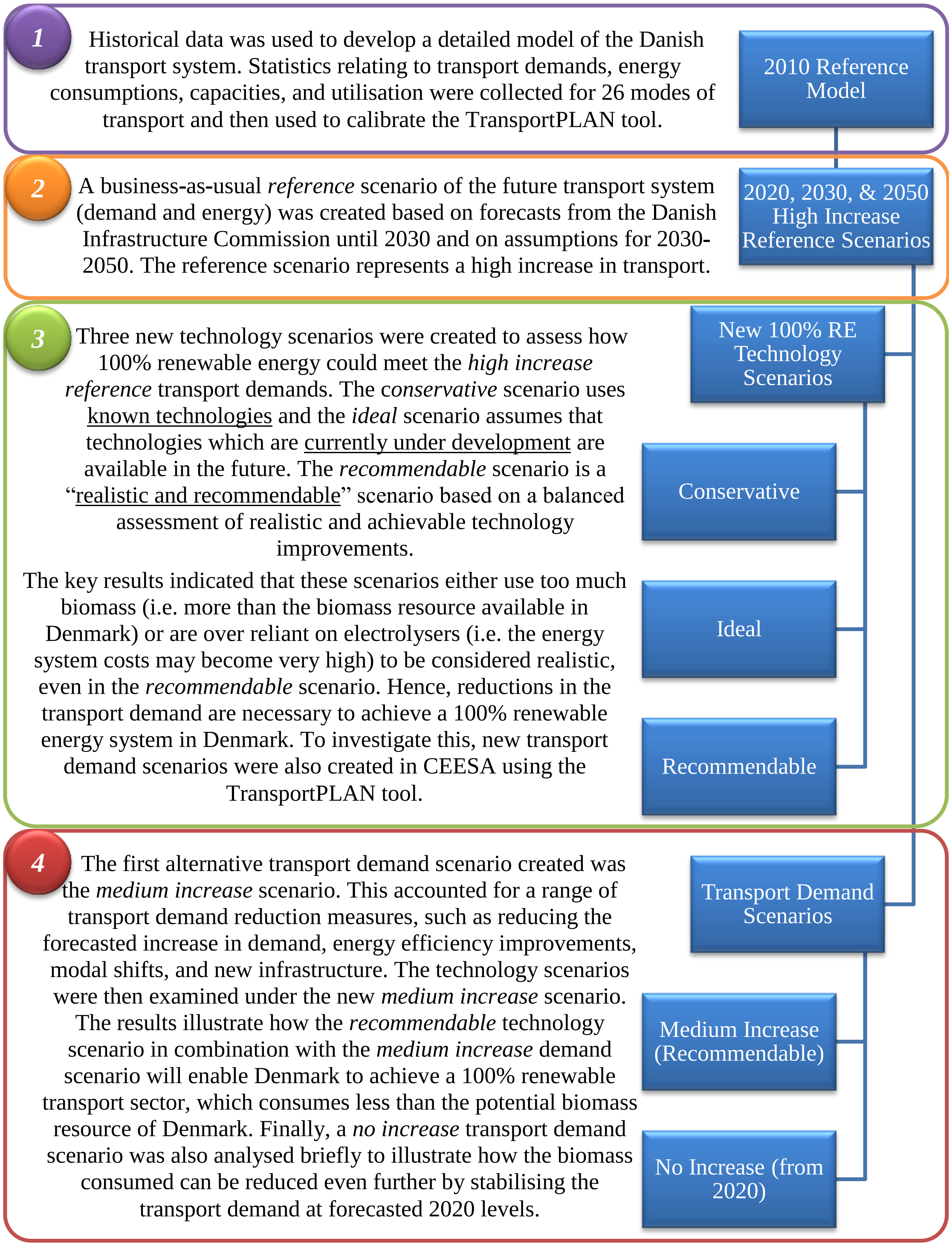

Figure 3.5: Transport scenarios created during the CEESA project, including a brief description of the scenarios and their main findings.

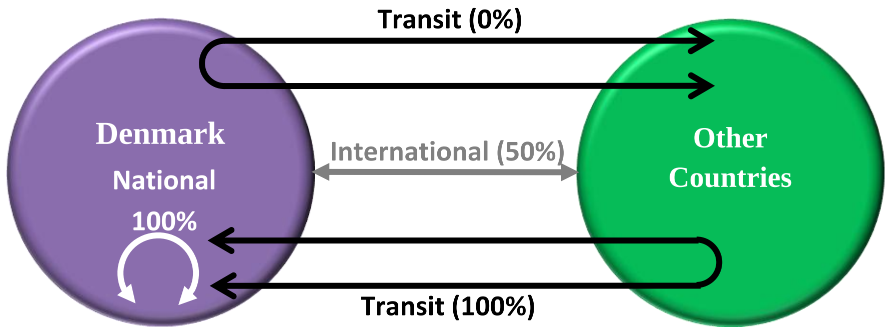

Figure 3.6: Boundary conditions defined when calculating the energy consumed in the Danish transport sector.

Once the *reference* was complete, the next step (see Figure 3.5) was to create a variety of 100% renewable energy scenarios which could satisfy the *high increase* transport demand forecasted in the *reference* (The term *high increase* defines this transport demand scenario since the *reference* forecasts a transport demand for 2050 which is double the current 2010 transport demand.) In total, three technology scenarios were designed which fit the following criteria: a *conservative* scenario is based on known technologies, an *ideal* scenario uses technologies which are currently under development, and a *recommendable* scenario is a "realistic and recommendable" scenario based on a balanced assessment of realistic and achievable technology improvements. To create these scenarios, the transport technologies needed to be assessed to establish what currently exists, what is in development, what is ideal, and what is realistic.

To establish the current state of transport technologies, the various fuels required were compared in terms of 1) primary energy consumption of conversion technologies, 2) the land area required and 3) the costs of different technologies. This enabled prioritisation between different "fuels" for transport technologies. From this, it was clear that direct electrification is the most energy efficient form of transport and also that biofuel consumption is a key concern for future 100% renewable energy systems, primarily due to the land-area required to produce them. For example, many biofuels are already available on the market so they are well established, but the land area required to produce these fuels is very large. To put this in context, if all of the petrol, diesel, and jet fuel consumed in Denmark in 2010 was supplied using existing biofuels, then the land area required would be 5-6 times the total agricultural land area in Denmark. In contrast, wind turbines require hundreds of times less land area to produce the same energy as second generation biofuels which are expected to be developed. Hence, there is a trade-off here: biofuel technologies are already well established so they are suitable for the *conservative* scenario, but in an *ideal* world the transport sector would be electrified as much as possible which will typically require more expensive technologies. These key differences formed the basis for the three technology scenarios subsequently created in the CEESA project.

As part of this work package, a number of detailed, generic and transparent analyses of current state-of-the-art battery electric vehicles have been conducted under realistic conditions. Such analyses show that the present technology has challenges to overcome before it can meet the general expectations as presented in most literature. Consequently, it should be stressed that the present technology needs further development in order to be able to fulfil the preconditions behind the CEESA scenarios.

For the *conservative* 100% renewable energy scenario, it was assumed that bio-DME/methanol would be used extensively in the transport sector. The only biofuel which would require less land-area than bio-DME/methanol is biogas. However, it was assumed that bio-DME/methanol will be easier to implement since commercial plants are already under construction and existing vehicles can be modified to use these fuels. Direct electrification was also used in this scenario, but in a conservative way: for example, in 2050, only 35% of private cars are electric even though over 95% of journeys are below 100 km and the range of commercially available electric vehicles today is approximately 160 km. After implementing these technological changes to the *reference*, it was clear that the *conservative* transport scenario will lead to a heavy dependence on biofuels: approximately 186 PJ of biofuel is necessary in 2050, but only around 60 PJ/year is available. Moving to 100% renewable energy using mainly existing technologies and under existing demand projections will therefore mean that Denmark is over dependent on biofuels.

To assess the other extreme, none of the transport technologies considered in the *ideal* scenario consumed biofuels, but instead the entire transport sector was electrified. Naturally for many transport modes the potential for direct electrification is limited, especially for modes with a large proportion of long journeys such as trucks and aeroplanes. Hence, liquid fuels are still required in the *ideal* scenario, but instead of using biofuels to create them, co-electrolysers are used to created synthetic fuels such as syn-DME/methanol. This creates a new challenge: uncertainty. At present the *ideal* scenario seems unlikely due to the uncertainties surrounding the development of synthetic fuels, particularly in relation to the development of adequate co-electrolysers. For example, after discussing the future of synthetic fuels with various stakeholders, it became apparent that there is no consensus at present on how syn-jetfuel could even be created in the future. Therefore, since the *ideal* scenario would require 131 PJ of synthetic fuel in 2050, it is too risky to assume that the technical development, technical capability, and adequate costs will be reached to produce such large volumes of synthetic fuel. Hence, the *recommendable* scenario includes a mix from both the *conservative* and *ideal* scenarios.

Once again, the main priority in the *recommendable* scenario is the direct electrification of the transport sector, with significant proportions of cars, vans, and rail directly electrified. Biofuels were then used to supply approximately half of the remaining liquid fuels, while half was supplied by synthetic fuels from co-electrolysers. However, even with this significant penetration of synthetic fuels, the biofuel demand of 78 PJ/year is still more than the biofuel resource of 60 PJ/year available in Denmark. Hence, to create a sustainable 100% renewable energy system in Denmark, the forecasted increase in the transport demand will need to be reduced. To investigate this, a *medium increase* scenario was also developed in the CEESA project using the TransportPLAN tool (see Figure 3.5).

To reduce the energy required in the transport sector, the following key changes were implemented in the *medium increase* scenario:

1. The high forecasted increase is reduced. In the *reference* scenario passenger transport is expected to increase by 80% between 2010 and 2050, while freight transport is expected to almost double. In the *medium increase* scenario, passenger transport increases by approximately 40% in 2050 compared to 2010. No major change in the demand for freight is included.
2. The efficiency of conventional cars is increased. Only the efficiency of cars is improved since there are already significant energy efficiency improvements in the *reference* for other vehicles: for example, if the efficiency gains for conventional vehicles in the *reference* were not included then the total energy demand for transport would be 427 PJ in 2050 and not the forecasted 285 PJ.
3. Vehicles are utilised more. In the *reference* model it was evident that the existing transport sector has very poor utilisation factors. For example, in the 2010 *reference* model national trucks only utilise approximately 42% of their capacity. In the *medium increase* scenario, utilisation factors were increased for different freight vehicles by approximately 5% of the original value.
4. Different modes of transport which are more efficient and use more sustainable fuels are utilised more in the *medium scenario*. For example, rail is a particularly suitable replacement for long road journeys since it is very efficient and it can be completely electrified. Therefore, the transport demand for electric rail was doubled in the *medium scenario*.

To incorporate these measures into TransportPLAN, a number of modules were added to the tool including a model shift module, infrastructure cost calculator, and an energy efficiency improvement module. Afterwards, the three technology scenarios were then assessed using this *medium increase* transport demand scenario. As displayed in Figure 3.7, there is a reduction in the overall energy demand of approximately 85 PJ for the *reference* and 40 PJ for the *recommendable* scenarios, if the *medium increase* transport demand is implemented. Therefore, implementing the *medium increase* scenario is not just beneficial for a 100% renewable energy system, it is also beneficial for the *reference* transport system. In addition, if the *medium increase* scenario is implemented with the *recommendable* technology mix, then the biofuel consumption in 2050 is reduced to approximately 60 PJ/year, which is in line with the biofuels available in Denmark. However, the key issue which also needs to be addressed in relation to this dramatic transition for the transport sector is cost.

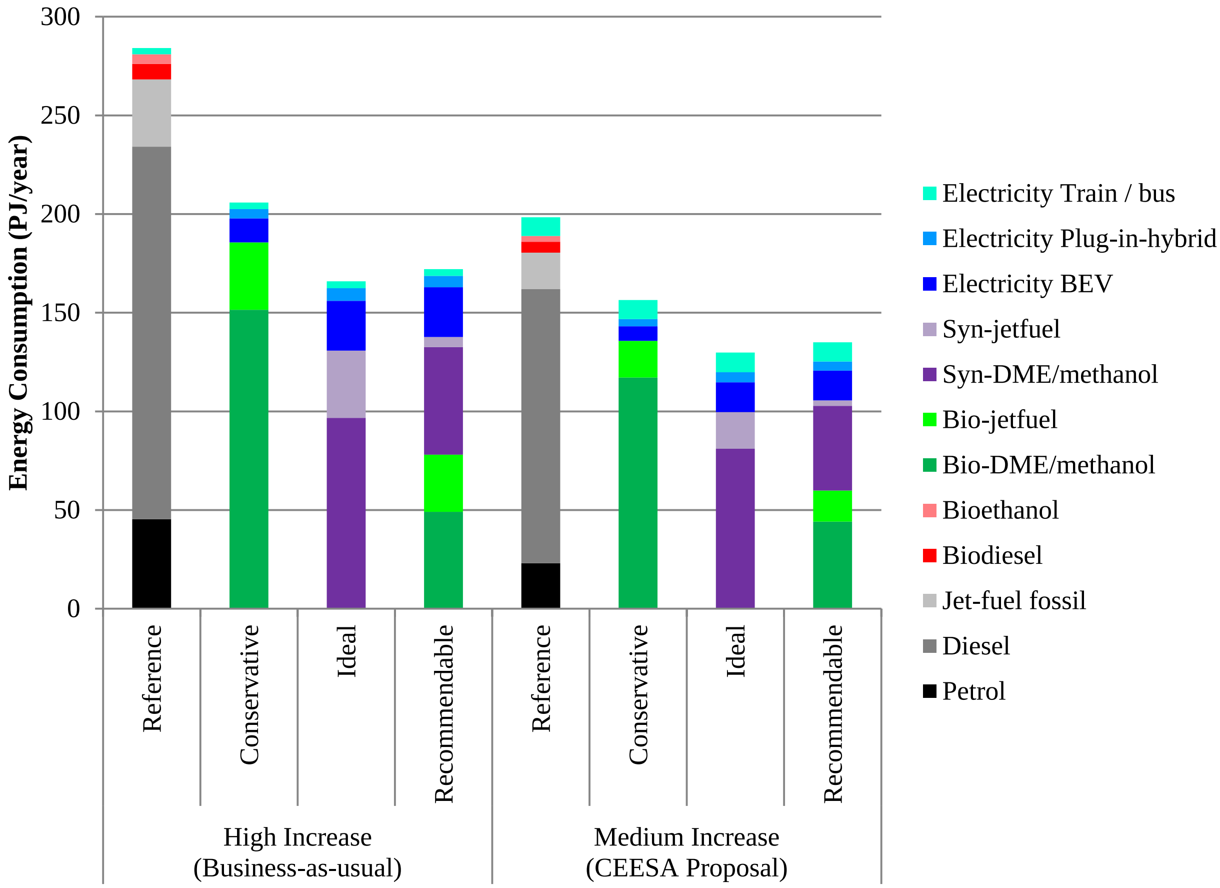

Figure 3.7: Energy consumed by fuel type in 2050 for the *reference*, *conservative*, *ideal*, and *recommendable* scenarios for a *high increase* and a *medium increase* in the transport demand.

To establish the costs relating to the transport sector, the entire energy system needs to be accounted for: in a 100% renewable energy system it is not only liquid fuel that is used extensively for transport, it is electricity also. Therefore, changes in the transport sector have implications for the electricity and heat sectors also. For example, even though the biofuel demand has been reduced to 60 PJ/year in the *medium increase recommendable* scenario, there may be an indirect increase in biomass for electricity production (which is investigated and discussed in work package 1). Here this is relevant since the costs associated with the variation in electricity demand can only be accounted for by modelling the entire energy system with and without the transport sector. Hence, these costs were calculated in conjunction with the energy system analysis in work package 1, which used the EnergyPLAN tool to model the complete energy system and the TransportPLAN tool to supply the transport inputs necessary (see Figure 3.5).

The results, which are displayed in Figure 3.8 for each scenario in 2050, indicate that the *medium increase* demand is cheaper than the *high increase* demand for all scenarios. The high increase and low increase demand scenarios are, however, not directly comparable, as the costs of having a medium increase instead of a high increase in passenger demand are not quantifiable in terms of the direct costs. If these measures are implemented, though, the savings amount to 20 billion DKK/year. It should be noted that the change also involves a significant expansion of the rail network. The market share of rail is expected to double until 2030. Figure 3.8 also indicates that the *reference* scenario is practically the same price as all of the 100% renewable energy scenarios for the *medium increase* in the transport demand. However, there is a clear distinction in the breakdown of the costs in the *reference* compared to the 100% renewable energy scenarios. In the *reference*, there are high fuel/energy costs which are caused by a high dependency on limited oil. In contrast, the 100% renewable energy scenarios have small fuel/energy costs, but higher investment costs since they use new and more efficient transport technologies. Hence, transforming to a 100% renewable energy transport sector will not require additional costs for society. Finally, since the *medium increase recommendable* scenario is relatively the same cost as the other *medium increase* scenarios, it makes sense to follow this pathway since there is a balanced consumption of biofuels and synthetic fuels from co-electrolysers.

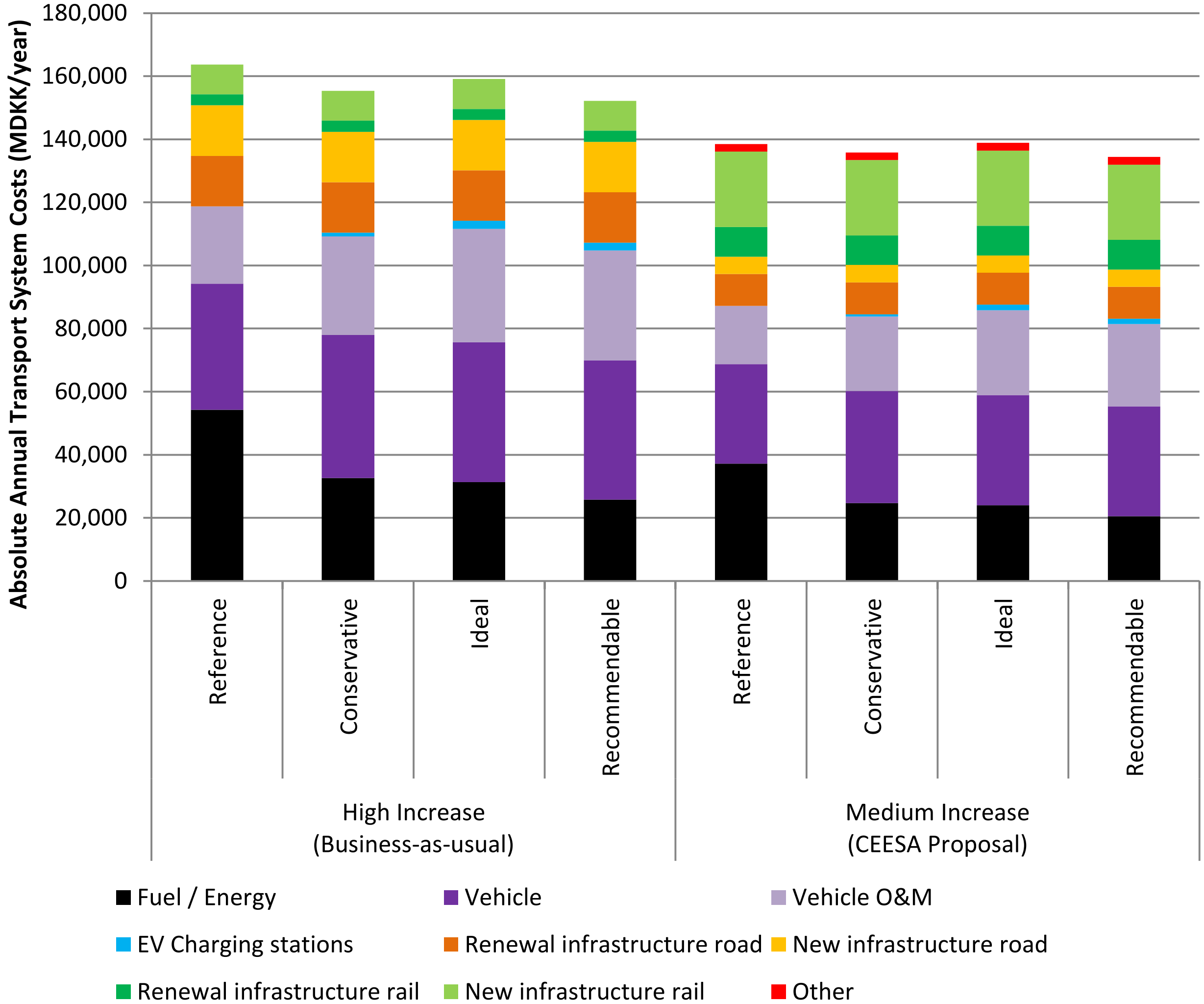

Figure 3.8: Transport system costs in 2050 for the *reference*, *conservative*, *ideal*, and *recommendable* scenarios for a *high increase* and a *medium increase* in the transport demand.

To demonstrate how the *recommendable* scenario could evolve with time, Figure 3.9 illustrates the energy demands for the *medium increase recommendable* scenario from 2010 to 2050. It is clear from the results below that direct electrification and bio-DME/methanol should be introduced by 2020 to begin the transition to a 100% renewable transport sector. This enables DME/methanol vehicles to develop while co-electrolysers for synthetic fuels are also developing. As syn-DME/methanol production advances, it will also supplement the bio-DME/methanol as an additional liquid fuel and thus reduce the dependency on biofuels. Therefore, after 2030 the share of biofuel begins to stabilise considerably as more syn-DME/methanol is introduced into the energy system. The objective here is to ensure that the peak demand for biofuels in the transport sector does not surpass the residual biomass resources available to the Danish energy system. Figure 3.9 also indicates that there is an overall energy reduction of approximately 115 PJ/year between 2010 and 2050 in the *recommendable* scenario, even though the transport demand is increasing (particularly for freight transport): this occurs since the vehicles used in the *recommendable* scenario are more efficient than those used in the 2010 *reference*. In comparison to the *high increase (business-as-usual) reference* scenario, there is also an overall energy saving of approximately 150 PJ (50%) in 2050 for the *medium increase recommendable scenario*, while both scenarios require the same costs (see Figure 3.8). Therefore, the Danish transport sector can be affordably transformed into a renewable and sustainable sector by 2050, by supporting more energy efficient transport technologies which are currently close to commercialisation and by reducing the high increase in the forecasted transport demand.

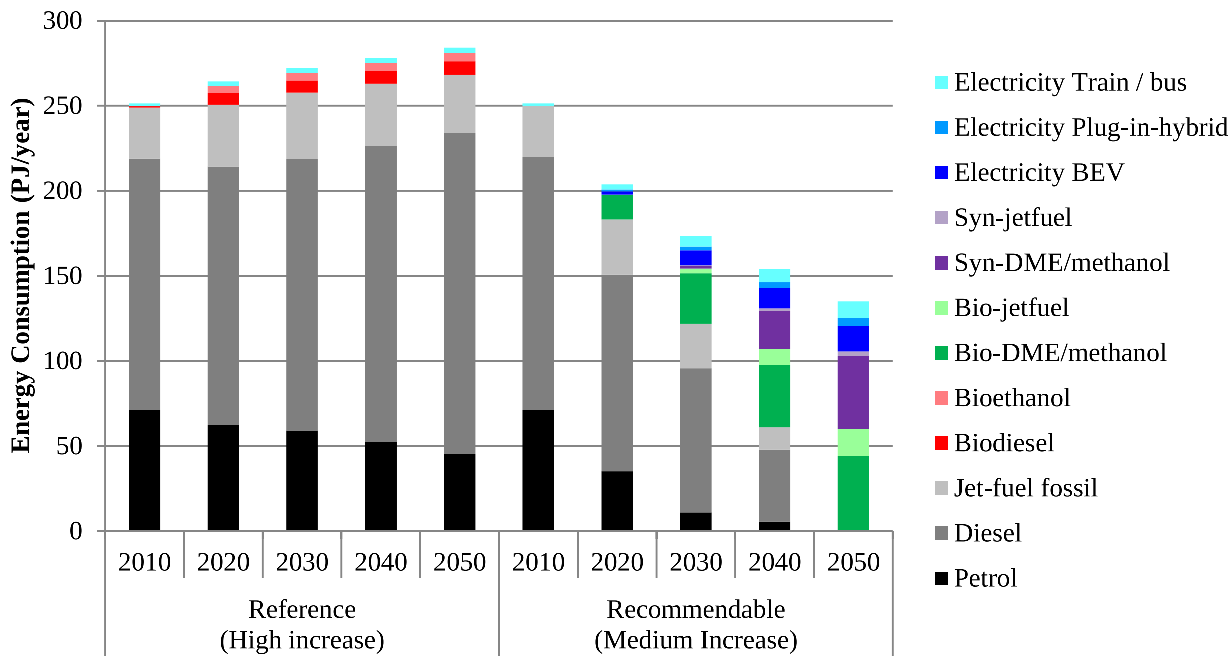

Figure 3.9: Energy consumed by fuel type for the *reference* and *recommendable* scenarios between 2010 and 2050 for a *high increase (business-as-usual)* and *medium increase (CEESA proposal)* respectively in the transport demand.

In the following section, the technology scenarios developed here are implemented with the *medium increase* transport demand into various 100% renewable energy systems using the EnergyPLAN tool. Subsequently, the energy-system-analysis results from work package 1 are presented and discussed.

3.3 Three Technology Scenarios reaching 100% Renewable Energy

The aim of the CEESA scenarios is to design and thoroughly analyse the transition from the present energy system, which is primarily based on fossil fuels, to a 100% renewable energy system by the year 2050. However, such transition highly relies on the technologies which are assumed to be available within such time horizon and can have different effects on the biomass consumption. To highlight such issues, the CEESA project has identified scenarios based on three different assumptions with regard to the available technologies. This methodology allows a better optimisation and understanding of the energy systems.

The issue studied is 100% renewable energy systems for Denmark. In this context, the Danish society is the primary target group. The aim of this feasibility study is to enhance the knowledge of the technical challenges of such energy and transport systems and to analyse the economic and environmental consequences for society. It should be noted that the principle in the boundary condition applied to both the energy and transport system is that if all countries applied the same boundary condition, all consumptions would be accounted for, and no elements would be counted twice. The project goal regarding the construction of 100% renewable energy scenarios includes 7 elements:

1) Create a variety of 100% renewable energy system scenarios for Denmark.
2) Analyse and integrate the transport sector into such systems.
3) Analyse the effects of using biomass resources in 100% renewable energy systems considering the limitations in the biomass resources.
4) Use energy system analysis to integrate flexibility and *smart energy systems* solutions into the electricity, heating and transport sectors as well as into the fuel supply to gas grids which utilise renewable energy.
5) Analyse the effects on fuel efficiency and greenhouse gas emissions.
6) Analyse the transition towards such a system from today until 2050.
7) Identify the socio-economic consequences of such scenarios, incl. job effects, commercial potentials, health effects and others.

In order to enable a thorough analysis of the different key elements in 100% renewable energy systems, two very different 100% renewable energy scenarios as well as one recommendable scenario have been created:

> ***CEESA-2050 Conservative:*** *The conservative scenario is created using mostly known technologies and technologies which are available today. This scenario assumes that the current market can develop and improve existing technologies. In this scenario, the costs of undeveloped renewable energy technologies are high. Very little effort is made to push the technological development of new renewable energy technologies in Denmark or at a global level. However, the scenario does include certain energy efficiency improvements of existing technologies, such as improved electricity efficiencies of power plants, more efficient cars, trucks and planes, and better wind turbines. Moreover, the scenario assumes further technological developments of electric cars, hybrid vehicles, and bio-DME/methanol production technology (including biomass gasification technology).*

> ***CEESA-2050 Ideal:*** *In the ideal scenario, technologies which are still in the development phase are included on a larger scale. The costs of*

undeveloped renewable energy technologies are low, due to significant efforts to develop, demonstrate and create markets for new technologies. For example, the ideal scenario assumes that fuel cells are available for power plants, and biomass conversion technologies (such as gasification) are available for most biomass types and on different scales. Co-electrolysis is also developed and the transport sector moves further towards electrification compared to the conservative scenario.

CEESA-2050: *This scenario is a "realistic and recommendable" scenario based on a balanced assessment of realistic and achievable technology improvements. It is used to complete a number of more detailed analyses in the project, including the implementation strategy, as well as in a number of sensitivity analyses. Here, however, less co-electrolysis is used and a balance is implemented between bio-DME/methanol and syn-DME/methanol in the transport sector. This is the main CEESA scenario.*

Here *Conservative* and *Ideal* are used in the sense that different technological developments will have different effects on the extent of the use of biomass resources, as well as the requirements for flexibility and smart energy system solutions. In all scenarios, energy savings and direct electricity consumption are given a high priority.

In the CEESA scenarios, the *smart energy system* integration is crucial. Electricity smart grids are only one part of this system. The scenarios rely on a holistic *smart energy system* including the use of:

1) Heat storages and district heating with CHP plants and large heat pumps.
2) New electricity demands from large heat pumps and electric vehicles as storage options.
3) Electrolysers and liquid fuel for the transport sector enabling storage as liquids.
4) The use of gas storage.

Such *smart energy systems* enable a flexible and efficient integration of large amounts of fluctuating electricity production from wind turbines and photovoltaics. The gas grids and liquid fuels allow long-term storage, while the electric vehicles and heat pumps allow shorter term storage and flexibility.

The transport sector poses two main problems in the transition to renewable energy: 1) The obvious easily accessible source, biomass, is limited and 2) the increase in the transport demands is historically high. The scenarios include a suggestion for a new transport system, with medium increase in demands (except goods) and more rail transport. To replace oil and keep the biomass consumption at a low level, the following strategy is applied: Focus is placed on maximising the use of electricity in the transport sector, and, where liquid fuels are needed, in some cars, vans, trucks and aviation, priority is given to DME/methanol.

With such fuels, conventional cars can be used in the short term (up to 3% blend), as bio-DME/Methanol is currently being commercialised based on waste products. With minor changes in vehicles, the share can be increased. In the scenarios, bio-DME/Methanol is produced from a combination of gasified biomass and hydrogen from electrolysers and not from waste products. In the longer term, land use effects are lowered further by replacing bio-DME/Methanol with syn-DME/Methanol, which requires co-electrolysers and carbon sequestration. This strategy reduces biomass use and allows the integration of more wind turbines and photovoltaic into the energy system in general, i.e., the transport sector becomes an important part of the smart energy system.

DME/methanol is used in the scenarios for the concrete calculations to illustrate the principle of using biomass resources in a combination with electrolysers to replace fossil fuels in the transport sector in the short term. In the longer term, carbon from other sources than biomass is used to replace larger amounts of fossil fuels without putting further strain on the biomass resource. Other types of fuels that fulfil this principle could also be relevant in the future, but the scenarios show that this principle can reduce the biomass consumption significantly.

All the above three technology scenarios are designed in a way in which renewable energy sources, such as wind power and PV, have been prioritised, taking into account the technological development in the scenarios and the total costs of the system. Moreover, they are all based on decreases in the demand for electricity and heat as well as medium increases in transport demands. Consequently, none of the scenarios can be implemented without an active energy and transport policy. However, sensitivity analyses are conducted in terms of both a high energy demand scenario as well as the unsuccessful implementation of energy saving measures. These analyses point in the direction of higher costs, higher biomass consumption and/or a higher demand for more wind turbines. The important differences between the scenarios are highlighted in Table 3.1.

Table 3.1, Main difference between the 100% renewable energy scenarios in CEESA.

	CEESA-2050 Conservative	***CEESA-2050-Ideal***	***CEESA-2050***
Renewable energy and conversion technologies			
Wind power Photo Voltaic Wave Power	12,100 MW -	16,340 MW 7,500 MW 1,000 MW	14,150 MW 5,000 MW 300 MW
Small Combined Heat and Power	Engines	Small Fuel Cell CHP	Engines / Fuel cells Gas turbine
Large Combined Heat and Power and Power Plants	Gas turbine Combined Cycle/ Combustion	Large Fuel Cell Combined Cycle CHP/PP	Combined Cycle / Large Fuel Cell Combined Cycle CHP/PP
Gasification for electricity and power production	Yes partly	Yes	Yes
Transport			
Direct electricity	87%	23%	22%
Bio-DME/Methanol	13%	0%	44%
Syn-DME/Methanol	-	77%	34%
Bio-DME/Methanol plants	Yes	No	Yes
Electrolysers for Bio-DME/Methanol plants	Yes	No	Yes
Co-Electrolysers for Syn-DME/Methanol plants	No	Yes	Yes

In the *conservative* technology scenario, wave power, photo voltaic and fuel cell power plants are not included and emphasis is put on bio-DME/Methanol and on direct electricity consumption in the transport sector. The electrolysers are based on known technology in this scenario. Smart energy systems and cross-sector system integration is required between the electricity system, district heating sectors as well as into the transport system and gas grid in all scenarios. The integration into the transport system and gas grids is, however, not as extensive in the *conservative* scenario as in the *ideal* scenario. In the *ideal* scenario, wave power, photo voltaic, fuel cell power plants, and a number of other technologies are used to their full potential, while, in the *recommendable* scenario, the technologies are assumed to be developed to a degree in which they can make a substantial contribution. For all technologies, sensitivity analyses are made in which they are replaced with existing technologies. The primary energy consumption for 2050 of the three scenarios and the reference energy system is compared in Fig. 3.10. Compared to the reference energy system, all the scenarios are able to reduce the primary energy supply to a level of approximately 500 PJ. There are, however, large differences between the structures of this primary energy supply, see Figure 3.11.

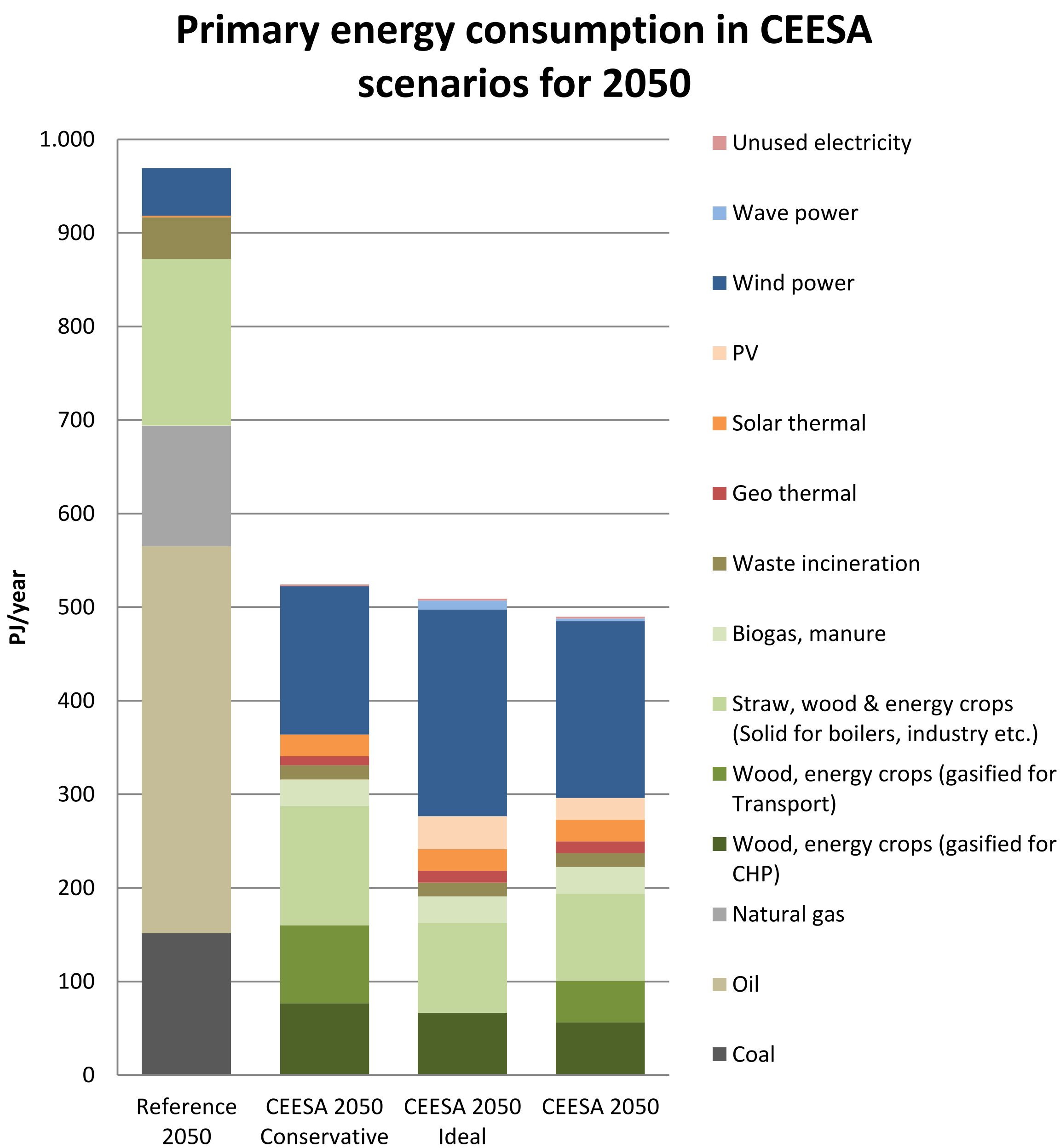

Figure 3.10: Primary energy supply in the 2050 reference energy system and the three CEESA 100% renewable energy scenarios.

In the *conservative* technology scenario, a 100% renewable energy system is possible with a total biomass consumption of 331 PJ. The *ideal* technology scenario can decrease this consumption to 206 PJ of biomass. In the CEESA 2050 *recommendable* scenario, the biomass consumption is 237 PJ and thus 30 PJ higher than in the *ideal* and 96 PJ lower than in the *conservative* scenario. In all three scenarios, hour-by-hour energy system analyses have been used to increase the amount of wind turbines to an amount ensuring that the unused electricity consumption, also referred to as excess electricity, is lower than 0.5 TWh (1,8PJ). These analyses also ensure that the heat supply and gas supply is balanced. The importance of that is visible in the differences in the installed wind power capacities in the three 100% renewable energy scenarios, i.e., the *ideal* scenario is able to utilise more wind power than the *conservative* scenario.

The *ideal* scenario uses the least biomass possible and requires a high degree of system integration and flexibility, while the *conservative* scenario uses the least possible biomass with a conservative assessment of the technological development. With more renewable energy sources and more efficient conversion technologies in combination with an integrated smart energy system, other sources of carbon can be integrated into the transport system, and hence reduce the overall consumption of biomass. In Figure 3.11, the biomass consumption is illustrated in the three scenarios. It is obvious that, although the overall primary energy supply can be reduced to 500 PJ in all scenarios, the technology choices in the 100% renewable energy system are crucial for the biomass consumption.

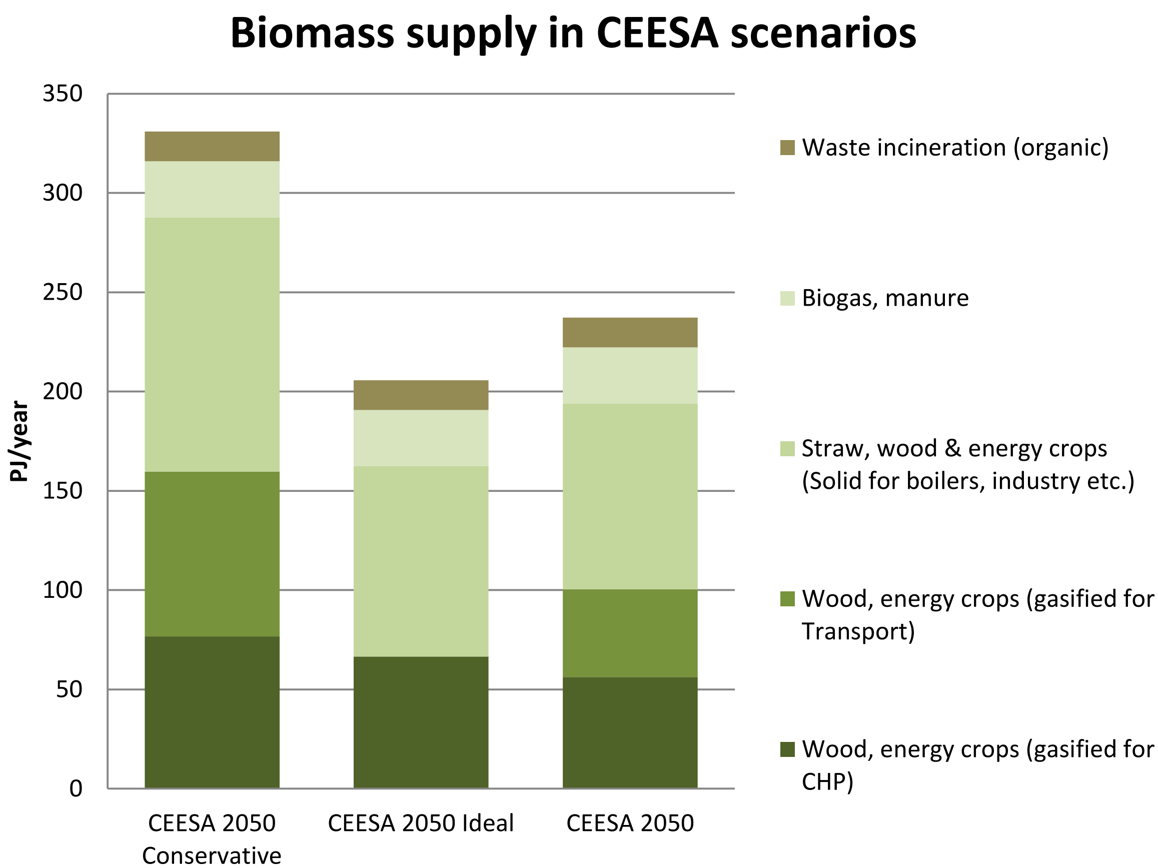

Figure 3.11: Biomass supply in the three CEESA 100% renewable energy scenarios.

The results of CEESA show that, in a business-as-usual scenario, the biomass potential is approx. 180 PJ/year. A shift in forest management practices and cereal cultivars could increase the potential further to approximately 240 PJ/year by 2050. The 180 PJ/year could also be increased to 200 PJ by enacting dietary changes. Such potential represents the use of residual resources only. This means that the CEESA 2050 *recommendable* scenario is kept within the boundaries of residual resources, and the CEESA 2050 *conservative* scenario illustrates that an active energy and transport policy is required to stay within these limits. It should be noted that a target of 240 PJ/year by 2050 implies a number of potential conflicts due to many different demands and expectations of ecosystem services, as this requires the conversion of agricultural land otherwise allocated to food crop production to energy crop production, potentially reducing food and feed production. All crop residues must be harvested, potentially reducing the carbon pool in soils. A way to reduce this conflict potential is to reduce the demand for biomass for energy or to further develop agriculture and forestry in order to increase the biomass production per unit of land.

If biomass in a future non-fossil society has to cover the production of materials currently based on petro-chemical products, even more pressure will be put on the biomass sector. In order to meet such demands, 40-50 PJ would have to be allocated to that purpose. In this respect, it should be noted that, in addition to the 240 PJ of residual biomass resources, waste resources are also available amounting to 33-45 PJ or a total of approximately 280 PJ. In this respect, CEESA 2050 *recommendable* and *ideal* would enable the allocation of biomass resources to the materials currently based on petro-chemical products.

In a sensitivity analysis, the CEESA 2050 *ideal* scenario has been taken to a further extreme, showing that, in principle, 180 PJ is possible; however, this comes at an additional cost which is elaborated below.

100% Renewable Energy and Large Reductions in fuel consumption

The current primary energy supply in Denmark (fuel consumption and renewable energy production of electricity and heat for households, transport and industry) is approximately 850 PJ, taking into account the boundary conditions applied to transport in this study, in which all transport is accounted for, i.e., national/international demands and both passengers and freight. If new initiatives are not taken, the energy consumption is expected to decrease marginally until 2020, but then increase gradually until 2050 to about 970 PJ. The reference energy systems follow the projections from the Danish Energy Authority from 2010 until 2030, and the same methodology has then been applied here to create a 2050 reference energy system. The measures of savings, transport as well as renewable energy and system integration between the electricity, heat, transport and gas sectors can reduce the primary energy supply to 669 PJ in CEESA 2020; 564 PJ in CEESA 2030; 519 PJ in 2040, and 473 PJ in CEESA 2050, respectively.

At the same time, the share of renewable energy from wind turbines, photovoltaic, solar thermal, and wave energy, as well as biomass will be increased. The share of renewable energy in the recommended energy system increases from about 20 % in 2010 to 42 % in 2020 and to about 65 % in 2030. If the oil and gas consumption in refineries and for the extraction of oil in the North Sea is excluded, 73 % is the share of renewable energy in the 2030 energy system. In 2050, the entire Danish energy system (incl. transport) is based on

100 % renewable energy. The primary energy supply is illustrated in Figure 3.12. The energy flows in the CEESA 2050 recommendable 100% energy system are illustrated in a sankey diagram in Figure 3.13.

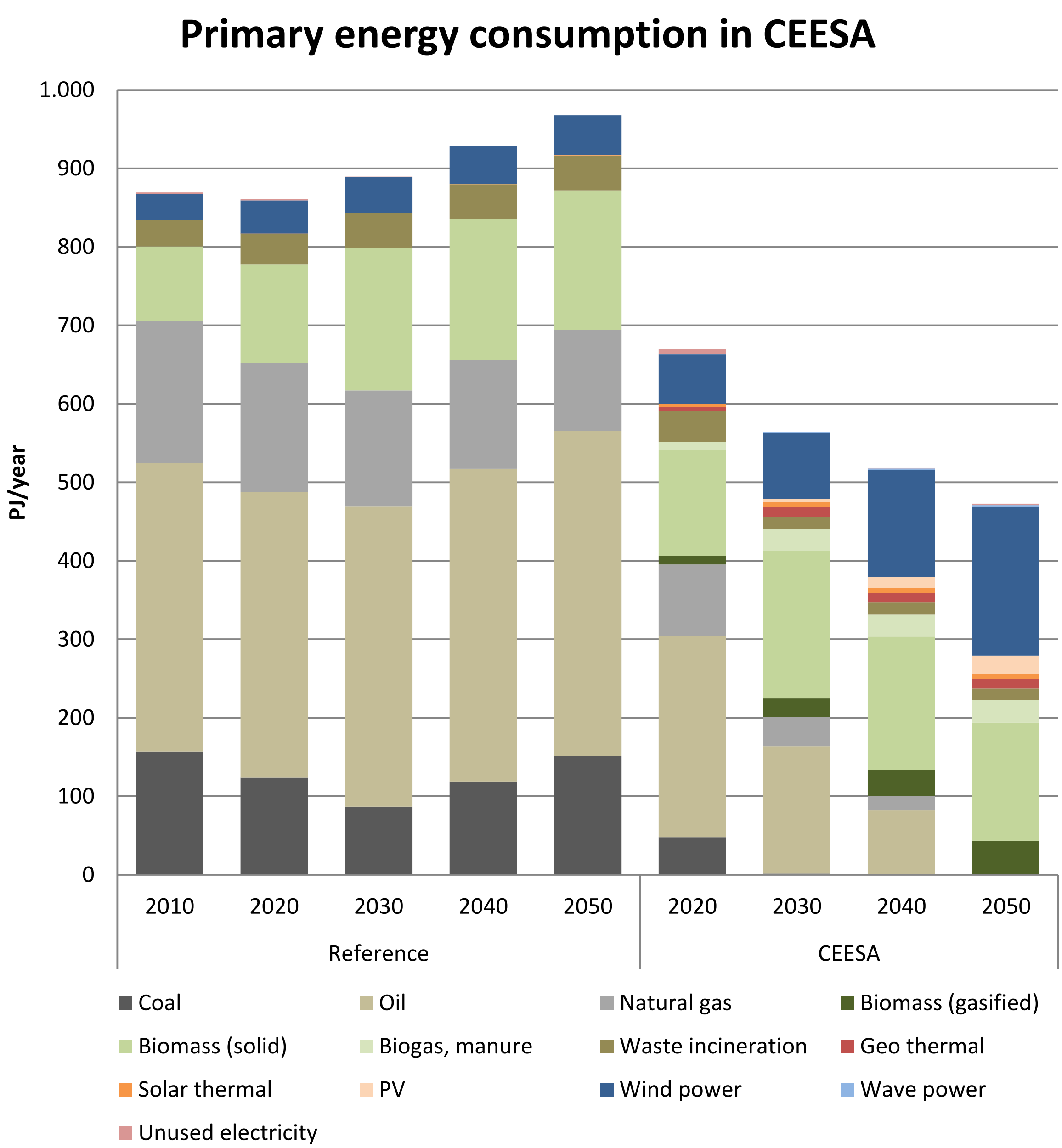

Figure 3.12, Primary Energy Supply in CEESA.

The energy system in CEESA 2020 is based on measures which can be realised with the current technology; however, some development of battery electric vehicles, hybrid electric and plug-in hybrid electric vehicles is assumed. The main focus in the short term is large heat pumps and heat storages in the district heating sector. In CEESA 2030, large parts of the transport system are changed, district heating systems are heavily expanded, the efficiency of power plants is increased, more mature and new renewable energy technologies are introduced, and further energy savings are implemented in electricity and heating as well as in the transport sector through the introduction of modal shift measures and going from a high increase to a medium increase in transport demand. In general, large parts of the fossil fuel consumption are replaced by electricity demands, especially within transport, with different types of electric vehicles and electrically powered trains. Special emphasis has been put on the transport sector in which the transition to renewable energy poses significant challenges due to the very high demand increases which are forecasted and an almost 100 % dependency on oil.

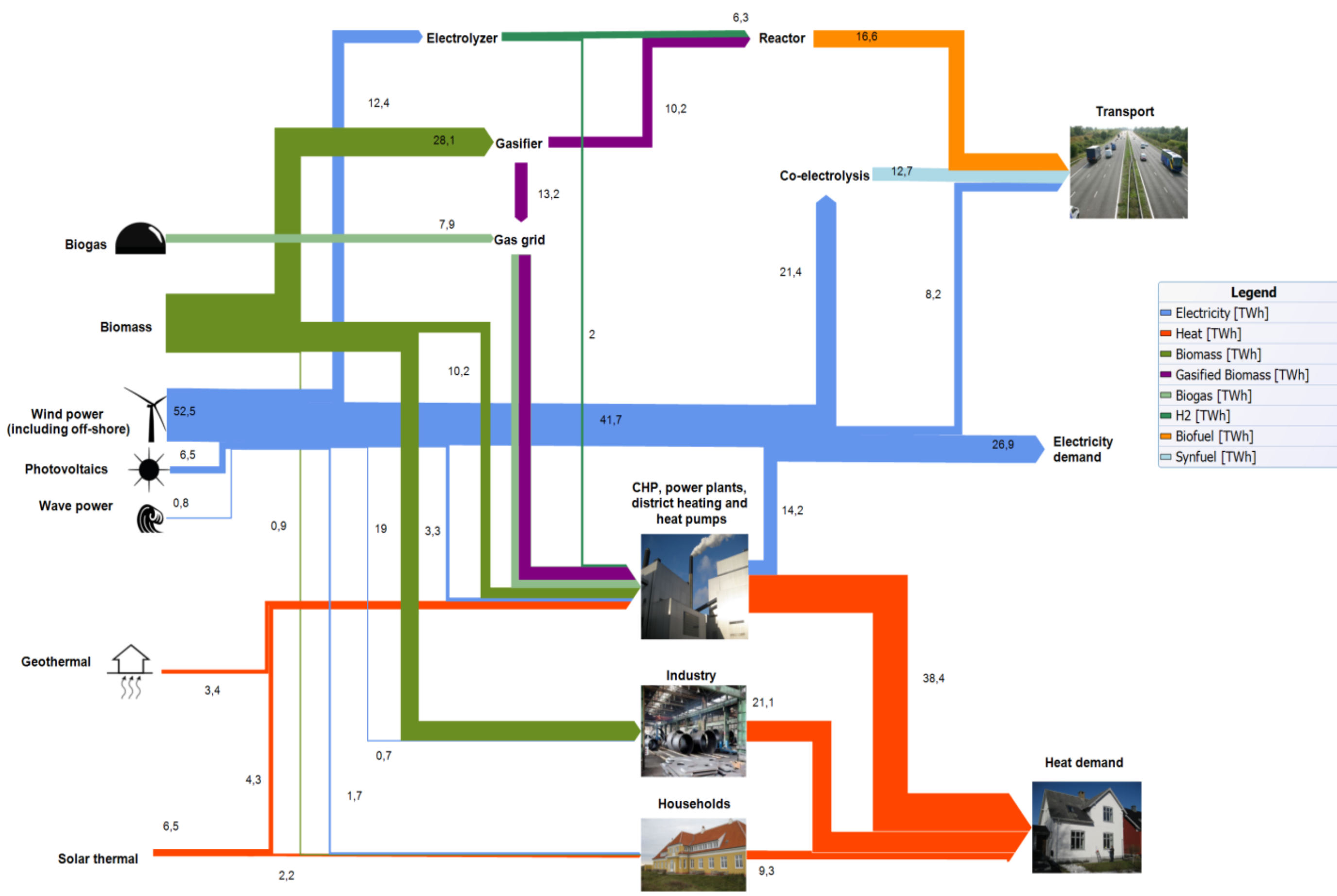

Figure 3.13, Sankey diagram of the CEESA 2050 100 % renewable energy scenario.

In CEESA, an energy system is designed which is based on 100 % renewable energy and combined with analyses of the energy system in the transitional years 2020 and 2030. Savings are implemented gradually and more renewable energy is introduced in these transitional years. 2040 has been included by interpolating between the 2030 and 2050 energy and transport systems. Substantial investments are required in savings, renewable energy, district heating, and notably in the transport sector. The transitional years are partly analysed to ensure that these energy systems do not stand in the way of the main objective and partly because of the Danish Government's objective that Denmark must use 100 % renewable energy in 2050. Hence, the technologies needed in the short term to enable this should be identified.

The CEESA scenarios document that it is possible to find technical solutions for a 100 % renewable energy system. However, a certain technological development becomes essential in the coming years, notably in enabling the efficient direct use of electricity in the transport sector with better electric, hybrid electric and plug-in-hybrid electric vehicles and in biomass gasification technologies (small and large scale). The results also show that, if these technologies are not developed sufficiently, the biomass consumption could be larger than in the CEESA 2050 *conservative* scenario.

In CEESA, a 100 % renewable energy system has been designed which may potentially be supplied by domestic residual biomass resources. It must, however, be emphasised that there is no objective in the CEESA project *not* to do international trade with biomass. The scenario recommended in CEESA, however, ensures that Denmark does not merely become dependent on imports of biomass, instead of being dependent on imports of oil, natural gas and coal, which is the case in the reference scenario (once Denmark does not have any resources left in the North Sea). It also ensures that the biomass consumption is within the limits of the Danish residual biomass resources. Looking at the global residual resources, the residual biomass potential is higher per person in Denmark, though, implying that Denmark should go even lower than the domestic residual biomass resources available.

Smart energy systems and cross sector integration

The integration of sectors is very important in 100% renewable energy systems to increase fuel efficiency and decrease costs. The most important step and the first step is the integration between the heating and the electricity sectors. In Denmark, this is already implemented to a large extent and approximately 50 % of the electricity demand is produced by CHP plants. Such integration requires thermal storages of today’s sizes (about 8 hours in average production), a boiler and district heating networks to enable the flexible operation of the CHP plants as already implemented in the Danish energy system. This can reduce the fuel consumption and help integrate fluctuating wind power effectively. 20-25% of the wind power can normally be integrated without significant changes in the energy system. With more than 20-25% wind power, the next step in the integration is to install large heat pumps.

In the CEESA scenarios, a significant amount of onshore and offshore wind power is installed by 2020. About than 50% of the electricity demand is covered from these sources.

This results in some imbalance in the electricity grid, and heat pumps alone are not able to ensure the balance. The transport sector needs to be integrated into the energy system with more than 40-45% wind power. As a consequence, some electric vehicles are implemented and flexible demand is included in households and industry. This, however, is not sufficient. Thus, small amounts of electrolysers based on known alkaline technology are also implemented to facilitate wind power integration and for the production of bio-DME/Methanol in combination with gasified biomass. This also enables the integration of larger amounts of renewable energy into the transport sector.

In 2030, a larger proportion of electric vehicles are included in a solution in which they are able to charge according to a price mechanism. In order to make sure that electric vehicles can fulfil this function, the low voltage grid needs to be enforced in some areas. The electricity production from onshore and offshore wind power in combination with photovoltaic is approximately 60% in 2030. In order to facilitate this, transport needs to be integrated further. In CEESA, this is achieved by implementing electric cars on a larger scale, i.e., from 2020 onwards.

In CEESA 2050, more and new technologies are necessary to make sure that the renewable energy is integrated efficiently into the system and that fossil fuels are being replaced totally. Hence after 2030, electrolysers for hydrogen production for bio-DME/methanol are gradually increased to provide larger amounts of liquid fuels to the transport sector and the electrolysers are more efficient. Also co-electrolysers are contributing on to produce syn-DME/Methanol without using biomass, but by using carbon sequestration from the electricity sector or other sources.

In the CEESA 2050 energy system, gasified biomass and the gas grid storages are also utilised in combination with the electric vehicles and fuel production in the transport sector as well as the district heating systems. This creates an energy system in which smart energy systems are integrated and the storage options are used in combination to enable the final scenario.

The CEESA project has taken a closer look at the balancing of gas supply and demand. Therefore, biogas and the gasification of biomass have been analysed on an hourly basis in the CEESA 2050 scenario in relation to a gas grid and storage and taking into account supply and demand. The aim is to evaluate the required storage capacity and peak demands for 100% renewable energy scenarios. The analyses ensure that there is a balance hour-by-hour in the gas supply and demand and that the current Danish salt cavern storage facilities are more than sufficient to facilitate this balancing.

Large reductions in greenhouse gas emissions

In CEESA, the greenhouse gas emissions from fossil fuels are reduced significantly in the energy system. In Figure 3.14., the greenhouse gas emission from the energy system in the CEESA scenario are illustrated in relation to the reference energy system, including an extra contribution from aircraft due to discharges at high altitudes. In CEESA 2020, the greenhouse gas emissions are reduced to 30 Mton CO_2-eq./year and in 2030 to 15 Mton

CO_2-eq./year. In 2020, the reductions are approximately 45% compared to 2000; in 2030, the reductions are 70%, and in 2040, approximately 85%. In 2050, the emissions are not zero due to aviation, but the emissions have been reduced to 2% compared to 2000 from these sources. Greenhouse gas emissions from industrial processes and from agriculture or land use changes are not included in this figure.

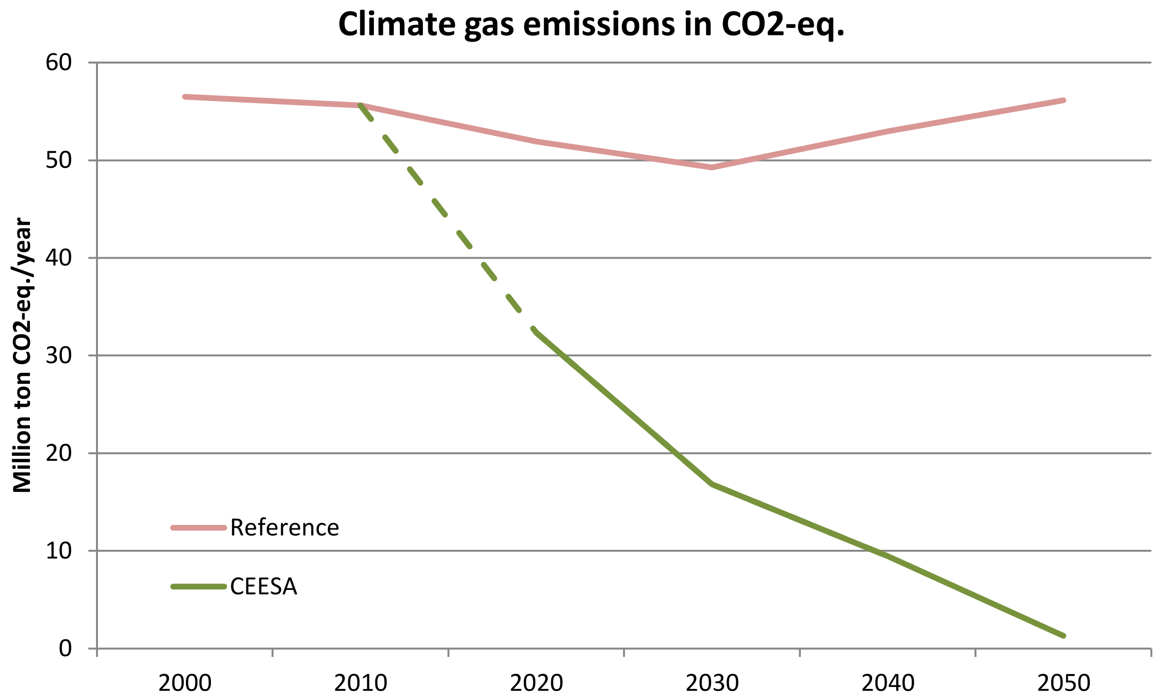

Figure 3.14, Emissions of greenhouse gases in CEESA.

Better socio-economic solutions with more renewable energy

CEESA is implemented over a period from now until 2050 by continuously replacing technologies, buildings and vehicles when their lifetime expires. Hence, many of the elements of the current energy and transport systems in society will need to be replaced even if the scenarios in CEESA are not implemented. Therefore, as a point of departure of this study, the expenses included are calculated as the extra costs generated through the investment in better facilities in comparison with the reference energy system. However, exceptions to this may be seen.

The socio-economic costs are calculated as annual expenses in each of the years 2020, 2030, and 2050, including an interpolated approximation of 2040. The annual costs in CEESA's energy systems are compared with the costs of the reference in each of the applicable years. The costs are categorised under fuel costs, operation and maintenance costs, and investment costs. The investment costs have been further divided into investment costs in the energy sector and extra investment costs in the transport system. The transport investment costs included are additional to the annual investment already made in the current (2010) system (approximately 28 billion DKK in road and rail). A real interest rate of 3 % is used in depreciation investments. The economic analyses are based on the latest assumptions regarding fuel prices and CO_2 quota costs, which were defined by The Danish Energy Agency in May 2009. Three fuel price levels are used. The middle price level is based on current fuel prices which correspond to an oil price of $122/barrel according to the Danish Energy Agency. The high fuel price is based on the prices in the spring/summer of 2008 and corresponds to an oil price of $132/barrel. The low price level is based on assumptions which The Danish Energy Agency used in its forecast in July 2008 and corresponds to an oil price of $60/barrel. Calculations are also done with long-term CO_2 quota costs of 229 DKK/tonne and 458 DKK/tonne for 2030 and 2050, respectively. The energy systems have been analysed with higher biomass cost than in these assumptions, which does, however, not change the overall results. The CO_2 quota costs do not include all potential costs, such as flooding for example, but are only anticipated quota costs. If these types of effects are included in the calculation, the energy systems in CEESA will have an economic advantage compared to the reference energy system.

As illustrated in Figure 3.15, a first result of the work in CEESA is that the total annual energy and transport system costs can now be quantified to approximately 170 billion DKK/year. As illustrated, the costs of the reference increase gradually. This is mainly due to increased costs in the energy system and also due to the investments required in road infrastructure and new vehicles, which are necessary to meet the high increase in the transport demand. In CEESA, the investment costs increase significantly; however, for the energy and transport systems, these infrastructure investments are necessary to improve the efficiency of the technologies utilised, to reduce demands and to consequently reduce the demand for fuel. Since the savings associated with these investments are larger than the initial investments, there is an overall decrease in costs in the CEESA scenarios. In conclusion, the 2020 energy and transport systems in CEESA are more than 20 billion DKK less costly than the reference energy system. This means that, by implementing known technologies, it is possible to implement changes that provide lower socio-economic costs than the current energy and transport systems. In the longer term, the costs of the CEESA scenario are rather stable; however, large investments are made in order to meet a 100% renewable energy system. The CEESA 2020 energy and transport systems even have lower costs than the current systems (approximately 7 billion DKK). Continuing the business-as-usual path will only enhance the socio-economic savings achieved by changing to a renewable energy system combined with energy savings.

The CEESA scenarios also propose energy systems which are more robust to fluctuations in fuel prices. It is worth noting that Danish society currently spends between 50 and 100 billion DKK/year depending on whether the fuel costs are low or high (the high costs represent real costs experienced in 2008). In the future, one must expect that the world will continue to experience fluctuating fuel prices and neither constantly high nor constantly low prices. Hence, energy and transport systems less dependent on fuels such as the systems proposed in CEESA are less vulnerable.

In addition to the potential economic savings in the renewable energy system scenarios mentioned above, society can benefit from savings in health costs, in commercial potentials and in extra employment effects. Health costs and commercial potentials are assessed in Background Report Part 1: "CEESA 100% Renewable Energy Scenarios towards 2050".

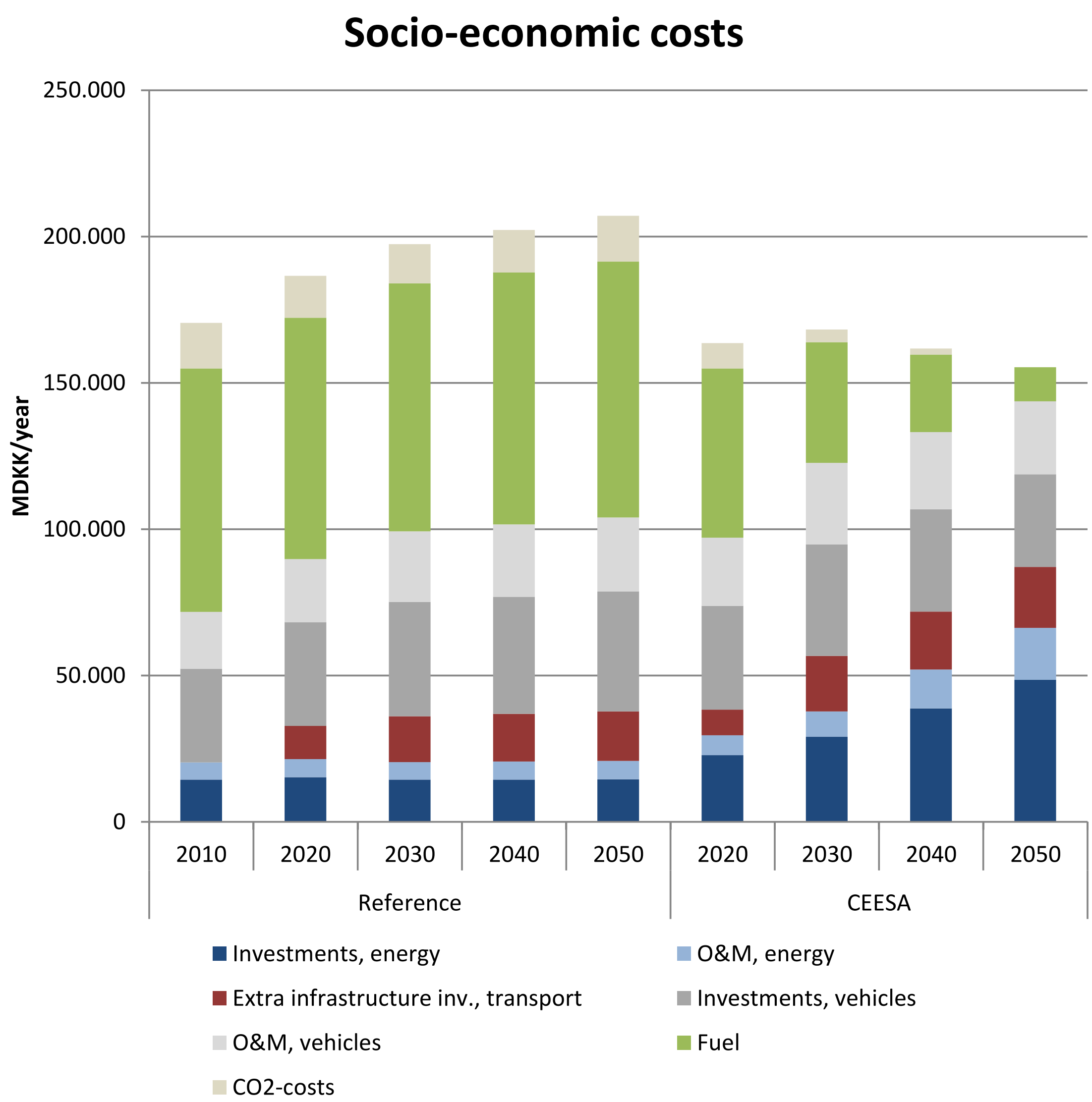

Figure 3.15, Socio-economic costs in the reference energy system and in CEESA from 2010 to 2050. Extra infrastructure costs are relative to 2010 total costs.

Employment effects

As a starting point for the estimation of the employment effect, the annual costs in the reference energy system and the CEESA scenarios are divided into investments and operations. An implementation of the CEESA scenarios includes increasing investment costs and increasing costs for biomass on the expense of lower costs for fossil fuels on the other hand. Such changes will include higher Danish employment while also improving the balance of payments. These effects on the amount of jobs in the energy sector and the effects on the balance of payment can be further increased if the commercial potentials in the form of increased exports are also realised.

In the CEESA scenarios, expenditures for fuels are reduced while expenditures for operations and maintenance are increased. In addition CEESA involves a heavy shift in the investments and also in increase of more than a quarter trillion, which is spread out over the period going forward to 2050. For each cost type, an import share has been estimated based on experiences from previous collections of foreign exchange and employment data for investment in energy facilities and in relation to infrastructure and buildings. In relation to the previous data, a general upward adjustment of the import share has been done, as these are known from experience to increase.

Employment effects have been estimated on the basis that, of the share that is left after removing the import share, two jobs are created for each million DKK. This includes derived jobs in the finance and service sectors. It should be emphasised that these estimates are subject to uncertainties and, again, it is emphasised that they are based on adjusted figures from previously collected data. The extra employment created in Denmark by the implementation of the CEESA scenarios compared with the reference has been estimated by the use of these methods and is assumed to correspond to approximately 20,000 jobs. Jobs will be lost in the handling of fossil fuels, but jobs will be created through larger investments in energy technology than in the reference, as well as larger investment savings. In the reference energy systems, large investments are made in roads, while in the CEESA scenarios, these are replaced by jobs and investments in rail infrastructure. Hence, the jobs related to transport infrastructure are almost the same, but they are shifted more towards rail infrastructure. In the implementation proposed in the transitional years, 20,000 extra jobs are created until 2020. Until 2030, the number of jobs decreases to approximately 14,000 and then increases again in the end of the period until 2050 to about 23,000 jobs. In the beginning of the period, the extra jobs are mainly connected to electricity, fuel and heat savings as well as the expansion of district heating until 2030. While in the end of the period, the increase is connected to increasing investments in renewable energy technology.

The comparison between the reference energy system and the CEESA scenario reveals that, while the number of jobs in transport infrastructure investments is at the same level, then these jobs in the reference energy system create a number of challenges that make it very difficult to reduce the dependency on fossil fuels in the long term. Hence, when this is the case, job creation that can enable a modal shift as well as initiatives to go from a high increase in passenger transport demand to a medium increase is desirable.

It is important for a number of reasons to place the large employment effort as early as possible in the period. The first reason is that the labour force as a share of the total population is falling in the entire period to about 2040 and therefore, the largest labour capacity to undertake a change of the energy system is present in the beginning of the period. The second reason is that the Danish North Sea resources will run out during the next 20 years. Hence, it is important to develop such energy systems and changes as early as possible in the period. Finally, the potential increase in the export of energy technologies which can replace the oil and natural gas exports will be reduced and could disappear entirely in the course of 10-20 years.

The above-mentioned effects on the employment do not include job creation as a result of increased exports of energy technology, i.e. the commercial potentials. These advantages will be an additional benefit of implementing the CEESA scenarios. With an assumption of a 50 per cent import share, an annual export of 200 billion DKK would generate in the order of up to 170.000 jobs, depending on where the exports would have been without an ambitious implementation of the scenarios, the extent of unemployment, and the potential employment of these people in other export trades. In relation to this, it should be noted that, all other things being equal, a share of Danish labour will be made available as the oil and gas extraction in the North Sea comes to an end. In addition, the energy system is more effective and also less vulnerable to fluctuations in energy prices. Hence, this can increase the competitiveness of the Danish society as such and of Danish businesses.

3.4 LCA of 100% RES Scenarios

A part of the CEESA project has focused on identifying important methodological aspects related to the performance of LCA of energy technologies and energy scenarios and further developing this methodological framework, as already discussed in section 2.7. On this basis, an LCA model for relevant energy technologies has been developed and selected scenarios have been modelled. The consequences of the use of biomass resources and the impacts related to crop changes in Denmark have been assessed and evaluated with respect to their importance to the Danish energy production. The main outputs of this work package therefore include the LCA of 100 % RES scenarios as well as 3 core methodological advances in LCA modelling. These key methodological advances are 1) the development of a methodology and database for modelling direct land use change (dLUC) from the growing of alternative energy crops, 2) a methodology for the modelling of indirect land use changes (iLUC) from the food and feed market responses to displacing a food/feed crop by an energy crop, and 3) a methodology for the identification of marginal mineral fertilizers on the market.

LCA results

The LCA study is based on the energy scenarios assessed by WP1. The study has involved the collaboration with WP1 for the set-up of the energy scenarios as well as the selection of the biomass conversion technologies and related efficiencies. Such collaboration has also aimed at improving the software EnergyPLAN in terms of biomass conversion technologies.

Significant efforts have been made to ensure the comparability between the energy scenarios defined in the CEESA project; i.e., that the services provided by each of the individual energy scenarios were identical, not only with respect to the energy services provided but also with respect to services such as food, feed, and animal production. This was specifically important with regard to the use of biomass resources and the area allocated to crop production. Other important methodological aspects were concerned with ensuring that the energy demand included in the CEESA scenarios also covered the energy demand for conversion within the energy sector as well the Danish energy production related to activities outside Denmark (e.g., materials, resources, etc.). This included an evaluation of the geographical scope of the assessment. Ensuring that energy technologies were represented by well- argued and transparent process data was also an important methodological focus and was included in the technological scope of the assessment.

The LCAs carried out in this work package followed a consequential approach, meaning that the environmental consequences related to introducing the energy scenarios were the focus of the LCA. With respect to the crucial issue of land use changes, the approach adopted in this assessment was in accordance with Schmidt (2007). However, different approaches and methodologies of the estimation of dLUC and iLUC do exist, though these are still work-in-progress in the LCA community (including the work currently carried out in the framework of this WP).

The energy scenarios evaluated in the LCA were: i)"2008" (reference), ii)"2030", iii)"2050CSV" (conservative, heavy transport based on fossil fuels), iiii)"2050RME" (heavy transport based on biodiesel produced from rapeseed), iiiii)"2050BtL" (heavy transport based on FT-biodiesel produced from lignocellulosic biomass). Results are shown in Fig. 3.16 and 3.17. The main findings of the LCA are summarised as follows:

- A consistent abatement of the greenhouse gasses (GHGs) (about 66-80% per unit of primary energy supplied by the system; the value varies depending on the scenario) can be achieved by implementing such energy systems (i.e. 2030 and 2050 results as compared to 2008 results). With respect to the 2050 scenarios, the best scenario from a GHG perspective was "2050BtL" (about 18 kt CO_2-eq/PJ), whereas the worst was "2050RME" (about 31 kt $CO_{2\text{-}eq}$/PJ). It has to be noted that, though the main differences between the scenarios relate to the transport fuels (biomass production and conversion), they also include a few differences regarding the implementation of wind and other renewable energy sources (e.g., photovoltaic, solar and heat pumps), according to the energy analyses. The difference between the scenarios "2050RME" and "2050BtL" (about 13 kt CO_2-eq/PJ) was caused by the magnitude of dLUC/iLUC. The impacts associated with rapeseed cultivation were significantly higher than those associated with willow cultivation due to the low yield. The global warming (GW) impact of the conservative scenario "2050CSV" was 19 kt CO_2-eq/PJ. If one focuses only on the 2050 scenarios, this result shows that significant iLUC due to energy crops cultivation can completely off-set the benefits of biofuels. This especially applies to the RME production (scenario "2050RME") in which the use of fossil fuels for heavy transport (conservative scenario) is preferable to biodiesel. In the case of BtL fuels, instead, the production of biofuels was slightly better than the use of fossil resources.

However, this difference is rather small and the uncertainties associated with crops yield, land use changes and conversion efficiencies (in gasification and Fischer and Tropsch processes) may reduce it further. Figure 3.17 shows the GW impacts associated with the production and use of diesel-like fuels.

- The residual domestic biomass resource was not sufficient to cover the energy demand estimated for 2050 by the energy system analyses. The cultivation of energy crops (e.g., willow) was thus required for the production of electricity, heat and biofuels. The amount of required energy crops was estimated at about 51 PJ (excluding biofuel production for aviation and heavy vehicles) and at about 127 PJ (including biofuel production for heavy vehicles and still excluding aviation).

- Overall, a significant decrease of the environmental impact category of acidification was observed with all energy scenarios assessed. This is mostly due to the reduced emissions of SO_2 and NO_x from fossil fuel combustion in power plants. The abatement of the total impact on acidification (AC) corresponded to about 41 - 60% (depending on the 2050 scenario) of the current environmental load (scenario "2008") per unit of energy supplied by the system. With respect to the 2050 scenarios, the emissions contributing to the (residual) environmental impact on AC were mainly associated with NO_x emissions from biodiesel-fuelled cars. The emission of NO_x from biodiesel-fuelled vehicles is, in fact, higher than the one of conventional diesel-fuelled vehicles. This is in accordance with the findings of Zhu et al. (2010), Sun et al. (2010), Joergensen et al. (2008), Mazzoleni et al. (2007) and Wang et al. (2000). Among the 2050 energy scenarios, the worst environmental performance was achieved by "2050RME" due to the impacts mentioned as well as an additional N-release associated with the increased use of fertilizers for rapeseed cultivation. This, however, was less significant for "2050BtL" due to the reduced fertilizer use in willow cultivation.

- Significant impacts on aquatic eutrophication (AE) (due to crops cultivation, e.g., rapeseed and, to a minor extent, willow). The environmental load was estimated at about double load compared to today per unit of energy supplied by the system.

- Significant land use change impacts (principally indirect), as mentioned above. The results underline that high land use change-related impacts may have as a result that the option of using fossil fuels for heavy transport becomes preferable to the production and use of biodiesel-like fuels.

- The results for total environmental impacts (Table 3.2) indicated that the future 2030 and 2050 energy systems had lower total environmental impacts than "2008" in terms of GW and AC. On the other hand, the total impact on AE was higher (for "2050RME" and "2050BtL") or similar (for "2030" and

"2050CSV"). Finally, the total impact on LO increased dramatically in all the selected energy scenarios.

The main challenge of such future energy systems was the provision of biofuels for heavy vehicles and aviation (i.e. the share of transport which was not based on electricity). With respect to aviation biofuels, very few studies were found in the literature and the suggested processes were considered not to be mature from a technical point of view. Thus, it was assumed that aviation fuels will still rely on fossil resources. With respect to heavy terrestrial transport (trucks, van, tractors, buses, etc.), the low efficiency of second generation ethanol technologies and transesterification processes justified the need for an additional cultivation of energy crops (e.g. rapeseed). The thermochemical pathway ("2050BtL") for the production of biodiesel from lignocellulosic biomass through gasification and the Fischer and Tropsch process required less land due to the higher yield of the perennial crops (e.g. willow). The related dLUC/LUC and eutrophication effects were also significantly decreased compared to the rapeseed scenario ("2050RME"). The results of the specific environmental impacts associated with the production and use of biodiesel-like fuels are shown in Figure 3.17.
One LCA was also carried out with the aim to highlight the key environmental aspects of producing biogas from separated slurry. This is a relatively new concept but a probable scenario for future biogas production in a 100 % renewable energy system, as it avoids the reliance on constrained carbon co-substrates (see Background Report Part 5), while achieving economically sufficient methane (CH_4) yields. Three scenarios involving different slurry separation technologies have been assessed and compared to a reference slurry management scenario. The results show that the environmental benefits of such biogas production are highly dependent upon the efficiency of the separation technology used to concentrate the volatile solids in the solid fraction. The biogas scenario involving the most efficient separation technology allowed a net reduction of the global warming potential of 40 %, compared to the reference slurry management. All details of this LCA study can be found in Background Report Part 5.

Table 3.2 Normalized and total LCA results for the selected environmental categories

	Category		Unit	Energy system				
				2008	2030	2050CSV	2050RME	2050BtL
Impacts	GW	Normalized	ktonne CO_2-eq/PJ	68	36	20	31	18
		Total	Mtonne CO_2	59	26	11	18	10
	AC	Normalized	ha/PJ	301	184	122	178	135
		Total	10^3ha	260	130	68	100	79
	AE	Normalized	tonne N/PJ	14	15	15	29	24
		Total	ktonne N	12	11	8.4	17	14
	LO	Normalized	Δha/PJ	-	591	872	2092	1790
		Total	10^3Δha	-	420	480	1200	1100

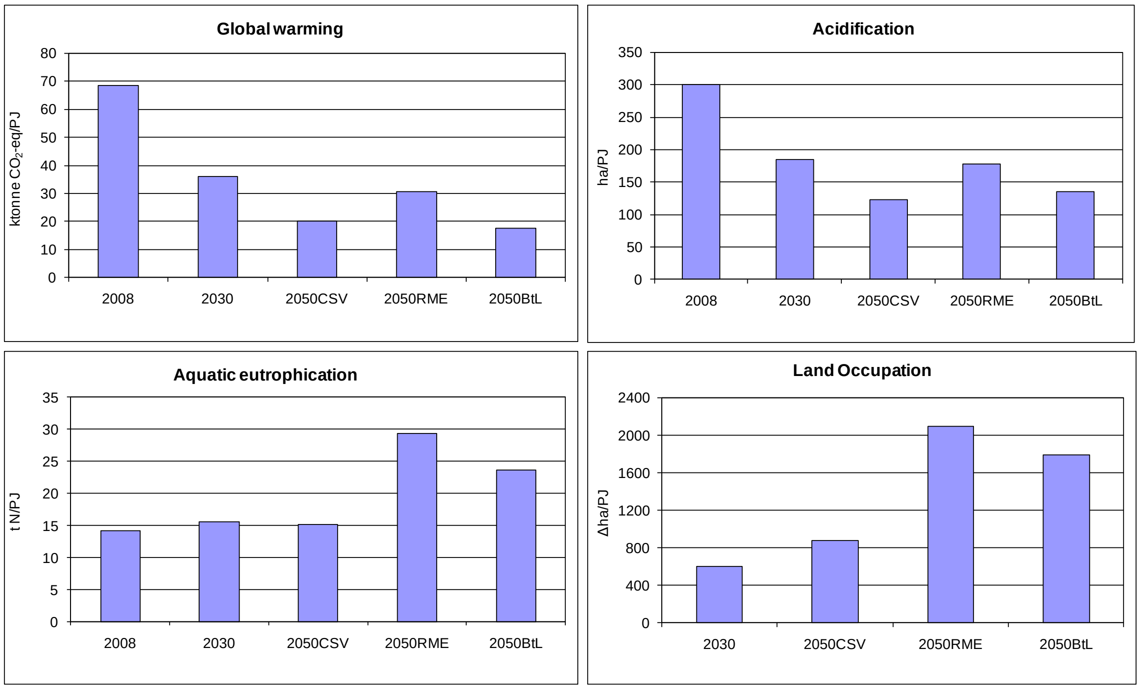

Figure 3.16: Normalized LCA results for selected environmental categories (impact per unit of primary energy supplied by the energy system)

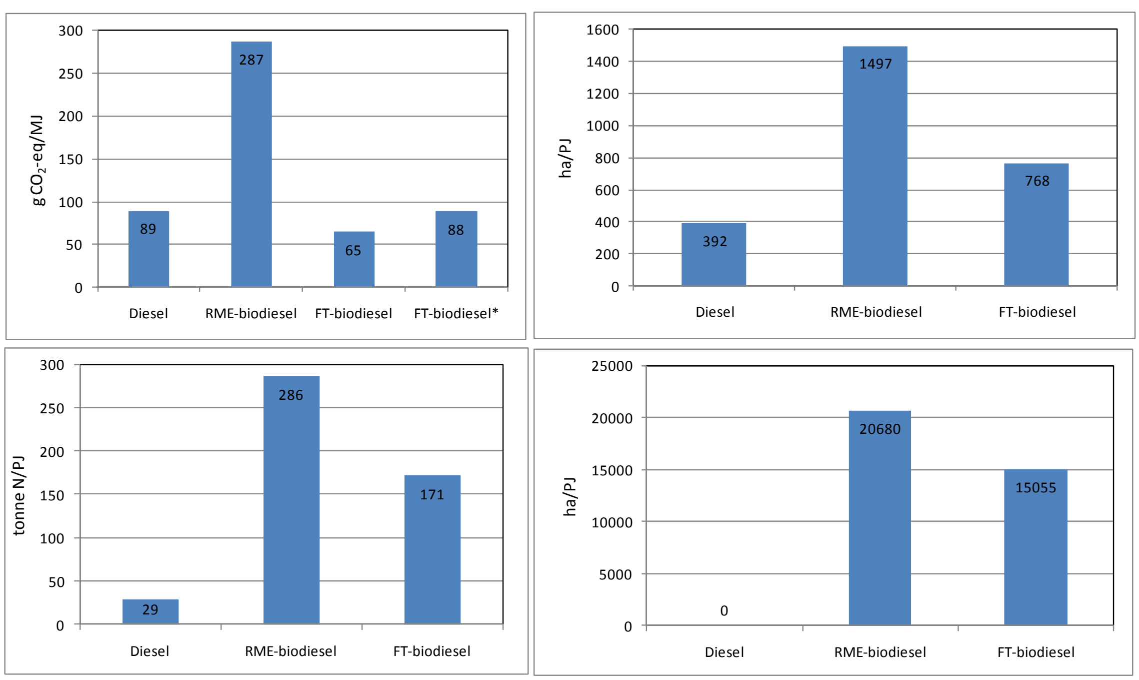

Figure 3.17: Impacts associated with the production and use of biodiesel-like for heavy transport (selected environmental categories)
***Excluding potential environmental benefits associated with biochar from gasification process**

Key methodological advances
The three key methodological advances made in the framework of this project, as listed earlier, are here only briefly summarised, as they are thoroughly detailed in Background Report Part 5.

A comprehensive consequential life cycle inventory database including a total of 432 combinations of crop production systems has been built. For all these combinations, output flows to the environment have been calculated and estimated. This database was necessary in this project in order to assess, with Danish specific data, the environmental consequences of the increased cultivation of relevant energy crops in a 100 % RES system. Such a consequential database represents a significant step forward compared to the databases already available (e.g., LCAfood). It integrates perennial energy crops (e.g. *miscanthus giganteus* and energy willow species such as *salix viminalis* or *salix schwerinii*); the data are disaggregated; a comprehensive load of environmental flows have been taken into account (all of these being based on state-of-the-art agro-ecological balances), and it exhibits a high level of detail. It allows, e.g., the comparison of the effects of: (i) the type of energy crop used, (ii) the soil type used, (iii) the climate type, (iv) the residues management (i.e. incorporation or harvest for energy), (v) the initial soil C level, and (vi) the horizon time for soil C turnover.

In order to fully model the environmental consequences of an increased bioenergy demand caused by a 100 % Danish RES system, a methodology has also been developed to assess the worldwide land use changes occurring as a response to dedicating existing agricultural land to energy crops in Denmark. Such land use changes are also referred to as "indirect land use changes" and have a greenhouse gas implication that must be included in the LCA in order to provide a complete carbon balance. The methodology developed focuses on identifying the amount and type of land that is converted to agriculture as a result of increased bioenergy demand in Denmark, identifying the share of the response coming from agricultural intensification and calculating the resulting environmental flows (essentially GHG). At the time of writing this report, the development of this methodology, which is further described in Background Report Part 5, is still in progress.

Finally, the third key LCA advance made in the framework of this project was the identification of the marginal mineral fertilizers. The results show that nitrogen (N), phosphorus (P) and potassium (K) marginal mineral fertilizers are:

- N: urea (global market) and nitrate-based fertilizers (ammonium nitrate or calcium ammonium nitrate) (European market)
- P: diammonium phosphate
- K: potassium chloride

The rationale behind these results is detailed in Background Report Part 5. These are the mineral fertilizers that should be used in the LCA.

3.5 Future power systems

The general aim of a part of the CEESA project (WP3) has been to qualify the hourly-based scenario analyses of future energy systems by investigating the continuous balancing of the electricity system in the shorter term and relating the scenario findings to the design of future control structures. This is a complex analysis, as the design space for current and future electricity systems is significant; the various technologies of the electricity systems each have their specific characteristics, and the overall system performance is a function of interplay between these technologies.

The analyses were manifested in two main parts each supporting a further development of the EnergyPLAN model. For the first part, one specific technology was selected - namely the analyses of electric vehicle-based (EV) battery storages to support the large-scale integration of wind power in Denmark. The second part encompasses a methodology development for the evaluation, analysis and selection of future control strategies for different power system structures.

The first part has been analysed using dynamic and static power system simulations conducted on Danish case studies of the electrical power system networks. Here Vehicle-to-grid (V2G) systems to provide flexible islanded power system operation were analysed in a distribution network of Lolland-Falster, establishing the condition that V2G may have a positive impact on the frequency stability of the power system. This initial work was followed by a more extensive work on the integration of V2G using the Load Frequency Control (LFC) (secondary control) model in the Western Danish power system; again demonstrating the importance of the role of V2G in future electricity systems. Other analyses of the Danish island of Bornholm have verified that V2G is an attractive alternative in substituting the conventional generator reserves to incorporate large amounts of wind power. Also the relevance of smart charging to effectively integrate the electric vehicles into the electrical distribution system was verified using the primary distribution network analysis on Bornholm.

The second part developed systematic approaches to system level assessment and design of alternative control strategies for future electric power systems. For energy system planning, only strong simplifications of the actual control strategies employed are of interest. It was found that these simplifications are typically based on ‘familiar abstractions’, which are simplifications of notions common in operations today. For future power system operation, some of today’s notions, such as “peak demand” or “base load generation” become less meaningful and thus need to be revised. A general paradigm of flexibility will be supported by probabilistic notions of balancing capacity. For the design of operation strategies, a more explicitly function-oriented and formal modelling approach is advised to keep the system complexity under control: the variety of controllable devices is bound to increase, and thus connection and control requirements should not be formulated with reference to a specific technology. In particular, the fundamental role of synchronous generators as primary suppliers of rapid reserves and frequency stability in power system operation will need to be reconsidered in the longer term. With regard to evaluation, a more explicitly risk-oriented modelling approach will enable an informed selection of future power system operation strategies.

On the other hand, the design of new control structures is an incremental and experimental development. It is based on the current state of knowledge, but it may develop independently and even contradict the familiar abstractions employed for energy planning models. It is therefore imperative to further develop simulation platforms that enable the evaluation of operation strategies in the context of future power system scenarios.

With a high reliance on wind power in the CEESA scenarios, the behaviour of this resource and technology is particularly important. EnergyPLAN does not capture the intra-hour fluctuations that wind power has, but studies of measured wind power time series have shown that the amplitudes of fluctuations scale with the timescale. That is, fluctuations decrease with a decreasing timescale, so that fluctuations below the one-hour level will tend to be smaller than the fluctuations already accommodated for in the EnergyPLAN modelling. The impact of wind power on the power transmission requirements has not been studied explicitly and additional requirements can be expected, in particular for the high wind share scenario. A smart distribution and interconnection of wind farms as well as local balancing with distributed energy storage are expected to mitigate these requirements to some extent, if the appropriate control solutions are implemented. Further studies with the developed simulation tools could quantify this trade-off.

In general, the CEESA scenarios contain many significant changes compared to the present system, and not all impacts of these changes could be analysed. So while the CEESA scenarios have been verified in hourly energy terms, they have not been verified in power terms. Analyses focusing on the role of electric vehicles in power systems have demonstrated, however, that these can have a role to play in future power systems by helping to support the frequency stability of the system. By extension, from these results, it can be claimed that the technologies included in the CEESA scenario with a capability of flexible adjustment (CHP, heat pumps, electrolysers, electric transport and flexible demand) are likely to provide sufficient potential for short-term balancing resources, if it can be activated by implementing the respective policy measures. One may safely claim that frequency stability will not be a fundamental barrier to the implementation of 100% renewable energy systems.

3.6 Policy Design and Implementation Strategies

The objective of the work package on market and public regulation (WP4) has been to define policies and market design in order to make a complete transition from fossil fuels to renewable energy sources in Denmark before 2050. A number of possible policy means of attaining the overall goals of the CEESA scenarios are discussed in this chapter.

It is found that the transition from the present energy system dominated by fossil fuels to a system dominated by renewable energy sources requires significant changes in existing policies, both on the supply and the demand side. This is a change from polluting energy systems that depend on depleting inputs to energy systems that depend on relatively abundant inputs and are relatively non-polluting and intermittent. This change requires a new paradigm. It requires infrastructure which can manage intermittent renewable energy sources in such a way that energy is available at the right time and in the right amount for the consumers. The policy instruments include systems of taxes, subsidies, tariffs, and other economic conditions in order to obtain an optimal effect.

In addition, a number of institutional and regulatory changes are proposed. A central question in this connection is the balance between the role of the market and the role of societal planning and regulation. When the long lifetime of many energy plants and infrastructures, including buildings, is taken into account, it is concluded that the balance needs to change to increase the role of long-term societal planning and regulation. A challenge to the transition planning is how to obtain an efficient co-ordination between investments in electricity, transport, and heating sectors.

A number of macro-economic barriers exist to the transition from fossil fuels to renewables, e.g., in relation to market structures that support "lock-in" to technologies based on fossil fuels. In Denmark, another barrier is the prevalence of high discount rates for the planning of future investments.

Some of the existing barriers can be removed (or reduced) by national changes of tariffs, taxes and other policies, and by changed planning methodologies and priorities at the national level, while others may need changes at the EU level. These changes will require alternative political decisions at high levels in Denmark and the EU. However, the political mechanisms which form the paths to these high-level decisions are not part of this report.

One of the main problems in a future energy system dominated by intermittent renewable sources (e.g., wind and solar energy) is the stability of the electric grid and the security of supply to electricity consumers. In this connection, biomass in different forms plays a central role as a storage element. But biomass is also in demand in the transport sector and for high temperature industrial process heat (transformed to a liquid fuel or to biogas), while the amount of Danish biomass, taking into account other uses of the land area, is rather limited. Due to the limited biomass resources, the CEESA scenario proposes that the best solution is to let electricity from wind and photovoltaic power replace the demand for biomass, where possible, and to stabilize the grid by other means than biomass, where relevant alternatives are available. This includes the systematic use of large heat pumps and heat storage, eventually combined with electric cars. In addition, new and efficient communication systems between energy suppliers and consumers are required, often described as "intelligent grids" or "smart grids". The appropriate policy means should be selected in accordance with these technological solutions.

Our proposals for policy instruments are based on a list of criteria in which highest priority is given to the efficient fulfilment of the overall goal of the CEESA project: 100 %

renewables in the Danish energy supply before 2050. Other criteria include consideration of economic efficiency, social balance in the policies, promotion of Danish employment and industrial production, and policies that support the involvement of the citizens in energy conservation.

We have not attempted to give quantitative numbers of all the proposed economic policy means (taxes, subsidies, tariffs etc.), but we have described the qualitative nature of the schemes supplemented by some quantitative examples. There are not yet many empirical results to indicate the efficiency of the policies. Thus, the policies will have to be adjusted as experience is gained concerning their efficiency. This adjustment is proposed to take place in connection with a bi-annual evaluation of the progress. A general conclusion is that it is not possible to use the same scheme for all sectors and that a democratic and open communication with the energy consumers and producers is important in order to obtain the desired results.

The transport sector has the fastest growing energy consumption and requires the most drastic changes in economic regulation. It is proposed that the taxation of private cars is changed, so that its main component is directly related to the number of kilometres driven per year. This should not await the introduction of an advanced road pricing scheme, but a road pricing scheme should be given high priority. There is an urgent need for investments in improved public transport systems.

Heat and electricity in buildings account for about 40 % of the Danish energy consumption. Stricter building codes have recently been introduced, and they should be updated as improved building designs are developed. The main problem in this sector is that many buildings have a lifetime of 50 to 100 years. Thus, it is not sufficient to wait for the "natural" replacement of the old building mass by low energy buildings. Instead, it is necessary to promote a radical renovation of the existing buildings. This will not be realized in time without significant changes in the present taxation and subsidy schemes. New schemes are proposed in this report. We recommend long-term low interest loans, heat tariffs dependent on consumption (without a fixed part), a graduated building tax related to the energy standard of the building and subsidies for the transformation to low energy houses.

Experience has shown that an efficient reduction of energy consumption by private households requires relatively high levels of energy taxes, but a general high energy tax creates undesired social unbalances. It is proposed to introduce a scheme with a cap on energy consumption where households with consumptions below the defined cap will have a low tax, while households with consumptions above the cap have a strongly increasing tax. In the longer term, this may be supplemented by a Personal Carbon Allowance (PCA) for each individual. The PCA could, in the first phase, be related to the private consumption of fossil fuels per person for heat and electricity, private car driving, and private air transport.

On the supply side, the future energy system will to a large extent rely on renewable sources with an intermittent energy production as wind and photovoltaic power. Offshore wind power has a large role to play and it is increasingly important that tendering procedures for establishing offshore wind farms are improved, especially in relation to economic efficiency and the involvement of citizens as participants. The legal rules for establishing onshore cooperative wind farms should be updated and new partners (e.g., Danish municipalities) should have more favourable possibilities to participate.

District heating systems are expanded, and where this is not possible, efficient individual heat pumps are promoted.

In the long term, the traditional market system (e.g., NordPool) might not be able to handle the large amounts of renewable production in a relevant manner. Today's power markets are mostly based on the marginal pricing principle and large amounts of renewable power production with low or even zero marginal costs reduce the prices on the market to very low levels, thereby creating a barrier to investment in new capacity. Thus, either a totally new market design should be constructed, or the present capacity market for renewable energy should be continued and further developed. A further development of the present system could be based on a flexible feed-in tariff that is adjusted in accordance with the maturing of the technologies and the implementation of the technologies in the energy supply system. The bidding system for offshore wind power projects should be improved to be more competitive.

The investments in the CEESA scenario result in positive socio-economic benefits and in the creation of new "green jobs" – of the order of magnitude of 20,000 new jobs before 2020.

These are some of the most important examples of the subjects treated in the work package on market and public regulation. More details are to be found in the main report and more examples are listed in the following Road Map. The time schedules for the policy changes are illustrated in the Road Map where focus is on the short-term policies as the relevant medium, while long-term policies are more uncertain and depend on the results in the short term.

Road Map for implementing a 100% renewable energy system by 2050:

The following outlines a Road Map related to the policy means of implementing a 100% renewable energy system by 2050. The years indicate the point in time when the proposals are supposed to be in operation. More details are given in the main text. Not all recommendations are included in the Road Map, for practical reasons, and main emphasis has been given to short-term recommendations. The subjects under each period have been listed under subtitles to facilitate the reading. Notice that the road map of this project fulfils the goals indicated in the plan of the new Danish government from October 2011.

2011 - 2015:

Planning, regulations and evaluations

- Completion of a comprehensive energy plan for the Danish transition to 100 % renewable energy supply made and published by the Danish Energy Agency (DEA)

- taking into account reports from the IDA Climate Plan 2050 (*IDA´s klimaplan, 2050*), the present CEESA plan 2011, the Danish Commission on Climate Change Policy (2010), etc. Firm national targets and milestones for the short, medium and long term are needed to attract enough investors.

- Establishment of a municipal energy planning procedure obliging all municipalities to set up detailed energy plans, including technical as well as policy measures.
- Enlargement of the existing energy conservation fund by economic contributions from district heating companies and gas companies.
- Ensuring a planning and investment policy that promotes the expansion of low temperature district heating systems.
- Establishment of a new institution with special responsibility for the technical and economic integration of intermittent renewable energy sources.
- Introduction of a bi-annual progress evaluation of the comprehensive energy plan - including new initiatives, if needed.
- Introduction of schemes that make it attractive for municipalities to own and operate energy plants based on renewables, especially onshore and offshore wind farms.
- Organizations that have cogeneration and/or large heat pump/heat storage systems with required abilities to integrate wind power are given ownership priority in wind energy projects.
- For onshore and near-shore wind turbines, the share which a project developer is obliged to offer to local and regional participants is increased from the present 20% to 60%.
- Establishment of a size limit for onshore wind turbines around 80-110 meters (around 1-2 MW) to protect nature value and reduce local opposition. Exemptions from this restriction may be given under special circumstances.
- Revision of the tendering procedure for offshore wind farms to make it more competitive and more attractive to small investors. The project developer should be required to offer a share of 50% to local and regional participants.
- Change of official discount rate in the planning of future energy systems to below 3 % p.a.
- Alternative systems for the regulation of local CHP production based on waste should be implemented if Denmark cannot obtain exemption from the liberalised EU waste market.

Tariff and tax systems

- Change of district heating tariff systems to phase out fixed charges.
- Removal of tax barriers to investment in large heat pumps in the district heating systems.
- Establishment of a policy that supports investment in large heat pump systems linked to district heating.
- Tax policy that promotes the introduction of certified heat pumps and heat storages in private households.
- Improved energy consultancy and long-term, low interest loans for house renovation financed by an enlarged energy conservation fund.

- The economy of intermittent renewables (e.g. wind and solar) should be based on flexible feed-in tariffs - replacing the spot market (NordPool) for these supply systems.
- Introduction of increased taxes on fossil fuels for industrial production combined with a recycling scheme favouring enterprises that promote significant energy conservation.
- Introduction of a new "green taxation" scheme for private households with a relatively low taxation on the consumption of heat and electricity below a specified cap and increasing taxation for consumption above the cap.
- Change of the annual tax on private cars to depend strongly on the kilometres driven. This change should not await an advanced road pricing system.
- A system should be established that compensate for the changed car tax structure in sparsely populated areas with insufficient public transport facilities.
- Extension of reduced tax on electric cars also after 2015 – until the electric cars are competitive in price on market conditions.
- Prohibition against the installation of new oil-fired boilers in private houses after 2015 and of new natural gas-fired boilers after 2020.

Transport sector:

- Systematic promotion of electric cars via purchase policies of municipalities and other public institutions combined with government subsidies for a national electric car charging system.
- Not higher taxes on fuels for buses and rail transport, than on fuels for air transport inside Denmark in order to establish equal competition between the different means of public transport.
- Improved bicycle paths in all cities and in the countryside with heavy traffic. Promotion of electric bicycles.
- Stronger investments in improved public transport, including fast train connections and improved bus and light rail transport.

Buildings:

- Energy labelling of all buildings combined with graduated green taxes on buildings.
- Investment subsidies for building renovation and installation of renewable energy technologies. This scheme should not allow required building renovations to be replaced by installations of renewable energy technologies.

Smart energy systems:

- The electricity, district heating and gas grids are interconnected and it should be ensured that all the grids are activated on the production and consumer sides.
- The electricity markets in Nord Pool are already able to activate producers and large consumers. Smart metering of electricity should enable electricity buyers to pool small consumer's flexibility and use this in the regulating power market and other markets.
- Smart metering of electricity, heat and gas should ensure that small consumers are aware of their energy consumption and motivate savings by information.

- Establishment of “intelligent metering” (two-way communication) in Danish households (with a yearly demand above a specified level), services and industries, and billing electricity consumers according to an hourly metering.

2015 - 2020:

Taxes and subsidies

- Benchmarking in relation to the energy efficiency of industrial production should be used where possible in connection with green taxes.
- Economic and technological support of the Danish manufacturing industry to promote a change from natural gas to biogas for high temperature processes by appropriate taxation schemes.
- An advanced road pricing system should be introduced before 2020 including the cost of all external social expenses.
- Public subsidies for the replacement of selected old houses by “passive houses”.

Research, development and demonstration (some examples)

- A national solar heating research and test station should be established before 2020.
- Development of new types of supplementary organic materials for biogas production, including algae production and special types of beets.
- Develop and demonstrate gasification technologies.
- Economic support for the research and demonstration of new PV technology, electrolysis, co-electrolyses, and fuel cells.
- Analysis of costs and technical possibilities of the transmission of biogas and/or gasified biomass in the natural gas transmission system in comparison with alternative solutions.
- Analysis of how the electricity market should be changed in order to handle a large proportion of wind- and PV-based electricity.
- Analysis of the effects of different types of ownership structures for renewable energy systems.

Smart energy systems:

- The electricity, district heating and gas grids are interconnected further by ensuring that all the grids are activated on the production and consumer sides in order to activate all feasible storage options.

Special schemes for mitigation of CO_2:

- A comprehensive analysis of the schemes of Personal Carbon Allowances (PCA) and Tradable Energy Quotas (TEQs) should be carried out before 2020.
- High-speed train connections have been implemented between a number of large Danish cities. Most local airports for national air traffic have been closed down.

2020 – 2030

- General evaluation of the Danish transition from fossil fuels to renewables as compared to official national goals. Establishment of a new comprehensive plan, if needed, for the background of climate development and new technological possibilities

- Introduction of supplementary policy means, if necessary, to fulfil the specified goals. Examples may be the scheme of Personal Carbon Allowances and Trading Energy Quotas (TEQs).
- Coal is phased out from the Danish energy supply.
- Most domestic air-traffic has been replaced by fast trains

2030 - 2050

- Oil and natural gas are phased out from the Danish energy supply system between 2030 and 2050.

4 Dissemination and interaction with other projects

As part of the dissemination, a dialogue has been established with industry and other potential beneficiaries. The CEESA project has conducted a work process in which interaction and collaboration with relevant research and development projects have been emphasised. The purpose has been two-fold. First, the CEESA project has been able to continually disseminate results in terms of the development of tools and methodologies by offering and applying these to specific projects and analyses. Second, the CEESA project has been able to benefit from the results both in terms of testing tools and methodologies and in terms of getting specific inputs to the analyses and scenario making of future sustainable energy solutions.

Such interaction and dissemination have included the following projects:

The IDA Future Climate project

In 2009, Aalborg University was involved in the Danish contribution to the international Future Climate – Engineering Solutions initiated by the Danish Society of Engineers, IDA, in which 13 organisations from 12 countries participated in the making of a combined plan to mitigate greenhouse gasses. Future Climate constitutes these organisations' contribution to the United Nations Climate Summit in Copenhagen in December 2009, COP15. The objective in the Danish plan, the IDA Climate Plan 2050, was to document that technically and economically feasible solutions to climate change exist which, at the same time, will ensure a continued positive economic development and an increased security of supply. Aalborg University carried out the technical energy system analyses and analysed the socio-economic consequences in the IDA Climate Plan 2050, which is documented in a technical background report. IDA's Climate Plan 2050 takes a starting point in IDA's Energy Plan 2030 from December 2006. Through workshops, seminars, conferences, and sub analyses the updates and adjustments needed were identified. In 2006, the process was organised in approx. 40 seminars and meetings with over 1,600 participants and, in 2009, additional seminars were organised. The inputs from this process were used in the IDA Climate Plan 2050. The Report was completed during the period from December 2008 to July 2009. IDA's Climate Plan 2050 was released on 11 May 2009 as a public consultation draft. The study is published and documented in (Mathiesen, Lund and Karlsson, 2011) and (Mathiesen, Lund and Karlsson, 2009).

The role of district heating in future renewable energy systems

The tools and methodologies developed during the CEESA project were used as the basis for a study of the role of district heating in future renewable energy systems. Subsequently, the results of the study were implemented in the CEESA analysis. Based on the case of Denmark, the study analyses the role of district heating in future renewable energy systems. At present, the share of renewable energy is coming close to 20 per cent. From such point of departure, the paper defines a scenario framework in which the Danish system is converted to 100 per cent renewable energy sources (RES) in the year 2060, including reductions in space heating demands by 75 per cent. By use of a detailed energy system analysis of the complete national energy system, the consequences in relation to fuel demand, CO_2 emissions and cost are calculated for various heating options, including district heating as well as individual heat pumps and micro CHPs. The study includes almost 25 per cent of the Danish building stock, e.g.., those buildings which have individual gas or oil boilers today that could be substituted by district heating or a more efficient individual heat source. In such overall perspective, the best solution will be to combine a gradual expansion of district heating with individual heat pumps in the remaining houses. Such conclusion is valid in the present systems, which are mainly based on fossil fuels, as well as in a potential future system based 100 per cent on renewable energy. The study is published and documented in (Lund. Möller, Mathiesen and Dyrelund, 2010) and (Möller and Lund, 2010).

EnergyTown Frederikshavn

Prior to the CEESA project in 2006, a number of Danish energy experts made the proposal that Denmark should convert the supply of a specific town to 100 % renewable energy by 2015. The experts pointed to Frederikshavn in the northern part of Denmark for a number of reasons: The town area of 25,000 inhabitants is well defined, the local support is high, and Frederikshavn already has a number of large wind turbines at the harbour. In February 2007, the city council unanimously decided to participate in the project and initiated a project organisation involving utilities and municipality administrators. Moreover, the local industry and Aalborg University were involved in the project. The tools and methodologies further developed during the CEESA project were used as a basis for the analyses. Moreover, the two projects joined forces in the development of tools for the analysis of geothermal energy in combination with waste used for CHP, in which the synergy between absorption heat pumps and steam production can be utilised together with steam storage options. The analyses

- presented the methodology of mapping the existing energy system, including transport, and defining the share of renewable energy, which is approx. 20 per cent in the present situation.
- introduced a proposal for a potential 100 % renewable energy system for year 2015 and a number of realistic short-term first steps, which would take Frederikshavn to approx. 40 per cent by 2009 or 2010.
- described detailed hour-by-hour energy system analyses of the proposal for a 100 % renewable energy system.
- and related the proposal to the perspective of converting Denmark to a 100 % renewable energy supply system.

The study is published and documented in (Lund and Østergaard, 2010) and (Østergaard and Lund, 2010).

Long-term Energy vision for Aalborg Municipality

The Sustainable Energy Planning Group at Aalborg University created a long-term energy vision for Aalborg Municipality based on the experience and methodologies accumulated in the CEESA project and related projects. At the same time, the study was incorporated as a case study of the design of public regulation measures defined in the CEESA project. The project has demonstrated how it is possible to meet all energy requirements using only locally available resources through a combination of ambitious energy savings, wind power, biomass and waste resources, biogas and geothermal energy. However, there are some requirements of reaching the ambitious goal of 100 % renewable energy use. Biomass resources must be reserved for industry, transport and industrial use only. Individual houses must either rely on heat pumps or be connected to district heating systems. Low-temperature geothermal energy in combination with absorption heat pumps seem promising for district heating production. This is an impetus to connect most of the district heating networks in the municipality, leaving only two distant networks outside the co-operation. Analyses have also focussed on the implementation of the ambitious heat savings and have looked into changes in the pricing mechanisms for district heating; mechanisms that will both preserve an economically viable district heating sector but also give district heating consumers incentives to conserve energy. The study is published and documented in (Østergaard et. al., 2010).

The NIK-VE project (Energy visions for the North Denmark Region)

The visions in the NIK-VE project are to have a future fossil-free and ash-free energy supply, where the materials and nutrients are used in a closed circuit; combustion is avoided as far as possible, and emissions are reduced to a minimum. In the project, the set-up scenarios only concern the northern part of Jutland, and scenarios are made for three years: 2007 (reference case), 2025 and 2050. In the 2025 scenario, biomass, the integration of renewable power supplies into the electricity system, and the development of hybrid vehicles based on batteries and fuel cells are developed. In 2050, no fossil fuels are used; biomass is used mainly for producing biogas and biodiesel to be used in the transport sector and not for heating or electricity supply; and the renewable energy supplies constitute an even larger share of the power production. Even though the scenarios are not the same as in the CEESA project, a lot of information has been shared among the NIK-VE and the CEESA projects, since the basic principles were based on the same ideas, and important synergy has been created in the discussions of the different scenarios in the two projects, including the composition of the future energy supply.

Interaction with Zero Energy/Emission Buildings project (ZEB)

The CEESA scenarios will be used in the Strategic Research Centre of Zero Energy Buildings, investigating the role of buildings in future renewable energy system. The preliminary results of the CEESA project during 2010 have formed the basis for the first investigations, leading to a conference paper in 2010 and a journal paper published in 2011.

Interaction with the iPower (SPIR) project

The methods developed for studying control architecture of future power systems will be considered in the Strategic Research and Innovation project “iPower”, launched in the spring of 2011. The challenge of interfacing economic evaluation and control structures at different levels of aggregation is a central issue in this project.

Danish Wind Power - Export and Cost

In a normal wind year, Danish wind turbines generate the equivalent of approx. 20 % of the Danish electricity demand. An analysis made by the CEESA group establishes that only approx. 1 per cent of the wind power production is exported. The rest is used to meet domestic Danish electricity demands. The cost of wind power is paid solely by the electricity consumers and the net influence on consumer prices was as low as 1-3 % on average in the period 2004-2008. In 2008, the net influence even ***decreased*** the average consumer price, although only slightly. In Denmark, 20 % of the wind power is integrated by using both local resources and international market mechanisms. This is done in a way which makes it possible for our neighbouring countries to follow a similar path. Moreover, Denmark has a strategy to raise this share to 50 % and the necessary measures are in the process of being implemented. The cost of CO_2 reduction by use of wind power in the period 2004-2008 was only 20 €/ton. Furthermore, the Danish wind turbines are not paid for by energy taxes. Danish wind turbines are given a subsidy via the electricity price, which is paid by the electricity consumers. In the years 2004-2008, such subsidy has increased consumer prices by 0.54 €¢/kWh on average. On the other hand, the same electricity consumers have also benefitted from the wind turbines, since the wind power has decreased the electricity market price on Nord Pool. On average, during 2004-2008, such effect decreased the consumer prices by 0.27 €¢/kWh and, consequently, the net influence during this period increased consumer prices by only 0.27 €¢/kWh, equal to only 1-3 % of the final consumer prices. In 2008, the net influence of wind power actually ***decreased*** the consumer price by approx. 0.05 €¢/kWh. Consequently, the influence of Danish wind turbines on the consumer electricity price is negligible. The study is published and documented in (Lund et al., 2010).

Publications generated by the CEESA project

Background reports

Part 1:
Mathiesen, B.V.; Lund, H.; Hvelplund, F.K.; Connolly, D.; Bentsen, N.S.; Tonini, D.; Morthorst, P.E.; Wenzel, H.; Astrup, T.; Meyer, N.I.; Münster M.; Østergaard, P.A.; Bak-Jensen, B.; Nielsen, M. P.; Schaltz, E.; Pillai, J.R.; Hamelin, L.; Felby, C.; Heussen, K.; Karnøe, P.; Munksgaard, J.; Pade, L.; Andersen, F.M.; Hansen, K.: "CEESA 100% Renewable Energy Scenarios towards 2050".

Part 2:
Mathiesen, B.V.; Connolly, D.; Lund, H.; Nielsen, M. P.; Schaltz, E.; Wenzel, H.; Bentsen, N.S.; Felby, C.; Kaspersen, P.; Hansen, K.; "CEESA 100% Renewable Energy Transport Scenarios towards 2050".

Part 3:
Østergaard, P.A.; Heussen, K.; Pillai, J.R.; Bak-Jensen, B.; Lind, M: "Electric Power Systems for a Transition to 100% Renewable Energy Systems in Denmark before 2050"

Part 4:
Hvelplund, F.; Meyer, N.I.; Morthorst, P.E.; Munksgaard, J.; Karnøe, P.; Hasberg, K.S.: "Policies for a Transition to 100% Renewable Energy Systems in Denmark before 2050".

Part 5:
Astrup, T.; Tonini, D.; Hamelin, L.; Wenzel, H.: "Environmental Assessment of Renewable Energy Scenarios towards 2050"

Journal Articles and Book Chapters

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Appendix 1: Design of Initial Scenarios

The Initial CEESA scenarios mentioned in chapter 1.1 are based on the two IDA 100 per cent RES scenarios of the Danish Society of Engineers described among others in the paper "Energy System Analysis of 100 Per cent Renewable Energy Systems" (Lund and Mathiesen, 2007). The two additional scenarios have been calculated simply by increasing the following demands to the level of the year 2004 (see overview in the table):

- The electricity demand of 29.45 TWh/year is increased to 35.54 TWh/year.
- District heating demand (including grid losses) is increased from 25.96 to 38.48 TWh/year and the hourly distribution is adjusted accordingly. (In the high-demand scenarios the duration curve equals the present shape, while in the low-demand scenarios, the shape is decided by savings done solely in the space heating demand (not grid loss and hot water))
- Individual heating is increased from 6.43 to 18.19 TWh/year (measured in net-heating demand and not fuel demand). The huge difference is caused partly by insulation (the hourly distribution is altered accordingly) and partly by including more houses in the district heating system in the low-demand scenario.
- Fuel demand for industry is increased from 26.23 to 41.28 TWh/year.
- The transport sector is the same, since the low-demand scenario is based on the principle of stabilising the transport work at the 2004 level. However, the fuel consumption is different, since the IDA scenarios involve a long list of initiatives replacing oil by electricity, hydrogen and biofuels, together with a shift from air and car transport to ships and trains.
- In both scenarios, the present year 2004 fuel consumption for the production and refining of oil and gas is excluded from the demands.

In all other aspect, all four scenarios are the same.

The main inputs and results are shown in the table below:

TWh/year	Low demand Biomass (IDA scenario)	Low demand Wind (IDA scenario)	High demand Biomass (2004 demand)	High demand Wind (2004 demand)
Electricity demand (TWh/year)	29.45		35.54	
District heating demand	25.96		38.48 *)	
(TWh/year)	6,43		18.19 **)	
Individual net heating (TWh(year)	26,23		41.28	
Industry (TWh/year)	35,08		35.08 ***)	
Transport (incl. air and ship)	0.00		16.88	
(TWh/year)				
North sea (Oil&gas production) + raff	96.92		96.92	
Total (demands) (TWh/year)				
Large FC CHP plants	64% el / 26% heat			
Small FC CHP plants	54% el / 36% heat			
Solar thermal	5,22			
Wave power	3,00			
Photo Voltaic	1,50			
Results (Primary Energy Supply)				
Solar thermal, Wave and PV	9.72	9.72	9.76	9,76
Wind Power (TWh/year)	18.71	53.79	18.71	72,88
Biomass (TWh/year)	91.92	55.75	144.16	85,64
Total (TWh/year)	120.35	119.26	172.63	168,28
Wind capacity (MW)	6,000	15,000	6,000	20,000
Electrolysers (MW-e)	6,000	16,000	8,500	18,500
Hydrogen storage (GWh)	200	3200	200	3200
CO_2-emission (Mt/year)	0	0	0	0

*) Divided into 2.22 + 14.03 + 22.23 = 38.48
**) Net heating demand (Fuel demand is 22.35 TWh/year)
***) Transportation is the same, however the fuel demand in 2004 was higher (56.33 TWh) due to less electricity and less trains and ships etc.

	JP	Petrol	Fuel/diesel	Ngas	Coal	Biomass
Individual. heating			8.51	8.48	0.01	5.35
Industry			17.78	16.34	2.47	4.69
Transport (relative on basis of 2030 numbers)	10.79	23.16	22.39			
North sea + raff.			8.17	8.71		

The CEESA project (Coherent Energy and Environmental System Analysis) presents technical scenarios as well as implementation policies and a road map of Denmark's transition from a fossil fuel-dominated energy system to a supply system based completely on renewable energy with a dominating part of intermittent sources like wind and solar power. Energy conservation and a certain technological development are prerequisites for this transition. The CEESA scenarios show how the transition can be performed before the year 2050 mainly by the use of known technologies combined with significant energy conservation.

The CEESA project has a focus on, among others, transport, electricity power systems and environmental assessment. The need for new systems thinking and new planning principles for energy investments is among the important observations in this scenario project. With dominant contributions from intermittent sources and limited amounts of biomass available, storage problems are solved by integrating the electricity, heat and transport sectors much more than in traditional supply systems based on fossil fuels. The CEESA project shows how this can be done in an efficient and economical way.

CEESA is a multidisciplinary co-operation which combines the forces of leading Danish researchers in the fields of energy and environment. The project is financed by the Danish Council for Strategic Research together with the participating parties and was conducted in the period 2007-2011.

The results of the CEESA project are presented in 5 background reports and a main summary report.

CEESA main report:

- Coherent Energy and Environmental System Analysis

CEESA background reports:

- Part 1: CEESA 100% Renewable Energy Scenarios towards 2050
- Part 2: CEESA 100% Renewable Energy Transport Scenarios towards 2050
- Part 3: Electric power systems for a transition to 100% renewable energy systems in Denmark before 2050
- Part 4: Policies for a Transition to 100% Renewable Energy Systems in Denmark Before 2050
- Part 5: Environmental Assessment of Renewable Energy Scenarios towards 2050

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