RENEWABLE METHANOL

An analysis of technological potentials in light of the EU biofuels policy objectives of Greenhouse Gas Savings, Security of Supply and Employment

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Master's Thesis
June 2013

Sustainable Energy Planning and Management

Aalborg University

Preamble

You are a smoker who smokes 20 cigarettes every day. The doctor tells you that you have to quit completely or it will kill you. Your response is to cut consumption by 10% until 2020. But by 2020, you will still be smoking 18 cigarettes per day! Clearly not a solution - something radical has to happen.

In order to eliminate your addiction completely, you need a plan. This Master's Thesis is an important part of such a plan, which aims to radically reduce greenhouse gas emissions in the European transport sector while securing energy independence and creating hundreds of thousands of jobs.

Per Sune Koustrup,
CEO Nordic Green

Preface

This Thesis was conducted during the fourth semester of the MSc. programme *Sustainable Energy Planning and Management* under the Department of Development and Planning at Aalborg University.

It intends to fulfill the final requirements for attainment of the abovementioned academic degree of Master of Science in Sustainable Energy Planning and Management.

The period of writing was 10.02.2013 – 10.06.2013, under the supervision of Assistant Professor Karl Sperling of Aalborg University and Per Sune Koustrup of Nordic Green in Aarhus. I thank them both greatly for their dedicated guidance and indispensable input throughout the entire course of this semester.

Furthermore, I thank my brother Daniel for his helpfulness and valuable linguistic assistance.

Ultimately and with all my heart, I want to express my deepest gratitude to Regina and Nina: without your love, your tolerance and your unlimited support in the last years, I could not have done it. This is for you.

Anybody who has been seriously engaged in scientific work of any kind realizes that over the entrance to the gates of the temple of science are written the words: 'Ye must have faith.'

Max Planck

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Abstract

Despite a number of successful European pilot projects and early commercial activities, there remains little eminent acknowledgement of renewable methanol as alternative transport fuel within the current political discourse on future sustainable mobility in the EU. To a large extent this is due to a lack of research findings on the specific potentials of renewable methanol as a viable fuel alternative in the European context. In order to expand the existing knowledge base in this respect, in this Master's thesis it is assessed how renewable methanol technology can contribute to achieving the three explicit objectives of EU biofuels policy: *Greenhouse Gas Savings, Security of Supply* and *Employment*. This research objective is approached by way of quantitative and qualitative analyses which in this form have not yet been undertaken.

With regard to *Greenhouse Gas Savings*, the potentials of renewable methanol are assessed by way of the Well-to-Wheels (WTW) analysis method for different renewable methanol pathways, as well as comparative fossil- and biofuel pathways. The findings of this analysis demonstrate that renewable methanol technology holds high potentials and favourable prospects: while the EU regulations on minimum greenhouse gas emissions savings of biofuels will become gradually more stringent in the coming years, the investigated renewable methanol fuel pathways not only generally comply with these regulations but far surpass them. In some cases, emissions savings of more than 90% compared to both fossil fuels and first generation biofuels can be achieved.

In view of the policy objective of *Security of Supply*, the feedstock-flexibility of renewable methanol technology is found to be a fundamental prospect since it enables the utilisation of wastes and other feedstocks which so far have been under-utilised in the production of biofuels. An evaluation of sectorial supply and demand projections for bioenergy-resources in 2020 demonstrates that feedstock availability is not expected to present a barrier to introducing and deploying renewable methanol technology on a large scale in the EU. Moreover, EU trade balance effects are modelled which promise a high potential for monetary savings if the currently projected biofuel imports to the EU in 2020 were to be substituted with domestically produced renewable methanol.

With regard to the *Employment* objective, the potential job creation effects of deploying renewable methanol technology in the EU are assessed, indicating significant potentials: two prospective outlooks on employment creation are modelled, in one case suggesting that up to 150,000 new jobs could be created in 2020 if domestically produced renewable methanol were to substitute the projected biofuel imports to the EU.

Based on the findings of these core analyses, political recommendations are formulated and discussed, aiming to offer policy-makers indications on how to activate the deployment of renewable methanol technology in the EU, and thereby optimising sustainable energy planning in the European transport sector in general.

List of abbreviations, units and chemical formulas

Abbreviations

1G	First generation
2G	Second generation
BEV	Battery-electric vehicle
CI	Compression ignition
CRI	Carbon Recycling International
DI	Direct injection
DME	Dimethyl ether
EC	European Commission
EROEI	Energy returned on energy invested
ETBE	Ethyl tert-butyl ether
EU	European Union
FCV	Fuel cell vehicle
FFV	Flex-fuel vehicle
FSU	Former Soviet Union
FQD	Fuel quality directive
GDP	Gross domestic product
GHG	Greenhouse gas
ICE	Internal combustion engine
ILUC	Indirect land-use change
MTBE	Methyl tertiary butyl ether
PM	Particulate matter
RED	Renewable Energy Directive
RES	Renewable energy system
RME	Rapeseed methyl ester
RON	Research Octane Number
RQ	Research question
SI	Spark ignition
SOEC	Solid oxide electrolyser cell
SRF	Short rotation forestry
TAME	Tert-amyl methyl ether
TTW	Tank-to-wheels
WTT	Well-to-tank
WTW	Well-to-wheels
USD	U.S. Dollar
VOC	Volatile organic compounds

Units and chemical formulas

%	Percentage
°C	Degrees Celsius
a	Year
CH_4	Methane
CH_4O / CH_3OH	Methanol
CO	Carbon monoxide
CO_2e	Carbon dioxide equivalent
E / e	Greenhouse gas emissions
EJ	Exajoule
H / η	Energy conversion efficiency
g	Grams
GW	Gigawatt

H_2S	Hydrogen sulphide
hl	Hectolitre
kcal	Kilocalories
km	Kilometre
kt	Kilotonne
MB	Million Barrels
MJ	Megajoule
mol	Mole
Mt	Megatonne
Mtoe	Million tonnes of oil equivalent
MW	Megawatt
N_2O	Nitrous oxide / laughing gas
nm	Nautical miles
NO_x	Nitrogen oxides
SO_x	Sulfur oxide
toe	Tonne of oil equivalent

List of figures, tables and images

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1 - Introduction: the challenge of reducing oil dependence in an increasingly mobile global society

The global depletion of natural resources, ecological degradation, and the threatening implications of climate change are critical pressures which have led to comprehensive national and international efforts to begin the transformation towards energy systems based on renewable resources. This implies all-encompassing structural reforms and poses particularly formidable challenges in the transport sector, which accounts for more than half of global oil consumption today and relies almost completely on fossil fuels (see Figures 1.1 and 1.2) [IEA 2012b; WEC 2011].

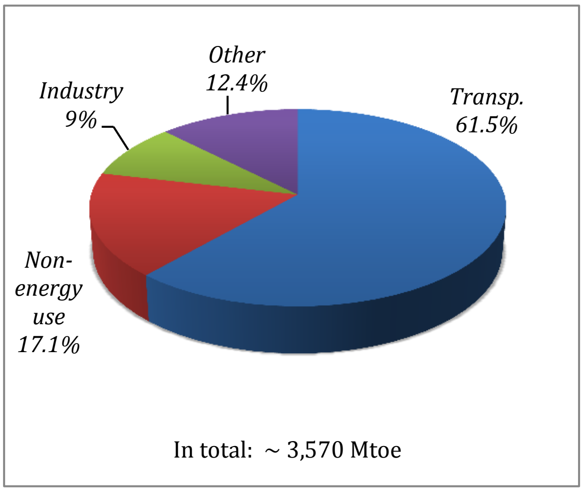

Figure 1.1 - Sectorial shares in world oil consumption in 2010 (%) [own illustration, based on IEA 2012b]

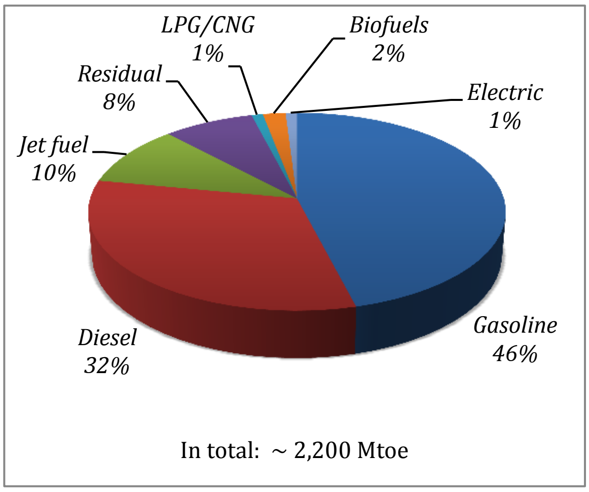

Figure 1.2 - Modal shares of world energy consumption for transport in 2010 (%) [own illustration, based on WEC 2011]

Global oil consumption in the transport sector will strongly increase as the demand for motorized individual transport and road freight continues to rise, particularly in developing and emerging countries (see Figures 1.3 and 1.4) [EIA 2013]. Against this backdrop, new technologies and alternative mobility concepts are being developed, aiming to tackle the challenge of reducing modern society's great dependence on oil.

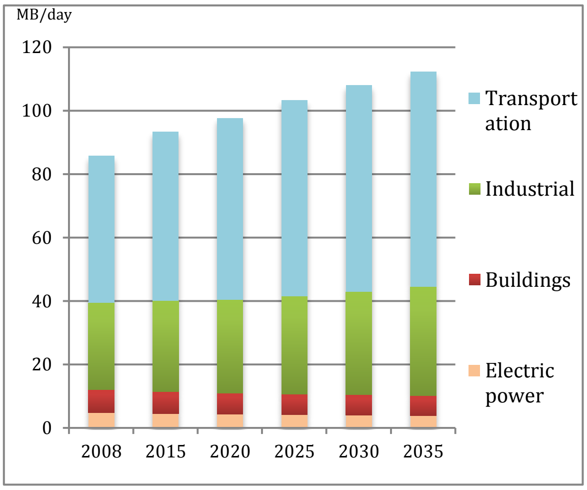

Figure 1.3 – World liquid fuel consumption (MB/day) 2008–2035, by sector [own illustration, based on EIA 2013]

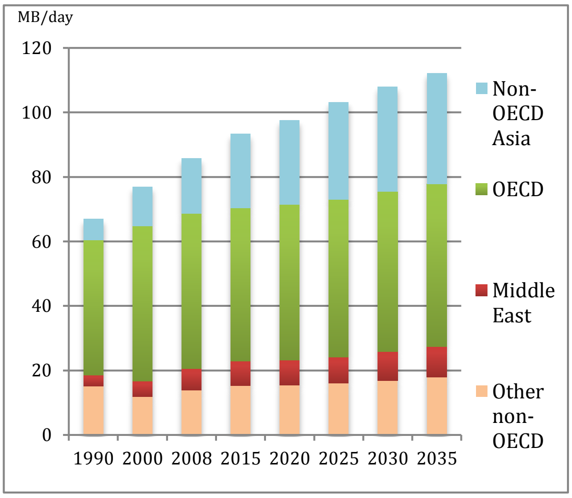

Figure 1.4 – World liquid fuel consumption (MB/day) 1990–2035, by region [own illustration, based on EIA 2013]

In what follows, the background and further context of this research are described. Section 1.1 introduces the reader to alternative and established mobility concepts, limits the research focus to the European Union (EU) transport sector and demonstrates its increasing greenhouse gas (GHG) emissions as well as its large dependency on petroleum imports. Section 1.2 describes the present development of biofuels in the EU and points towards advanced biofuels as integral components of a sustainable mobility future. Moreover, it puts focus on renewable methanol as the core topic of investigation and describes the need for specific research concerned with its potentials and prospects in a European context. In section 1.3, the concrete research questions of this study are particularised, and the analytical structure of the study is described and illustrated.

1.1 - Alternative mobility concepts, EU transport sector greenhouse gas emissions and petroleum import dependency

Over the years, numerous scientific and non-scientific publications have emphasised different technological concepts in their outlooks, roadmaps and recommendations for future transportation. In equal measure, the medial discourse has produced different technologies as being feasible mobility concepts of the future. This multitude of highlighted technological approaches clearly shows that there is no single and outstanding road towards sustainable transportation, but that future mobility will depend on a mix of technological concepts and strategies which are currently being pursued.

Two predominant future mobility concepts which have been undergoing immense research and development activities in the past few years are hydrogen-mobility and electric mobility concepts. Advocated by different groups of politicians, scientists, and industry stakeholders, it is likely that these concepts will play increasingly important roles in the future. However, a global transport sector fully based on hydrogen or renewable electricity in fact remains a distant future scenario. Technological immaturity and often poor economic feasibility remain strong barriers to be overcome. Although for road transportation, battery-electric vehicles (BEV) have recently shown promising progress in this regard and are increasingly deployed, hydrogen-based fuel cell vehicles (FCV), which for years had been deemed by many as the sustainable transport technology per se, continue to struggle with their need for impractical technical infrastructure and, in the foreseeable future, cannot be offered at reasonable cost [Winterkorn 2013; Olah et al. 2009].

Against this backdrop it remains most likely that for decades to come, the majority of land-, sea-, and air-based vehicles will continue to rely on internal combustion engines (ICE) which today are used in more than 99% of all transport applications, thereby relying on relatively cheap and abundant materials such as iron. Importantly, besides being a well-established propulsion technology, the ICE can rely on a long-existent sophisticated transport and distribution infrastructure for liquid fuels which are stored and handled relatively easily.

Consequently, even as BEV, FCV or miscellaneous hybrid systems increasingly penetrate the land-based transportation sector, maximum efficiency gains and the use of alternative fuels in

ICE technology pose the largest realistic potential for the transport sector to achieve global-scale environmental improvements and increased independence from oil in in the medium-term.

Due to the global political and societal goal of reducing GHG emissions [UN 1992], legislation is accordingly being constantly put into place in many countries across all continents. More or less ambitious GHG emission reduction targets go hand in hand with new transport sector-specific regulations such as vehicle emissions-limits or alternative fuel blending requirements.

The study at hand focusses on the situation in the EU where, while GHG emissions in other sectors have generally been falling, transport-related GHG emissions have increased by more than 30% since 1990 [EC 2013c]. This trend is illustrated in Figure 1.5. Figure 1.6 shows that road-based transport accounts for by far the largest share of all GHG emissions from the transport sector.

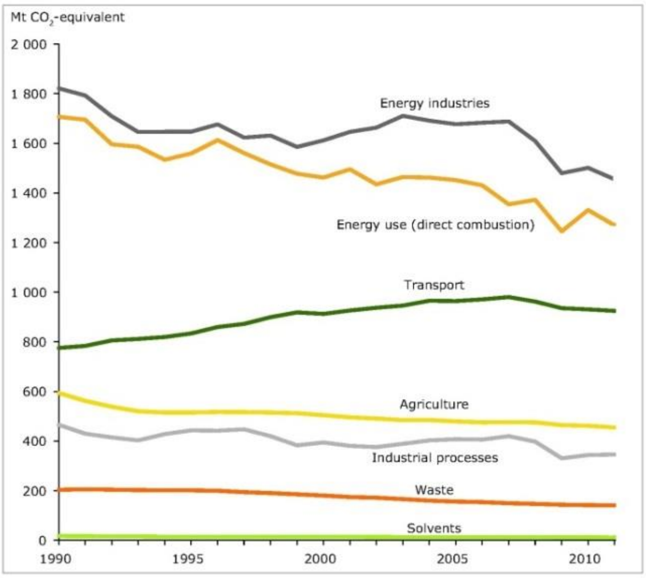

Figure 1.5 – EU GHG emissions 1990-2011 (Mt CO_2e/a), by sector [adapted from EEA 2012]

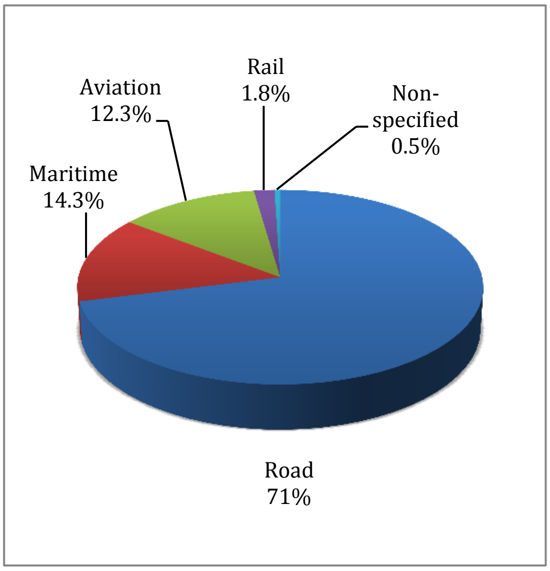

Figure 1.6 – Shares of GHG emissions in EU Transport sector 2009 (%), by mode [adapted from EEA 2012]

Against this backdrop, the EU member states are obligated through the *Renewable Energy Directive* (*RED*) [EU 2009a] to assure that by the year 2020 at least 10% of their respective transport energy consumption is covered by renewables. Achieving this objective corresponds to replacing an estimated 50 billion litres of fossil transportation fuels in 2020 [Bentsen and Felby 2012].

Besides reducing GHG emissions, these policies are also to be seen as part of the EU strategy to reduce its heavy dependence on petroleum imports: at 32% in 2010, transportation accounted for the largest share of final energy consumption in the EU, ahead of the residential and industrial sectors (see Figure 1.7). Roughly 94% of this transport consumption was based on petroleum of which roughly 84% was imported [EUROSTAT 2012], a continuing trend over the last decade (see Table 1.1). In 2011, petroleum imports represented a daily bill of up to 1 billion € and brought about a significant EU trade balance deficit of roughly 2.5% of GDP [EC 2013a]. Furthermore, over the past four years price shocks have caused additional annual costs of 50 billion € [EC 2013a].

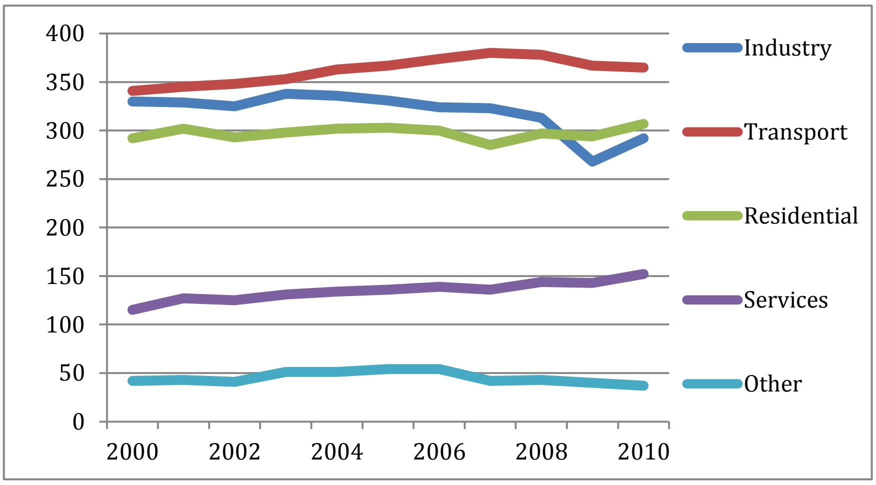

Figure 1.7 - Final energy consumption (Mtoe/a) in the EU 2000-2010, by sector [EUROSTAT 2012]

Year	EU petroleum imports (%)
2000	75.7
2001	77.3
2002	75.9
2003	78.5
2004	79.8
2005	82.3
2006	83.5
2007	82.4
2008	84.2
2009	83.1
2010	84.3

Table 1.1 – Development of EU import dependency on petroleum fuels 2000-2010 [EUROSTAT 2012]

1.2 - 1G and 2G biofuels, renewable methanol and the need for EU-specific research on its potentials and viability

As indicated above, alternative renewable fuels, in particular liquid biofuels, have been designated to play a central role in mitigating GHG and reducing the EU's dependency on petroleum imports. Since being promoted through various political measures such as blending requirements or according national subsidization and taxing schemes, their production has grown continuously, reaching 13 Mtoe in 2010, a share of 4.4% of total transport fuel consumption in the EU (see Figures 1.8 and 1.9[1]). As such, biodiesel fuels constitute roughly 75%, while other biofuels, particularly ethanol, account for the remainder [EU 2012]. Mostly, these fuels are blended with conventional fossil fuels in order to be compatible with the present vehicle and fuel infrastructure. Higher or pure blends may require minor adaptations [EC 2013a].

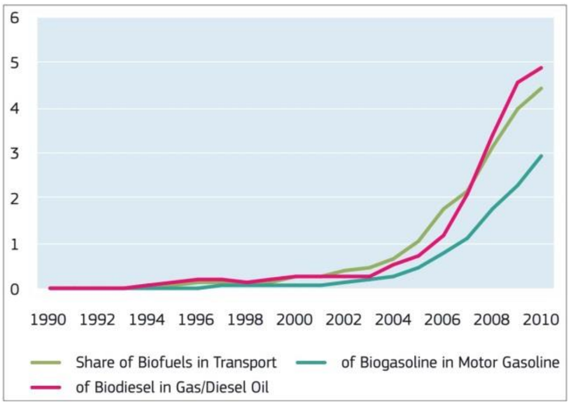

Figure 1.8 – Development of biofuels production in the EU (ktoe/a) 1990-2010 [EU 2012][1]

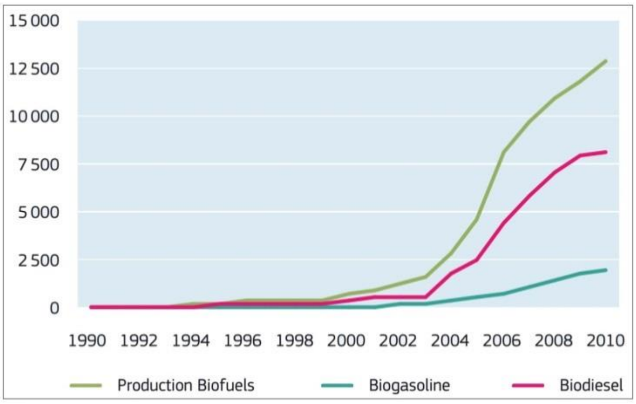

Figure 1.9 – Development of biofuels shares (%) in EU transport fuel consumption 1990-2010 [EU 2012][1]

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[1] The red *Biodiesel* curve here accounts for biodiesel, biodimethylether, Fischer-Tropsch diesel, cold-pressed plant oil and other liquid biofuels which are added to, blended with or used straight as transport diesel. The blue *Biogasoline* curve represents mainly bioethanol but also accounts for biomethanol, bio-ETBE and bio-MTBE [EU 2012; EUROSTAT 2013].

The total generation of GHG savings through biofuels in the EU in 2010 is estimated at 25.5 Mt of CO_2e [EC 2013a]. This estimation, however, does not include the effects of associated agricultural intensification and indirect land use changes (ILUC). Accurately quantifying GHG emissions of these effects is a difficult undertaking which entails a high degree of uncertainty. However, it is likely that these effects significantly reduce the estimated GHG savings proclaimed so far.

In recent years, an intensive scientific and political debate on how to deal with the implications of ILUC has taken off [Elbersen et al. 2012; EC 2012b]. Moreover, the ongoing discourse on limitations in land and resources for the production of biofuels, and on their negative impacts on biodiversity, ecosystem services and food prices [Ecofys 2012; CIFOR 2012], has led to a shift in public attitude and political perspective towards further growth of so-called first-generation (1G) biofuels which are essentially based on food crops. In order to minimize these negative impacts, advanced, so-called second-generation (2G), biofuels which are produced from wastes and residues, or from cellulosic non-food materials and lignocellulosic materials, are being increasingly promoted by EU policy makers [EC 2012b; EC 2013a]. However, mostly they stand in early stages of commercial development and are not yet produced on scales large enough to meet the EU blending quotas for renewable transport fuels [EU 2009a; EU 2009b].

In view of the apparent negative implications and according problematic outlook for 1G biofuels, research and development in the field of advanced 2G biofuels is of great importance in order to pave the road towards a sustainable mobility future. Thereby, the explicit objectives of EU biofuels policy remain [EC 2008]:

- *Greenhouse Gas Savings*: Whilst GHG emissions in the EU are otherwise declining, they continue to grow in the transport sector. Biofuels are a vital component to mitigating this development and to establishing sustainable mobility and a low-carbon economy in the coming decades.

- *Security of Supply*: The transport sector's near-complete dependence on imported petroleum products makes the EU economy vulnerable to geopolitical instability and oil price volatility. This implies major risks for the EU economy and inner security. Biofuels are an important component to reduce this foreign dependence.

- *Employment*: Biofuels open up new domestic and foreign markets and create jobs along their entire value chain. This can be of significant economic benefit, particularly in rural and underdeveloped areas of the EU.

In light of these explicit objectives of EU biofuels policy and the strong need for research in the field of advanced 2G biofuels, the study at hand highlights renewable methanol, which recently has been attracting increasing scientific attention [Olah et al. 2009; Bromberg & Cheng 2010; IRENA 2013]. Existing research on renewable methanol has been undertaken selectively and at scattered geographic ends, indicating encouraging prospects in terms of achievable GHG savings and its potential for energy storage and as a compatible transport fuel alternative in future energy systems with high shares of renewable electricity [Lund et al. 2011; Mortensgaard et al. 2011].

However, despite successful European pilot projects and early commercial activities in this field, there remains little eminent acknowledgement of renewable methanol as an alternative transport fuel within the current political and public discourse on future sustainable mobility in the EU [EC 2013c; IRENA 2013; CIFOR 2012]. To a large extent this is due to a lack of research findings on the specific potentials of renewable methanol as a viable fuel alternative in the European context.

Thus, in light of the desired sustainable development in the transport sector, there exists a clear need for research which assesses the suitability and applicability of renewable methanol fuel in the concrete case of the EU. In order to expand the existing knowledge base in this respect, this study's main aim is to assess how renewable methanol technology can contribute to achieving the three explicit objectives of EU biofuels policy: *Greenhouse Gas Savings*, *Security of Supply* and *Employment*. This research objective is approached by way of quantitative and qualitative analyses which in this form have not yet been undertaken.

1.3 - Research questions, analytical approach and description of study structure

The elaborations on the need for EU-specific research on renewable methanol in the above section give rise to the formulation of the following main research question (RQ) which is to be addressed in the course of the analyses of the study at hand:

- *Main RQ: Which potentials does renewable methanol technology possess in regard to the EU biofuels-policy objectives of Greenhouse Gas Savings, Security of Supply and Employment?*

In order to investigate these issues in a well-structured, successive, and logically sound manner, this study is divided into a number of chapters with according objectives for knowledge creation:

After describing the general analytical framework and important methodological issues in chapter 2, chapter 3 gives a comprehensive overview on various technical aspects of renewable methanol, its chemical and physical properties as transport fuel in ICE, and on different concepts for its production.

Chapter 4 assesses the potentials of renewable methanol with regard to the EU biofuels-policy objective of *Greenhouse Gas Savings.* Thereby, a comprehensive Well-to-Wheels (WTW) analysis of different renewable methanol pathways and comparative fossil and 1G biofuel pathways produces new results on the overall GHG emissions performance of renewable methanol fuel.

Chapter 5 investigates the potentials of renewable methanol with regard to the other two explicit EU biofuels-policy objectives *Security of Supply* and *Employment.* To do so, a fundamental analysis of the availability of bio-resources for renewable methanol production is undertaken. Based on this analysis, potential employment effects of large-scale implementation of renewable methanol technology in the EU are projected, as are the potential effects on the EU trade balance.

Within the scope of these analyses, it is also discussed how renewable methanol technology provides or contributes to two underlying qualitative biofuel-requirements which are not necessarily implied in the explicit objectives of EU biofuels policy, but which the author finds to be of imperative significance. These are, firstly, the highest possible efficiency in the utilisation of bio-resources and, secondly, the integratability in future energy systems with a high share of renewable electricity.

Generally and unless stated otherwise, the elaborations, assumptions and projections in this study are geared towards the potentials of renewable methanol technology in the EU in a temporal frame until 2020.

Chapter 6 summarizes the findings of the proceeding analyses and provides the base for the formulation of according political proposals in chapter 7. These political proposals have the aim of giving policy-makers indications and tentative recommendations for how to concretely make use of the identified potentials of renewable methanol with regard to sustainable energy planning in the EU transport sector. Thereby, the following secondary RQ is addressed:

- *Secondary RQ: Which political measures could advance the implementation of renewable methanol as a sustainable energy technology in the EU?*

The described structure of this study is illustrated in Figure 1.10:

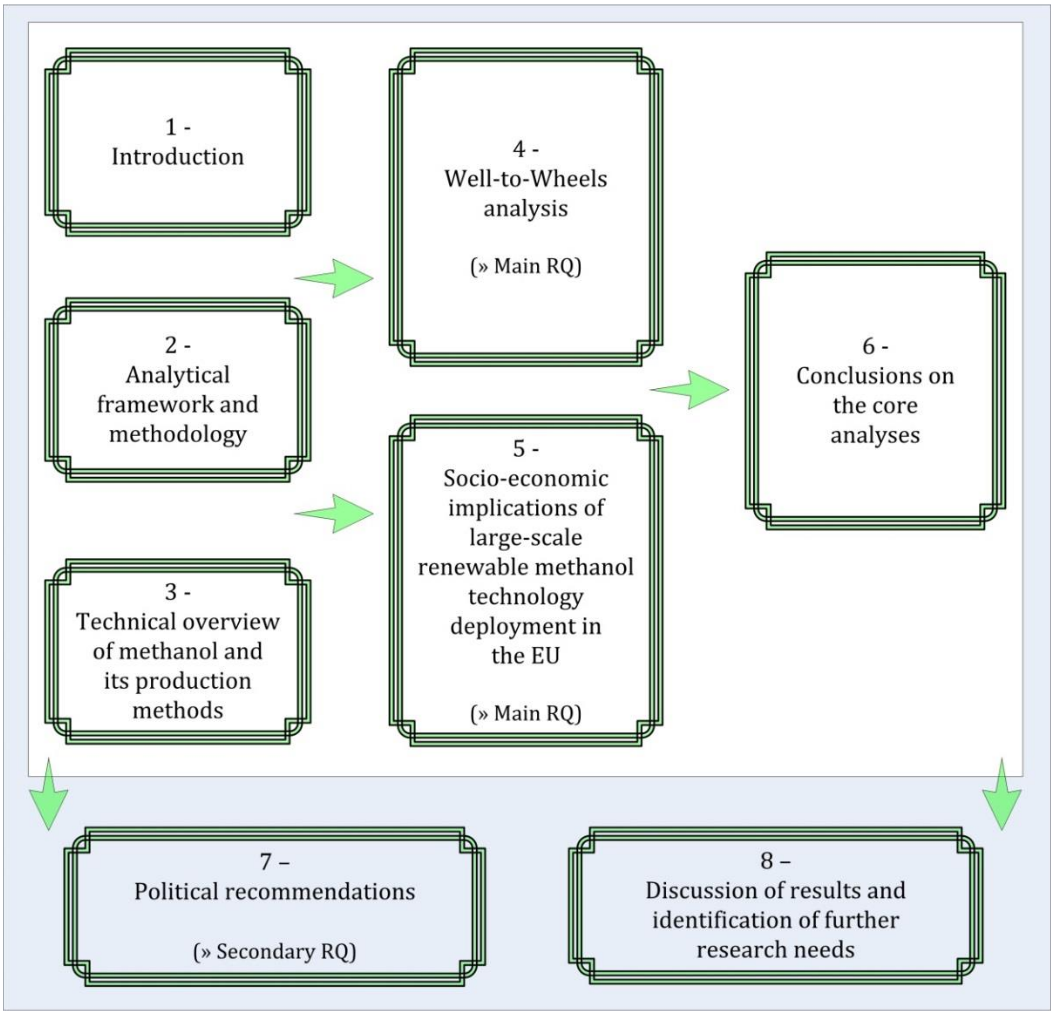

Figure 1.10 - Illustration of study structure

2 - Analytical framework and methodology

This chapter defines the author's theoretical and analytical approach towards investigating the potentials of renewable methanol in view of the objectives of EU biofuels policy. Section 2.1 conceptualises and integrates the objectives of this study from a sustainable energy planning perspective. Section 2.2 defines renewable methanol as a technological concept with complex societal implications going beyond its technical dimension. Section 2.3 describes the WTW-analysis method which is applied in order to assess the potentials of renewable methanol technology with regard to GHG savings.

2.1 - Analysis system boundaries within sustainable energy planning and conceptualisation of the research context

Figure 2.1 illustrates how the research focus of this study is embedded in a larger context of interrelated sub-systems within the energy system. These interrelated sub-systems are the heat, electricity and transport sectors. Two fundamental domains underlie each of the sub-systems: the technical domain and the institutional domain. Sustainable energy planning must relate these domains in order to produce meaningful and applicable results which can optimize societal benefits by the use of environmentally and economically feasible technologies and strategic policies.

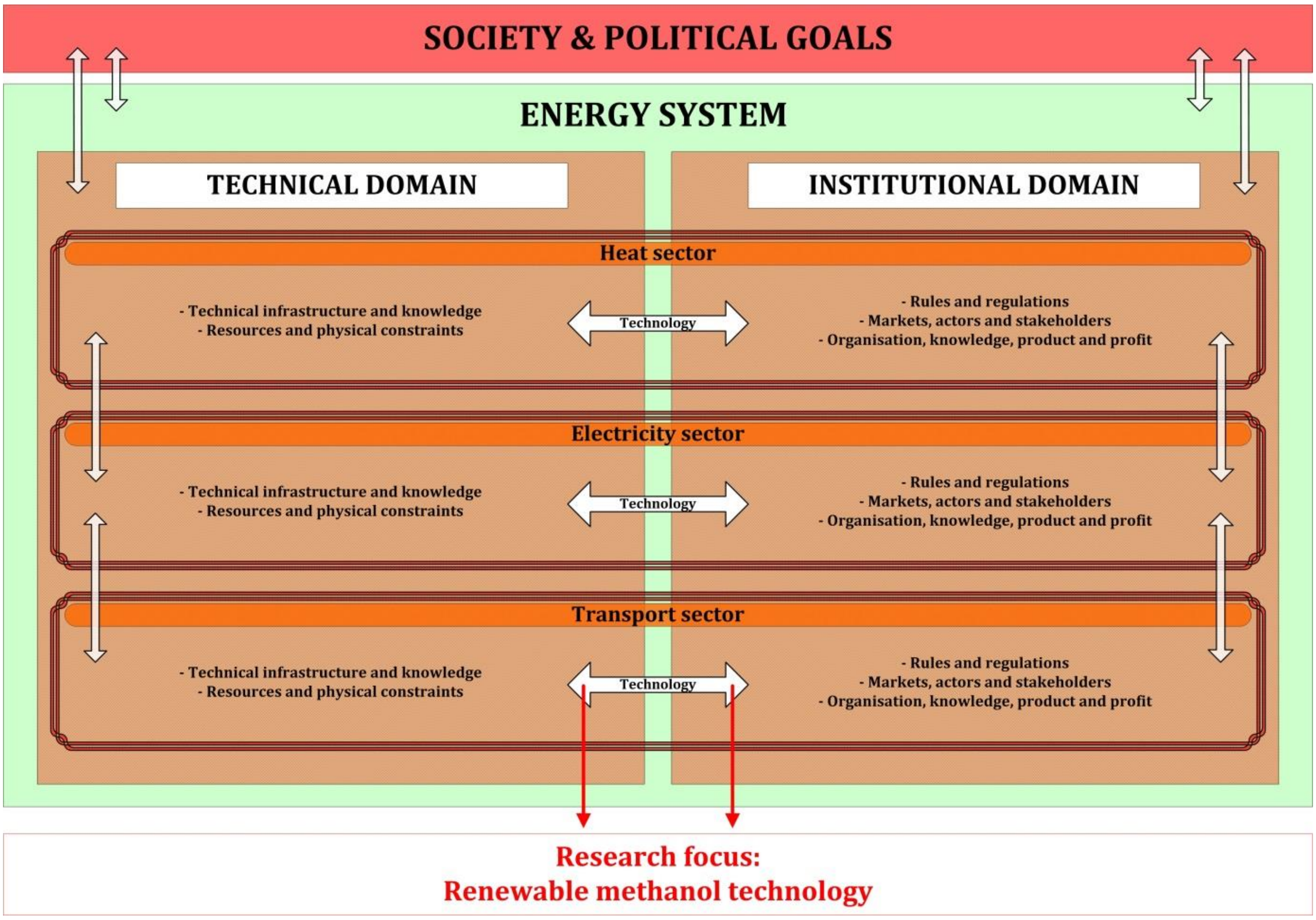

Figure 2.1 - Conceptualisation of the research context

In spite of the explicit focus on renewable methanol in this study, the following considerations are essential from a holistic sustainable energy planning perspective.

While it is indeed possible to perform experiments or conduct specific analyses within only one of the two fundamental domains, the meaningfulness and applicability of the produced results will certainly be limited if the other domain is not taken into consideration. For example, a strictly technical optimisation of a mechanical device is of no value in itself. Only through certain mechanisms in the institutional domain can the achieved technical optimisation achieve any greater value for society.

In similar measure, experiments and analyses which take place within only one of the sub-systems must take into account the existing interrelations with other sub-systems. Only then can eventual synergies between these sub-systems be promoted and eventual conflicts be prevented or mitigated. For example, a technical innovation which is achieved in the electricity sector is likely to affect the transport and heat sectors as well. Such effects could be of a primarily technical nature, thereby affecting primarily the technical domains of both the transportation and heat sectors. However, due to the inextricable interrelation between the fundamental domains, there will certainly be secondary effects in their institutional domains as well.

Consequently, in order to produce meaningful results, the analyses in this study touch on both fundamental domains: while the WTW-analysis in chapter 4 can be seen to take place mainly within the technical domain, its results become meaningful only by further analysis of their implications for sustainable development and in light of the EU biofuels objectives. Similarly, the analysis on the availability of bio-resources in chapter 5 can in itself be ascribed primarily to the technical domain but it is also of fundamental and decisive importance to the subsequent analysis of the potentials of renewable methanol in regard to *Security of Supply* and *Employment.* Finally, only a holistic reflection on the produced results and their reciprocal implications can provide an adequate argumentative base for sound political recommendations.

2.2 – Technology and choice awareness in the societal context

In spite of the fact that it can be utilised in a multitude of technical applications, in accordance with the conceptualisation of Müller [2003], renewable methanol in itself is regarded as *technology* hereinafter. Thereby, *technology* goes beyond a purely technical dimension and is accredited with complex organisational and economic implications as well. Fittingly, Figure 2.1 illustrates technology as linking the technical and the institutional domains.

According to Müller [2003], "*Technology is one of the means by which mankind reproduces and expands its living conditions. Technology embraces a combination of four constituents: Technique, Knowledge, Organisation and Product.* (…) *A qualitative change in any of the components will eventually result in supplementary, compensatory and/or retaliatory change in the others.*"

Thereby, *Technique* refers to the necessary physical components of a technology, for instance energy inputs and raw materials. *Knowledge* refers to the theoretical and practical understanding that is essential to creating and innovating technology. *Organisation* refers to the managerial and coordinative dimension which is of importance when implementing the technology in society. The *Product* is the result if all these constituents are combined. It has a practical value and enters a consumption process. Hvelplund [2005] adds *Profit* as a fifth constituent, referring to the economic benefits which can be attained by utilising the technology.

Throughout the analyses in this study, each of the constituents of renewable methanol technology is addressed in some respect. For example, the *Technique* constituent is addressed in the assessment of different renewable methanol production pathways in the WTW-analysis as well as in the analysis on the availability of bio-resources in the EU. The *Knowledge* constituent is addressed in the elaborations on the innovative development of future methods for renewable methanol production in energy systems with high shares of renewables electricity. The *Product* and *Profit* constituents are mainly addressed in the socio-economic assessments of employment and trade balance effects, while the *Organisation* constituent is addressed in the concluding formulation of tentative political recommendations for EU policy makers.

Figure 2.2 illustrates Müller's concept of technology [2003] and shows that all constituents interrelate and cannot be completely isolated from one another. This also refers back to the interrelatedness of the technical and institutional domains, described in section 2.1.

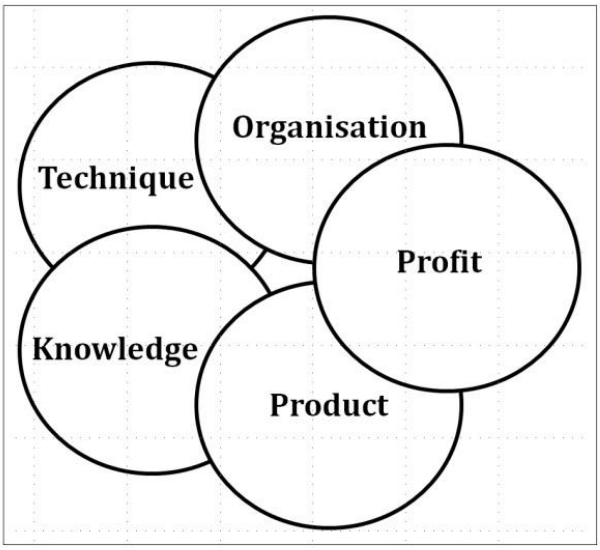

Figure 2.2 - Constituents of technology [adapted from Hvelplund 2012]

This encompassing conceptualisation clearly depicts the multitude of technical, social and economic implications of technology in a societal context. In light of the general objective of this study, which is to investigate a technology that is not yet established in society, it thereby also re-emphasises the aforementioned need for specific research which assesses the suitability and applicability of renewable methanol fuel in the concrete case of the EU.

In this context it must be noted that it is in fact of fundamental importance to raise societal awareness to the choice of alternative technological options which might imply environmental, social and economic advantages [Lund 2008]. Choosing such options would often imply changes in several, or all, of the five constituents of an existing technological set-up. Following Hvelplund [2012], such profound structural changes can be described as *radical technological changes* and will most often challenge well-established organisations, posing a threat to their assets, profits or positions. Consequently, they will not promote these alternatives or advocate substantial changes themselves, despite their potentially advantageous social and environmental implications. In fact, such alternatives will often be actively opposed or even eliminated before having gained sufficient attention or approval in public discourse and by political decision-makers.

Thus, by producing new knowledge concerning the potentials of renewable methanol technology with regard to the EU biofuels-policy objectives of *Greenhouse Gas Savings, Security of Supply* and *Employment*, the author explicitly aims to raise choice awareness and contribute to the creation of choice at a societal level.

2.3 - The Well-to-Wheels (WTW) analysis method

The WTW analysis method is used in chapter 4 of this study to assess the GHG emissions and overall energy efficiency of different renewable methanol pathways and of a number of comparative fossil- and biofuel pathways. As such, the calculations and produced outcomes incorporate all energy inputs and emissions which take place along the pathway of a fuel.

A pathway covers the entire life chain of a fuel, beginning with the extraction of raw materials and ending with the conversion of the final fuel to kinetic energy in an ICE-based car with an emissions-standard of 95 gCO_2/km, thereby complying with recent EU regulations on GHG emissions from new passenger cars in 2020 [EC 2012a]. While the method can be used to produce results on local emissions of pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), or sulfur oxides (SO_x), in view of the research objectives of this study, the WTW-analysis at hand focusses on global GHG emissions as well as on the overall energy efficiency of the investigated fuel pathways.

In general terms, a WTW-analysis can be regarded as a specific life cycle assessment (LCA) of transport fuels. Consequently it is dissociated from a full LCA, or cradle-to-grave analysis, which is used to assess the environmental impact of transport vehicles themselves rather than the impact of the fuel in use [Braungart & McDonough 2002]. An LCA/cradle-to-grave analysis would therefore include additional parameters which are not included in a WTW analysis, for instance the consumption of resources and emissions of GHG in the construction and disposal of vehicles (see Figure 2.3).

Moreover, the WTW analysis at hand does not regard energy inputs and emissions outputs for the construction of required fuel infrastructure such as refineries, pipelines or ships. On the one hand, this is due to the lack and ambiguity of such data, and on the other hand, the impact of these additional inputs on the overall performance of the fuel pathways is assumed to be rather small over time [CONCAWE 2011b]. However, in view of the research objectives and system boundaries of this study, the chosen WTW-analysis method constitutes a purposeful approach.

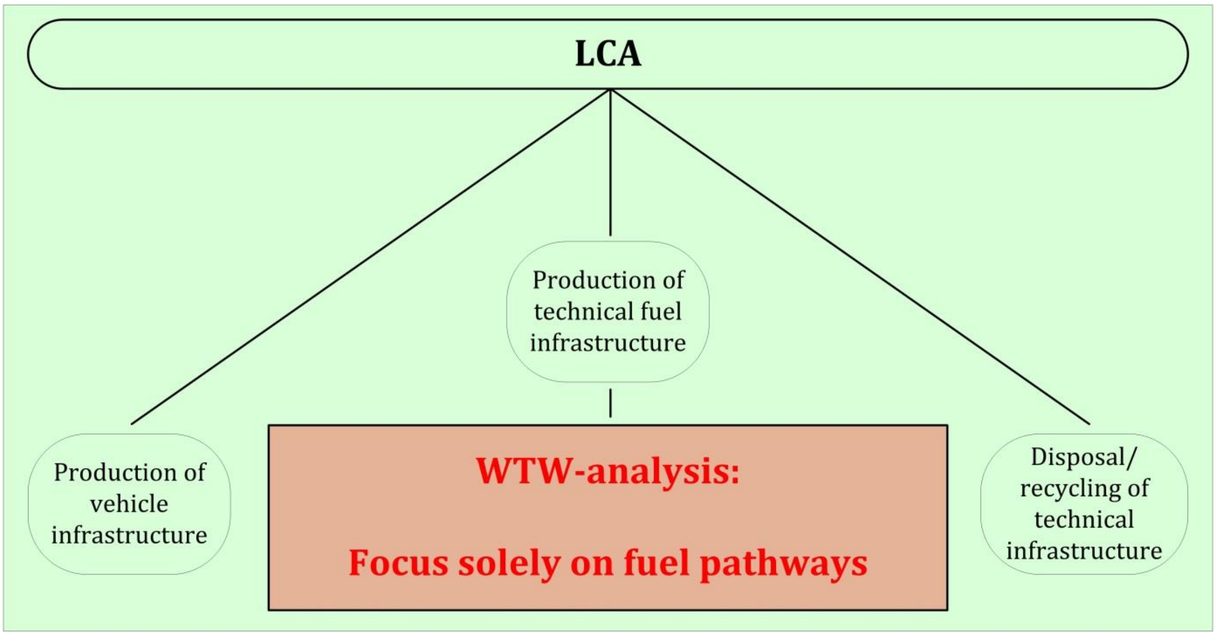

Figure 2.3 – System delineation between WTW-analysis and LCA

Methodologically, the WTW-analysis in this study is based on the methodology described in *Annex V* of the *RED* [EU 2009a], as it allocates all energy inputs and emissions outputs along a fuel pathway to one of four discrete steps. This allows for a technology-neutral comparison of very different fuel pathways and products.

The first three discrete steps, the so-called Well-to-Tank (WTT) chain, represent the combination of efforts necessary to extract a raw material, convert it into a final fuel product, and deliver it to the vehicle. The fourth and final, so-called Tank-to-Wheel (TTW) step accounts for the terminal conversion of the chemical energy bound in the fuel to kinetic energy in the ICE. Thereby, the WTW-steps consist of a complex collocation of energy inputs and GHG emissions outputs.

In the WTW-analysis at hand, the first step of a fuel pathway accounts for all efforts which are undertaken in order to extract or harvest primary energy carriers and, in some pathways, the conditioning of the primary energy carriers before they are transported to the fuel production site. Depending on the pathway, this transportation is undertaken by ships, trucks, or via pipeline.

The second step accounts for all efforts associated with the processing and transformation of the primary energy carriers, or raw materials, to produce the final fuel product. Depending on the pathway, this can include refining processes, a gasification process, or other methods.

The third step accounts for all efforts in storing, trucking and shipping the final fuel product over an assumed weighted-average distance to refueling stations within the EU.

The final step accounts for the fuel combustion in an ICE-based car with an emissions-standard of 95 gCO_2/km. As such, depending on the chemical properties of the investigated fuel products, they produce varying energy efficiencies and GHG emissions.

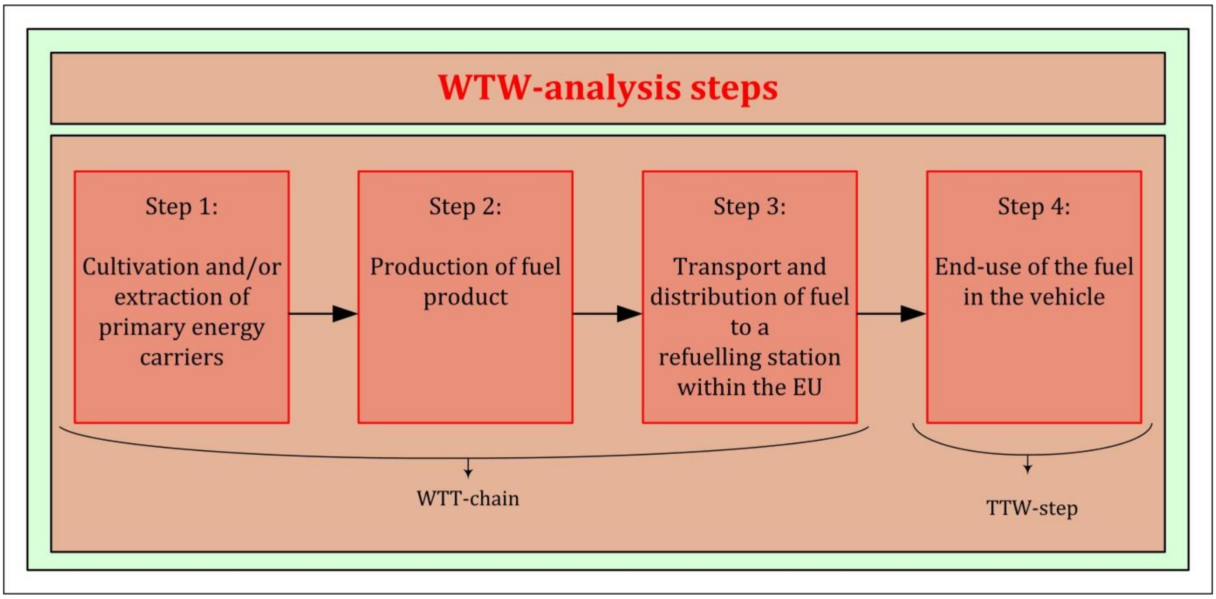

Figure 2.4 – WTW-analysis steps

The input values for the undertaken calculations on GHG emissions (produced in g CO_2eq/MJ[2]) and energy efficiency (produced in %) mainly stem from the report *Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, Version 3c* and its appendices [CONCAWE 2011a-c], prepared and issued by the *Joint Research Centre of the European Commission's Institute for Energy and Transport* in collaboration with *CONCAWE, the oil companies' European association for environment, health and safety in refining and distribution*. This report constitutes a body of 11 documents and 594 pages in its current third updated version and is currently the most broadly accepted scientific source of reference data for assessing energy flows and emissions of fuel pathways in the European context.

All outputs which are found in this body of documents are calculated by a software model which refers to an extensive database of energy and emissions factors for all efforts associated with WTT chains of fuels. Besides additional input from a number of scientific literature sources, a number of assumptions are also made by the author due to the lack of required data. These assumptions are based on related data in scientific literature and on personal communications with experts in the respective fields.

The investigated fuel pathways contain a high degree of complexity, depending on a wide range of inputs and competent assumptions. For example, primary inputs include the process energy required for fuel production and refining processes while secondary inputs include, for example, the energy inputs required for the production of nitrogen fertilizers which are used in the farming of biofuel feedstocks. Naturally, such complexity goes along with an irremovable degree of uncertainty in the produced results.

Adding to this uncertainty, though potential uses of by-products of fuel production processes are accounted for, the model cannot always represent the concrete energetic utilization of these by-products in the real world. For example, in the investigated 1G ethanol pathway, excess bagasse from sugarcane cultivation is accounted to provide process heat and electricity in the ethanol

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[2] According to their varying reactivity, the unit *CO_2e* accounts the following values to different greenhouse gases: CO_2: 1; CH_4: 25; N_2O: 298 [IPCC 2007].

production step although in reality it might not actually be utilized in this way. Generally, the use of by-products for the generation of process energy can have a significant impact on the energy and GHG balances of a fuel pathway and, consequently, on the produced outputs of the WTW-model. In spite of this, in the study at hand the system boundaries can only be extended to account for the most plausible and common energetic utilization of by-products. However, although these parameters contain uncertainty and can only be partially grasped, this does not affect the essential validity and significance of the final results. This is confirmed by including a 10%-uncertainty factor in the calculation and representation of the final outputs.

Although it is certain that GHG emissions can be attributed to changes in land-use and carbon stocks, and it is highly likely that these emissions are of significance to the GHG performance particularly of 1G biofuel pathways, ILUC-related GHG emissions are excluded from the WTW-model in this study and only mentioned in passing. This is because the nature and magnitude of land-use changes are currently still subject to a scientific debate which has not yet produced widely accepted reference data [Ecofys 2010; Searchinger 2010; Malins 2012]. Similarly, GHG absorptions could be credited if previously degraded land is restored for the cultivation of bioenergy carriers. However, due to the same ambiguity of the available data base for these emissions parameters, they are also disregarded in the calculations of this analysis.

By way of illustration, this high degree of variation between scientific evaluations of ILUC-related GHG emissions is captured by Ecofys [2010] who have conducted a comparative assessment of according studies:

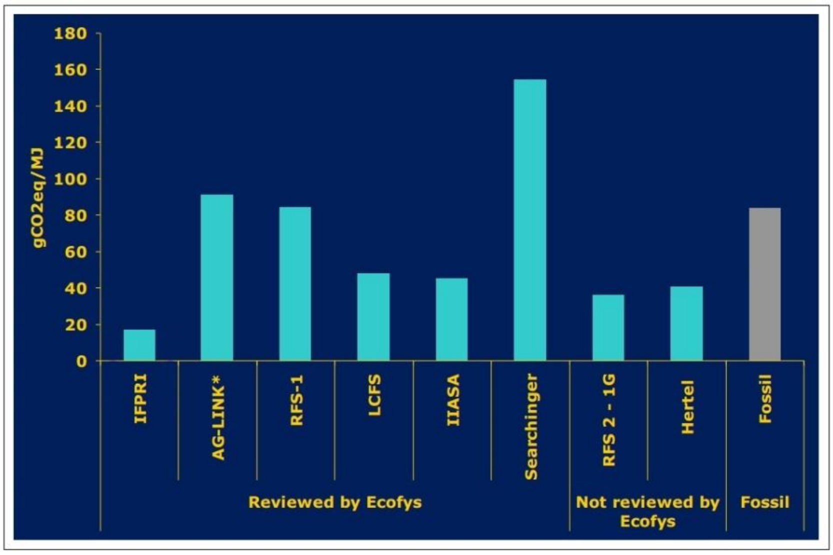

Figure 2.5 – Estimations on ILUC-related GHG emissions by different authors (referring to a weighted average of corn-based ethanol and soy-based biodiesel) [adapted from Ecofys 2010]

Despite these issues, the WTW-analysis method allows for an encompassing analysis of the *Greenhouse Gas Savings* potential of renewable methanol technology in view of the research objectives of this study. Moreover, the produced results concerning the overall energy efficiency of the investigated renewable methanol and comparative biofuel pathways, gives clear indication of how efficiently they utilize biomass resources. This is of particular significance in view of the further assessment of renewable methanol technology with regard to *Security of Supply*.

3 - Technical overview of methanol and its production methods

This chapter briefly describes the most important chemical properties and current uses of methanol in section 3.1. Section 3.2 gives an abstract of the historical development of alcohol transport fuels in general. In section 3.3 the technical properties of methanol as transport fuel in ICE are described. Section 3.4 highlights different renewable methanol production processes, categorized with regard to their demand for biomass feedstock and their technological maturity. The elaborations in this chapter thereby provide a necessary knowledge base for the analyses in the later chapters.

3.1 - Basic chemical properties and current uses of methanol

Methanol is the most basic of all alcohols, containing only one carbon atom. Under standard conditions for temperature and pressure, it is a colourless, flammable and highly volatile liquid which mixes with many organic solvents and in any ratio with water. It burns with a faint blue, barely visible flame to produce carbon dioxide and water [METHANEX 2006]. Often it is also referred to as *wood alcohol* because it was first produced through the pyrolysis of wood. Moreover, it should be noted at this point that renewable methanol is chemically identical with fossil-based methanol. Table 3.1 depicts its most important basic chemical properties:

Table 3.1: Properties of methanol [Olah et al. 2009; MI 2013a]

METHANOL / METHYL ALCOHOL / WOOD ALCOHOL (Chemical formula / Semi-structural formula: CH_4O / CH_3OH)		
Molecular weight	g/mol	32.04
Chemical composition	%	C: 37.5
		H: 12.5
		O: 50
Freezing point	°C	-97.7
Boiling point	°C	64.6
Density at 20 °C	kg/m3	791
Energy content	MJ/kg	19.7
Flash point	°C	11
Auto-ignition point	°C	470
Heat of Vaporization	kJ/kg	1,170
Flame Temperature	°C	1,870
Research Octane Number (RON)		109
Heat of Vaporization RONeq		24

For many decades methanol has been an important chemical feedstock in a wide range of industrial applications. Today, the largest share of global production is used in the production of formaldehyde, acetic acid, solvents, anti-freeze, plastics and paints [MI 2013a].

In 2012, global demand stood at more than 61 Mt and it is expected to more than double to 137 Mt by 2022 [IHS 2013]. Large-scale industrial production is based almost entirely on fossil feedstock, particularly natural gas with a share of roughly 80% [MI 2013c]. However, increase in global demand is largely driven by China which possesses large coal large reserves and is rapidly expanding its production capacity. Although the methanol demand for chemical industrial applications is still increasing, the methanol demand for transport applications is currently the fastest growing market segment and has risen from 4% of global production in 2005 to 23% in 2010 [MMSA 2012]. Particularly in China, where coal-based methanol was appointed a strategic fuel in 2007, this growth has led to more than half a billion Chinese passengers being transported by vehicles running on methanol-blends today (METHANEX 2013).

3.2 - A brief jaunt into the history of alcohol fuels

In the context of this research, it should be mentioned that alcohols have been used as transport fuels since the early years of automotive development. Already in the late 19th century, ethanol-powered ICE had replaced steam engines in European farming machinery and soon after, ethanol was the preferred fuel option in early automobiles by Otto and Benz [Gustafson 2013]. It was easily distilled from fermented sugars, and European countries, with little or no oil resources, were particularly keen to produce ethanol fuel in their domestic agricultural sectors.

Some years later, when mass production of automobiles was first pioneered by Henry Ford in the United States, the engines were still designed to run on both alcohol fuels and gasoline. At the time, regular competitions between alcohol-fuelled and gasoline-fuelled vehicles were held in order to determine which proved the best performance. Soon, however, ethanol was no longer economically competitive due to the increasing availability of cheap gasoline, particularly in the United States, which possessed large petroleum resources. Moreover, the powerful *Standard Oil Trust* actively opposed the further development and deployment of alcohol fuels [Olah et al. 2009]. Consequently, developers started to favour and optimize engines running solely on gasoline.

Image 3.1 – Henry Ford and Thomas Edison driving in an ethanol-fuelled Ford Model T in 1917 [Shere 2013]

Research efforts by German company BASF in the first quarter of the twentieth century resulted in the ability to commercially produce synthetic methanol from coal. Soon after, German coal-based methanol production was strongly intensified, both in an effort to achieve energy independence and due to military considerations. While methanol fuel in fact played a major role in Europe until the end of the Second World War, subsequently the interest in alcohol fuels decreased as petroleum resources were readily and cheaply available [Olah et al. 2009].

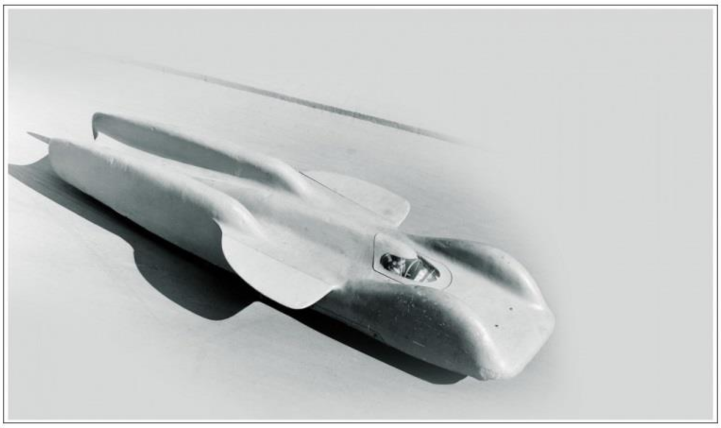

Image 3.2 – Mercedes-Benz T80: fuelled by high-methanol blend and intentionally designed to break the world land speed record in 1940 [Mercedes-Benz 2013]

It was not until the oil crises in the 1970s that the interest in alcohol fuels grew again. Methanol was proposed as an alternative fuel in the United States by Reed and Lerner [1973], who described a number of technical advantages of methanol fuel and emphasised its potential to replace gasoline in the U.S. transport sector. Moreover, extensive test series carried out by Volkswagen in Germany from 1975 onwards, and by Ford and other car manufacturers in California in the 1990s, produced positive results on the engine performance, pollution reduction and fuel economy of methanol fuel [Olah et al. 2009; Ward & Teague 1996]. Although low oil prices eventually ended greater plans for large-scale methanol fuel deployment, between 1993-1998 Ford did in fact sell an M85[3] *Taurus* model at the same price as its gasoline version, and at its peak more than 20,000 of these cars were driving in the U.S. [Ford 2013; P. Koustrup, personal communication].

Ethanol on the other hand was strongly promoted in Brazil where a dedicated national programme *ProAlcool* strongly promoted the cultivation of sugarcane for ethanol fuel. This eventually resulted in millions of Brazilian vehicles fuelled by domestic ethanol [Coelho et al. 1999]. Eventually, the intermediate comeback of cheap petroleum and the discovery of domestic oil resources off the Brazilian coast stifled the ethanol market. However, while ethanol production stood below 1 billion l in 1975, it stood at 26 billion l in 2009 [Bentsen and Felby 2012] and so-called flex-fuel vehicles (FFV), which are able to run on mixtures of gasoline and alcohol, continue to dominate the Brazilian market today.

In sum, throughout the decades, the development of automotive alcohol fuels has been closely linked to the development of petroleum prices and thereby has undergone phases of growth and of stagnation. In recent years, the global demand for alcohol fuels has increased again, particularly for ethanol in the United States and Europe, and for coal-based methanol in China.

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[3] M85 is a fuel blend of 85% methanol and 15% gasoline.

3.3 - Characteristics of methanol as transport fuel

Methanol can be used in various transport fuel applications. Currently it is most widely used for the production of methyl tertiary butyl ether (MTBE) and tert-amyl methyl ether (TAME), common oxygenating gasoline additives which are used to increase engine performance through improved fuel combustion efficiency. These so-called octane-boosters replaced other lead-based additives, which were generally phased out in the early 1990s. The fastest growing transport application however is its use as a blended component in conventional commercially available gasoline fuel. Moreover, methanol and its derivate dimethyl ether (DME) are used as a diesel substitute in compression ignition (CI) engines. In view of mobility concepts based on propulsion technologies other than the ICE, methanol furthermore holds potential as a hydrogen source for FCV.

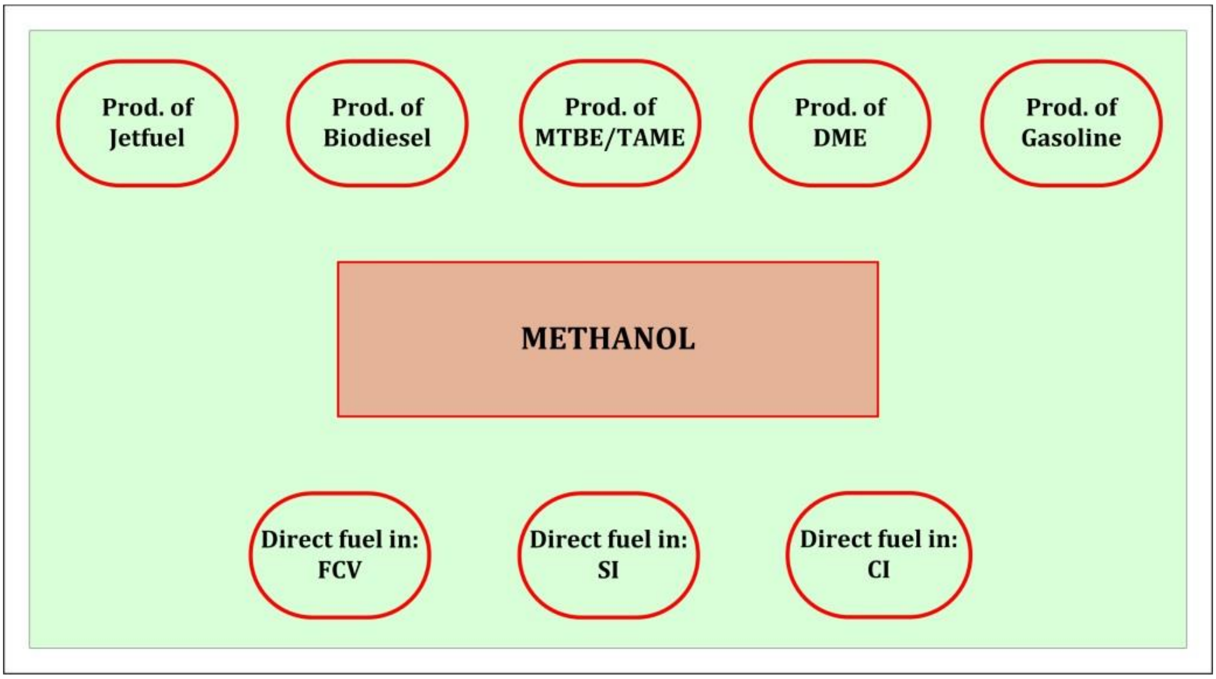


Figure 3.1 – Transport fuel applications of methanol

In the following, the characteristics of methanol fuel are further described. The focus lies on its use as neat fuel in gasoline spark ignition (SI) engines, since this is its application which is investigated in the latter WTW-analysis. Generally no adjustments must be made to gasoline-fuelled vehicles in order to run on methanol blends below 10% [SAE 1993]. For higher blends, some adjustments to the fuel tank as well as to the fuel distribution and injection components are usually necessary. Moreover, there is a need for a variable sensor which can determine the alcohol content in the fuel in order to optimise the combustion [Olah et al. 2009]. It should be noted however that recently it has been stated that in modern cars with electronic fuel injection, only adjustments to the engine control unit software and an exchanged fuel pump seal are required to run on neat methanol fuel [Zubrin 2013]. Furthermore, certain components used in the storage and distribution of methanol must be of different design and chemical composition than those used for gasoline to prevent corrosion and intermixture with water [Olah et al. 2009].

Methanol is a relatively simple chemical and contains roughly half the energy density of gasoline, which is a more complex mixture of different hydrocarbons and additives. However, despite its lower energy content, it has a higher research octane number (RON) of 109 (the RON of gasoline normally lies between 92-98). While a high octane rating is usually associated with properties such as high power, fast acceleration and high top-speed, the following efficiency-related advantages over gasoline are more important in the context of this research:

- The higher RON of methanol signifies that in the combustion chamber of the spark ignition engine, the fuel/air mixture can be compressed to a smaller volume before being ignited by the sparking plug. Accordingly, the so-called compression ratio of methanol is higher: while the ratio of methanol is about 27:1, that of gasoline is about 9:1. The compression ratio can be defined as the maximum volume of the combustion chamber when the piston is furthest away from the cylinder head, divided by its minimum volume when the piston is closest to the cylinder head. More simply put, the higher compression ratio of methanol signifies that a more complete combustion of the fuel/air mixture in the engine is possible [EB 2013b]. As a result, the potential occurrence of so-called engine knocking in the cylinder is strongly reduced. Engine knocking can be described as the uncontrolled combustion, or self-ignition, of the fuel/air mixture if the temperature in the combustion chamber is too high. This knocking effect leads to high mechanic and thermic stress in the engine and can cause severe damage. In using high-octane methanol fuel with a low flame temperature (methanol: 1,870°C / gasoline: 2030°C) the combustion temperature is decreased and its proclivity to detonate is reduced. Thus, a higher compression ratio is achievable, allowing for a more complete combustion, increasing efficiency and generally reducing emissions of NO_x, SO_x, particulate matter (PM) and volatile organic compounds (VOC) [Nowell 1994; EB 2013b; MI 2013b]. Figure 3.2 illustrates the relation between the RON, CR and the SI engine efficiency:

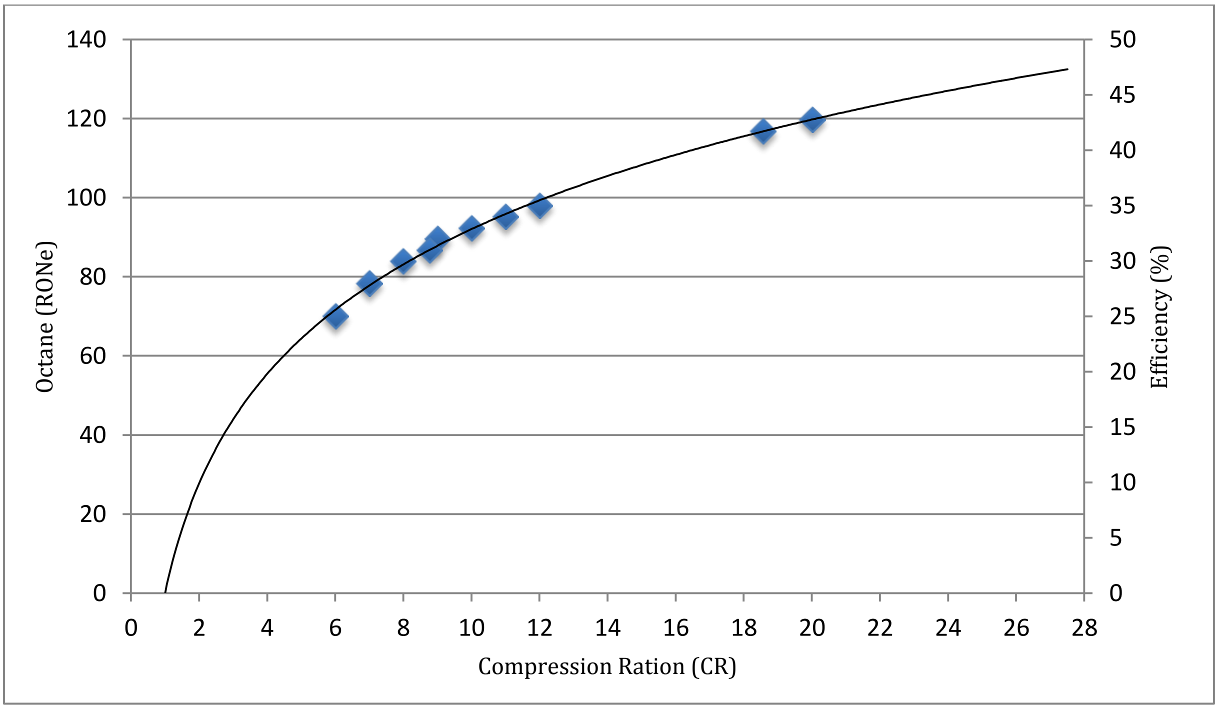


Figure 3.2 – Relation between RON, CR and SI engine efficiency [P. Koustrup 2013; based on Hamilton 1995]

- The 3.7 times higher heat of vaporization of methanol signifies a greater absorption of heat when it passes from the liquid to the gaseous state. This induces a substantial cooling effect of the fresh charge, particularly in modern direct injection (DI) engines which have gained widespread use in recent years, especially in Europe [P. Koustrup, personal communication]. This relative cooling effect is equivalent to a RON increase of 24, significantly improving the overall thermal efficiency and knock resistance of methanol combustion even further [Olah et al. 2009; Stein et al. 2012]. Naturally, this applies most strongly in engines which are specifically optimized for methanol fuel but it is also the case in conventional gasoline engines if slight modifications are undertaken [Nowell 1994]. In this context and in light of the advantages described above, additional efficiency improvements, fuel economy and environmental advantages could also follow from smaller and lighter engine blocks and reduced cooling requirements in engines optimized for methanol fuel.

In sum, the combustion properties of methanol signify a superior thermal efficiency and fuel economy over gasoline fuel and also explain why, despite being only half as energy-dense, the same power output can be achieved with less than double the amount of methanol.

Confirming these observations, comparative fuel test results by Brusstar & Bakenhus [2002] show that overall thermal efficiency levels of over 40% can be reached in SI engines by using neat alcohol fuel. This exceeds even state-of-the-art diesel engines. This knowledge is used by the author in the WTW-analysis model in chapter 4, in applying a vehicle-efficiency range (step 4) for the investigated alcohol fuels which is greater than the efficiency of gasoline.

3.4 - Production methods for renewable methanol

This section offers descriptions of different methods for the production of methanol from renewable resources. They are categorized with regard to their demand for biomass feedstock and their technological maturity: while the *near-term* and *medium-term* methods of renewable methanol production are based on gasification of biomass-feedstock (see sections 3.4.1 and 3.4.2), their final product is referred to as *bio*-methanol. On the other hand, the described *long-term* method of renewable methanol production does not depend on biomass resources but relies on the capture and chemical recycling of CO_2 (see section 3.4.3). Therefore, it is not described as *bio*-methanol, but in what follows is referred to as renewable methanol.

3.4.1 - Current and near-term method for the production of bio-methanol

In the near-term (meaning the coming years until at least 2020), bio-methanol production will continue to be based on more or less the same technical principles as the production of almost all fossil-based methanol today: these principles are the thermochemical reforming of the feedstock through gasification, and the subsequent catalytic conversion to methanol.

As such, the technology is highly flexible with regard to possible feedstocks since any kind of biomass resource is principally suitable for the production process via gasification. This includes, for instance, products and residues from the agricultural and forestry sectors, municipal waste, animal waste, aquatic plants and algae. Enzymatically converting biomass to methanol is not further regarded here because almost all efforts in the area of enzymatic conversion of biomass to alcohol are currently focussed on ethanol.

According to Olah et al. [2009], solid biomass feedstock is usually dried and pulverized at first, reducing the moisture content to an optimal 15-20%. Then the biomass is heated at 400-600°C to obtain a pyrolysis gas consisting of carbon monoxide, hydrogen, methane, volatile tars, carbon dioxide and water. In so doing, the pyrolysis also produces a significant amount of charcoal as residue. In a second gasification step, this charcoal is reacted with oxygen at 1.300-1.500°C, producing additional carbon monoxide.

The final product of the gasification steps, the so-called syngas, must then be modified in order to reach the optimal composition for the subsequent methanol synthesis: this includes the removal of CO_2, technically problematic tars, and the generation of at least twice as many H_2 molecules as CO molecules in the syngas [Hamelinck & Faaij 2001]. In the final methanol production unit the syngas is then synthesized to methanol over a heterogeneous copper-based catalyst. For this, an excess of hydrogen in the syngas is desirable for optimal methanol formation. The synthesis accords to the following equations:

$$CO + 2H_2 \rightleftharpoons CH_3OH$$
$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O$$
$$CO_2 + H_2 \rightleftharpoons CO + H_2O$$

The third equation describes a reaction in which carbon monoxide is produced which then can react further with present hydrogen to produce methanol. Naturally, the progress of these reactions depends on the precise syngas composition and reaction conditions such as pressure and temperature. Therefore, controlling these conditions is of importance in order to optimize the methanol synthesis. As the resulting crude methanol is partly contaminated with by-products, it is distilled in one or more distillation columns to achieve the desired purity.

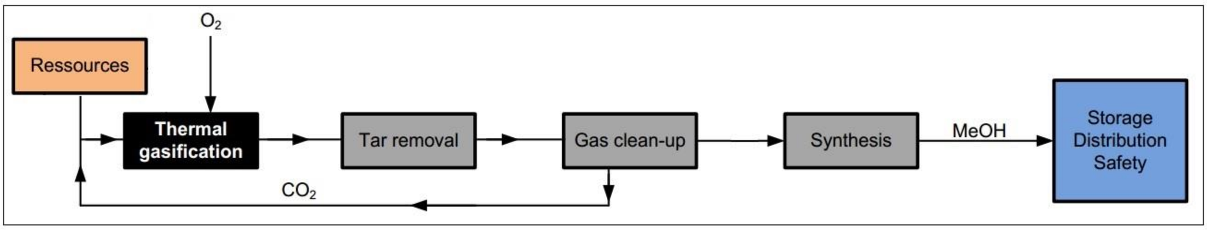


Figure 3.3 – Simplified illustration of biomass-to-methanol process via gasification and subsequent synthesis [Adapted from Mortensgaard et al. 2011]

Usually, a part of the biomass feedstock itself is burned to generate the required process heat for gasification. This eliminates the need for an external energy source. However, if an external renewable energy source such as solar or wind power were used instead, the efficiency of biomass utilisation could be improved. For the same reasons, a renewable energy input for the drying of the biomass feedstock pre-gasification is desirable.

Naturally, the biomass-to-methanol efficiency of plants based on the technical concepts described above will vary according to their concrete biomass feedstock and technical arrangement. In the evaluation of different bio-methanol pathways in the WTW-analysis in chapter 4, efficiency values ranging from 59.2–65.8% are therefore applied (step 3), based on information acquired from different scientific sources [Mortensgaard et al. 2011; T. Ekbom, personal communication; CONCAWE 2011a].

In this context it should also be noted that various research and development (R&D) activities are currently concerned with optimising gasification processes of different biomass feedstocks and the efficiency of biomass-gasification is expected to increase between 5-10% in the coming years through technical innovation [Bromberg & Cheng 2010]. On the other hand, the improvement potential, with regard to the methanol synthesis efficiency, is rather limited since this step represents a long-established procedure, well known from conventional natural gas-based methanol production [P. Koustrup, personal communication].

Currently operating producers which use the production principles described above include Dutch company *BioMCN* which produce bio-methanol from crude glycerine (a residue of biodiesel production), and the Canadian company *Enerkem* which operates a facility converting municipal solid waste to methanol, derived ethanol and chemicals. Moreover, in Sweden *Värmlandsmetanol* relies on forest residues for the production of bio-methanol and the consortium *BioDME* uses black liquor feedstock to produce bio-DME via bio-methanol.

3.4.1.1 - Production of bio-methanol from upgraded biogas

The production of bio-methanol from upgraded anaerobically digested biogas is technically very similar to the production of methanol from natural gas, which today is the most widely used feedstock due to relatively low capital and operating costs. Upgraded biogas is also referred to as biomethane.

In order to upgrade raw biogas to biomethane quality, the raw biogas mainly requires removal of carbon dioxide, water and impurities such as hydrogen sulphide. Ideally, the high hydrogen content of biomethane then enables a straightforward production process involving the steam reforming of the biomethane in order to obtain syngas, the purification of the syngas, subsequent catalytic synthesis and final distillation.

Because the suppressing of unwanted CO_2 emissions in the steam reforming of methane is technically difficult and requires a high energy input, it is disadvantageous to the process efficiency and economy. Moreover, it can be regarded as relatively inefficient because methane is first transformed to carbon monoxide in an oxidative reaction and then is reduced with hydrogen to produce methanol. Although current R&D activities are expected to yield efficiency improvements in the near future [IRENA 2013], directly transforming methane to methanol would therefore be more desirable and improve both, efficiency and economics. However, although the direct oxidation of methane to methanol is actively being researched, so far it has been difficult to establish a practical process which is competitive with syngas-based methanol production [Olah et al. 2009].

Figure 3.4 illustrates a concept where biogas is stored temporarily in the natural gas network before being processed to methanol. This concept is represented in the WTW-analysis in chapter 4. Although not yet commercialised, the storage and transportation of the biogas in the natural gas grid enables bio-methanol production in large-scale cost-effective facilities. Starting in 2014, *BioMCN* will take into operation such a facility in the Netherlands [BioMCN 2013c].

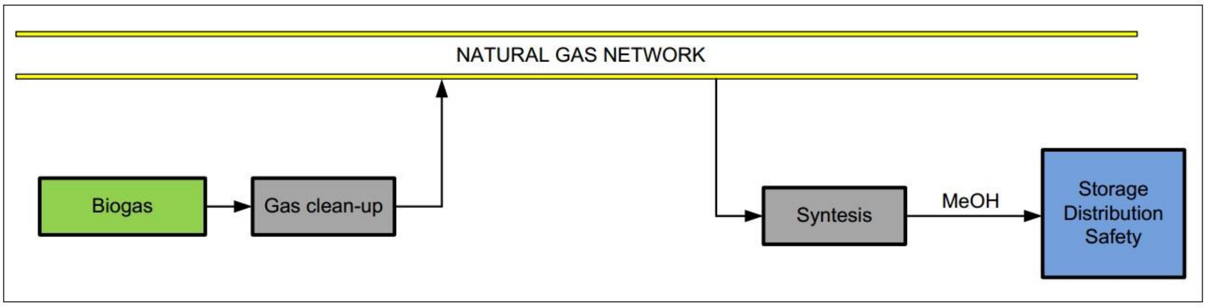


Figure 3.4 - Methanol synthesis based on biogas temporarily stored in the natural gas grid [Adapted from Mortensgaard et al. 2011]

3.4.2 - Novel mid-term method for the production of bio-methanol

An advanced concept for the gasification-based production of bio-methanol is described by Mortensgaard et al. [2011]. In this novel concept, the methanol production is optimized by the addition of a regenerative solid oxide electrolyser cell (SOEC) to the process. It is expected that this concept will gain concrete significance between 2020 and 2030.

Most importantly in this *novel* concept, hydrogen can be derived from the SOEC-electrolysis in order to optimise the syngas composition for the subsequent methanol synthesis. In optimising the syngas composition, a much-improved exploitation of the carbon in the biomass feedstock can be achieved. Therefore, despite the higher electricity consumption of the plant through the integration of SOEC, the overall plant efficiency is greatly increased.

As such, the demand for hydrogen in the syngas is the main controlling parameter for the SOEC unit, determining its capacity and activity. Moreover, pure oxygen can be derived from the SOEC-electrolysis in order to improve the gasification efficiency and, compared to the gasification with ambient air, to gasify the biomass without producing unwanted NO_x. The benefit of nitrogen-free syngas is that the gas clean-up and further process steps downstream are greatly facilitated, further improving the efficiency and economy of the entire process [Hamelinck & Faaij 2001]. Moreover, compared to the gasification with ambient air, the gasification of pure oxygen can take place at higher temperatures, thereby lowering the content of tars and unwanted components in the syngas. Excess heat from the gasification process is used to generate inlet steam for the SOEC unit, improving the overall efficiency.

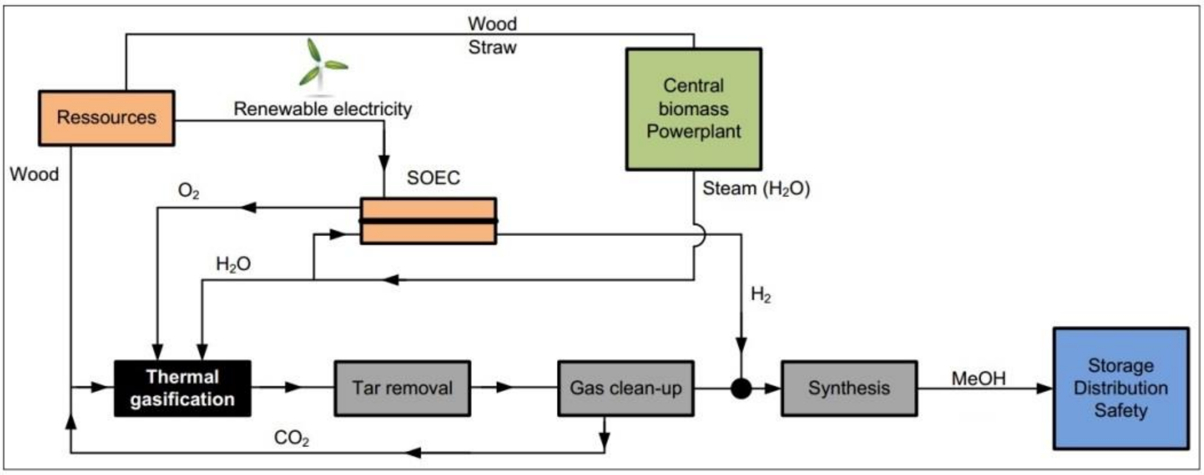


Figure 3.5 – Novel concept of bio-methanol production, integrating SOEC [Adapted from Mortensgaard et al. 2011]

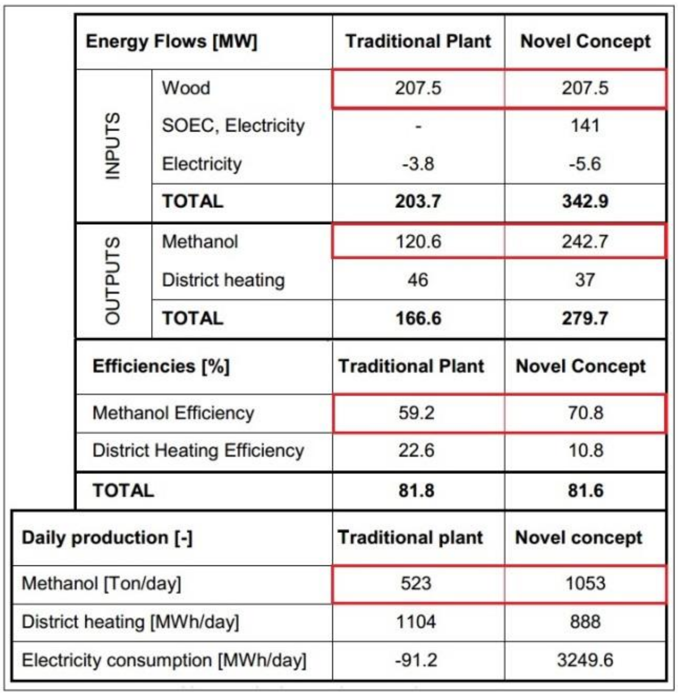
It would also be possible to increase the efficiency of this concept by coupling it with a biomass-based power plant, sharing a common biomass feedstock and extracting steam from the biomass boilers for the electrolysis in the SOEC unit. Moreover, if a district heating network were connected to the plant, the overall efficiency could be increased even further. Clearly, this would have positive implications for the plant economy [IRENA 2013].

The gasification unit of the plant should be able to operate independently from the SOEC unit. In so doing, it could continue to operate at regular full load while, in accordance to the spot market electricity price, the SOEC unit may operate only in part load. This would reduce the impact of volatile electricity spot market prices on the methanol output and consequently would improve the plant economy particularly in future energy systems with higher shares of variable and uncertain renewable electricity.

To sum up, while in the *near-term bio-methanol production method,* described in chapter 3.4.1, large amounts of carbon dioxide must be removed to optimise the syngas composition for the subsequent methanol synthesis, this carbon can be exploited through the addition of hydrogen in the *novel* concept. Thereby, the so-called carbon efficiency is doubled and twice as much methanol output can be produced from the same amount of biomass input. In view of potential biomass constraints it is clear that improving the carbon efficiency of biofuel production processes is of great importance. Thus, the upgrading of biomass energy inputs via renewable electricity-based electrolysis is very likely to become more relevant in the future [Lund et al. 2011; Grandal 2012].

Table 3.2 depicts the input/output performance of the *novel* concept, in comparison to the *current and near-term* concept of bio-methanol production on wood-feedstock basis. The doubling of the methanol output in the novel concept as well as the efficiency parameters of 59.2% in the *current and near-term* method and 70.8% in the *novel* concept are applied in the respective pathways in the WTW-analysis in chapter 4 (step 3).

Table 3.2 - Near-term method vs. novel concept of bio-methanol production: energy efficiency and output balance [Adapted from Mortensgaard et al. 2011]



Energy Flows [MW]		Traditional Plant	Novel Concept
INPUTS	Wood	207.5	207.5
	SOEC, Electricity	-	141
	Electricity	-3.8	-5.6
	TOTAL	**203.7**	**342.9**
OUTPUTS	Methanol	120.6	242.7
	District heating	46	37
	TOTAL	**166.6**	**279.7**

Efficiencies [%]	Traditional Plant	Novel Concept
Methanol Efficiency	59.2	70.8
District Heating Efficiency	22.6	10.8
TOTAL	**81.8**	**81.6**

Daily production [-]	Traditional plant	Novel concept
Methanol [Ton/day]	523	1053
District heating [MWh/day]	1104	888
Electricity consumption [MWh/day]	-91.2	3249.6

3.4.3 - Long-term method for the production of renewable methanol

Despite innovations with regard to the efficiency of biofuel production, limited biomass resources cannot be expected to cover the entire demand for liquid transport fuels in the long-term [Hedegaard 2008; IEA 2012a]. Consequently, non-biomass advanced renewable fuel alternatives are being developed and will have to be deployed in order to eventually gain full independence from fossil fuels. In this broad context, an approach which has recently gained increasing attention is the on-site capture of CO_2 emissions and their chemical recycling to methanol, using hydrogen obtained from renewables-based electrolysis or other methods of cleavage [AFS 2013; CRI 2013b]:

$$CO_2 + 3H_2 \xrightarrow{\text{catalyst}} CH_3OH + H_2O$$

Suitable catalysts for the synthesis are of a very similar nature to those used in the production of methanol via syngas. However, research in this field is active and improved catalysts are currently being developed. The hydrogen input can be derived from renewables-based regenerative electrolysis but other renewable hydrogen supply methods are possible as well, for instance through photocatalytic splitting of water. Capital investment for a methanol plant using this technology is comparable to the capital investment of gasification-based methanol plants [Olah et al. 2009]. Limiting factors for the scale of such plants are, rather, the price of electricity and the availability of carbon dioxide.

A wide range of possible sources exist for the capture and purification of carbon dioxide emissions, for example large power plants or factories producing cement, aluminium or steel. The process of recovering CO_2 from these gas streams is a well-developed procedure which can be based on a number of chemical and physical processes. Furthermore, the capture of carbon dioxide emissions is technically and economically most feasible if they are relatively concentrated. For example, flue gas emissions from fossil-based power plants are highly suitable for recovery as they contain up to 15% CO_2 by volume. In comparison, the average regular atmospheric CO_2-concentration is only 0.0398% by volume [ESRL 2013]. The capturing of CO_2 from these concentrated emissions sources requires its purification from pollutants such as hydrogen sulphide (H_2S) and SO_x, otherwise technical problems such as the degradation of the catalyst systems will occur [Kohl & Nielsen 1997].

It seems clear that capturing even a small fraction of the global industrial CO_2 emissions represents a huge potential for the production of renewable methanol and its derivatives. Recently, American-Icelandic company *CRI* has started to operate a commercial-scale methanol plant in Iceland based on these principles. *CRI* takes advantage of the low prices for renewable electricity and the availability of concentrated CO_2-emission from a local geothermal power plant [CRI 2013a]. Moreover, *Blue Fuel Energy* from Canada uses the principles described above to produce methanol, derived DME and gasoline [BFE 2013]. It is clearly difficult to project when this concept can and will be feasibly deployed on larger scales. However, in what follows it is not expected to play a large-scale role before 2030 [Olah et al. 2009].

Graves et al. [2010] claim an electricity-to-fuel efficiency of 70% in a state-of-the-art plant using this technology. This value is also represented in the respective pathway in the WTW analysis in chapter 4 (step 3).

4 - Well-to-Wheels analysis

This chapter assesses the potentials of renewable methanol technology primarily with regard to the EU biofuels-policy objective of *Greenhouse Gas Savings.* Thereby, the author makes use of the WTW analysis method, introduced in section 2.3, to assess the GHG emissions and overall energy efficiency of different renewable methanol pathways which incorporate the production methods described in section 3.4. The produced WTW efficiencies thereby indicate how efficiently given natural resources are utilized and therefore must also be viewed as important parameters in regard to the *Security of Supply* objective.

The WTW-analysis moreover includes different fossil- and biofuel pathways which are of relevance in the EU transport context, thereby creating a base for comparative evaluation. The range of comparative fuels is chosen according to the delimitations of this analysis, focussing on liquid fuels in ICE: gasoline, diesel, fossil methanol, ethanol and biodiesel.

The author has sought to ensure that the chosen renewable methanol pathways are of potential relevance in the European context and to identify the most thorough and up-to-date data available as input for the calculations. Thereby, no renewable methanol pathways are included which are based on municipal waste, animal waste, aquatic plants or algae. On one hand, this is due to a lack of according basic data and, on the other hand, the marginal potential relevance of these feedstocks for renewable methanol technology within the time frame of this study.

Section 4.1 describes the fundamental calculative parameters and assumptions which define the WTW model. Section 4.2 produces and describes the results on the WTW GHG emissions and efficiencies of the investigated renewable methanol pathways. Thereby, the *near-term*, *medium-term* and *long-term* concepts of renewable methanol production (see sections 3.4.1, 3.4.2 and 3.4.3 respectively) are incorporated. Section 4.3 evaluates the WTW GHG emissions and efficiency performance of the renewable methanol pathways in comparison to the chosen comparative fossil- and biofuel pathways, thereby producing comparative results. Section 4.4 summarizes the findings of the proceeding sections and concludes on the identified potentials of renewable methanol technology in regard to the EU biofuels policy objectives of *Greenhouse Gas Savings* and *Security of Supply.*

4.1 - Introduction to calculations

The WTW GHG emissions of the investigated fuel pathways are produced in g CO_2e/MJ and are the sum of the respective emissions from all efforts and processes in each of the four discrete WTW steps:

$$E_{\text{(WTW GHG emissions of fuel pathway)}} = \Sigma \{e(c)_{\text{(GHG emissions of step 1)}}, e(p)_{\text{(GHG emissions of step 2)}}, e(td)_{\text{(GHG emissions of step 3)}}, e(u)_{\text{(GHG emissions of step 4)}}\}$$

Consequently, the WTW GHG emissions of the investigated fuel pathways are calculated as follows[4]:

$$E = e(c) + e(p) + e(td) + e(u)$$

In step 1, *e(c)* accounts the emissions from all efforts associated with the cultivation and extraction processes of raw materials. Depending on the fuel and its production pathway, this can include emissions from harvesting or collecting primary energy carriers, emissions from potential waste or leakage and from the production of necessary chemicals and support products needed for the cultivation or extraction processes.

In step 2, *e(p)* accounts the emissions from all efforts associated with processing the fuel. Depending on the fuel and its production pathway, this can include emissions from the processing itself but also from potential waste and leakage and from the production of necessary chemicals and support products which are used in the processing step.

In step 3, *e(td)* accounts the emissions from all efforts associated with transporting and distributing the fuel to fuelling stations within the EU. This can include emissions associated with storage as well as the transport and distribution in both ships and trucks.

In step 4 (TTW), *e(u)* accounts the emissions from the fuel combustion in the vehicle engine. A value of zero has been chosen for biofuels due to the underlying assumption of carbon-neutrality: this means that the biomass feedstock has absorbed and bound CO_2 during its natural process of plant growth. During its decomposition or its combustion, this bound amount is set free, closing the carbon cycle and neutralizing the carbon balance. All associated external emissions of biofuels are accounted for in the previous steps of the WTT chain.

The WTW efficiencies of the investigated fuel pathways are produced in % as Energy Returned on Energy Invested (EROEI[5]). Thereby the WTW efficiency of a fuel pathway is the product of the respective efficiencies of all efforts and processes in each of the four discrete WTW steps:

$$H_{\text{(WTW efficiency of fuel pathway)}} = \Pi \{\eta(c)_{\text{(efficiency of step 1)}}, \eta(p)_{\text{(efficiency of step 2)}}, \eta(td)_{\text{(efficiency of step 3)}}, \eta(u)_{\text{(efficiency of step 4)}}\}$$

As the data input for the efficiency calculations of the respective fuel pathways stems from the same sources as the inputs for the calculations of their GHG emissions, the coherence of the calculations and the validity of the results are ensured. Thereby, the WTW efficiencies are calculated as follows:

$$H_{\text{(WTW efficiency of fuel pathway)}} = \eta(c) * \eta(p) * \eta(td) * \eta(u)$$

---

[4] Although in the investigated biofuel pathways the calculations refer to renewable raw materials, fossil energy inputs are currently used in *e(c), e(p)* and *e(td).*

[5] The EROEI can be described as the *"ratio of the amount of usable energy acquired from a particular energy resource to the amount of energy expended to obtain that energy resource"* [Murphy & Hall 2010]. In the study at hand the values refer to: MJ (fuel output) / MJ (energy input).

In accordance to the above, in step 1, $\eta(c)$ accounts all energy inputs associated with the cultivation and/or extraction of raw materials.

In step 2, $\eta(p)$ accounts for all energy which must be invested in order to process or refine the fuel product.

In step 3, $\eta(td)$ accounts all energy inputs associated with the transport and distribution of the fuel to fuelling stations within the EU.

Lastly, in step 4 (TTW), the end-use efficiency $\eta(u)$ accounts for the energy loss which occurs when chemically bound energy is converted to kinetic energy in the ICE. Thereby, a vehicle-efficiency range is applied for the alcohol fuels which is 10-40% higher than the vehicle-efficiency of gasoline fuel. This is done in order to account for the superior combustion properties, thermal efficiency and fuel economy of alcohol fuels, particularly methanol, described in section 3.3.

Throughout the following sections, the respective fuel- and pathway-specific inputs and underlying assumptions for the calculations are further clarified and discussed. Furthermore, the Annex chapter of this study includes data tables which show the inputs for the calculations.

4.2 - WTW GHG emissions and efficiencies of renewable methanol pathways

This section assesses the GHG emissions and efficiencies of renewable methanol pathways which incorporate the *near-term*, *novel medium-term* and *long-term* production methods described in section 3.4.1, 3.4.2 and 3.4.3. Thereby, the *current and near-term* and *novel medium-term* pathways rely on gasification of biomass-feedstock (crude glycerine, waste wood via black liquor, farmed wood, waste wood and biogas in the *current and near-term pathways* and farmed wood in the *novel medium-term pathway*) in order to produce bio-methanol (sections 4.2.1 and 4.2.2). The *long-term* pathway relies on the capture and chemical recycling of CO_2 (section 4.2.3).

4.2.1 - Current and near-term bio-methanol pathways

This section incorporates the concept of bio-methanol production via biomass gasification and subsequent methanol synthesis. This concept is described in section 3.4.1. Moreover, it includes a biogas-based pathway as is described in section 3.4.1.1.

At first, the results of the WTW GHG emissions and efficiency models of all pathways are presented in section 4.2.1.1. Subsequently in section 4.2.1.2, these results are explained in detail by describing specific assumptions and the concrete nature of the respective pathways.

4.2.1.1 - Results

Figure 4.1 and Table 4.1 depict the WTW GHG emissions of the current and near-term bio-methanol pathways:

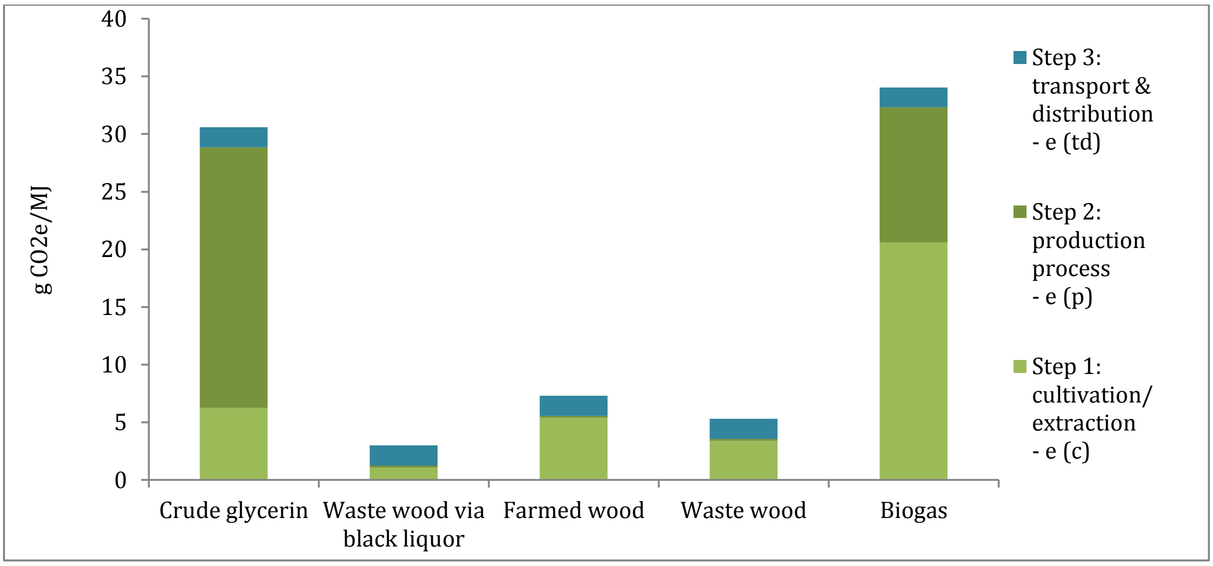


Figure 4.1 - WTW GHG emissions of current and near term bio-methanol pathways (g CO_2e/MJ)

It can be seen that the *Waste wood via black liquor* pathway has the lowest GHG emissions of all current and near-term bio-methanol pathways. This is due to a low energy input required for the extraction and provision of raw materials for the fuel production process.

The highest WTW emissions appear in the *Biogas* pathway which can be attributed primarily to the high energy input for the cultivation of maize and barley and, secondly, to the energy-intensive methanol production process through steam reforming of upgraded biogas. However, the results for the *Biogas* pathway imply a certain improvement potential as the production of methanol from biogas is expected to become more energy-efficient in the near future [IRENA 2013]. Similarly, the GHG balance of the *Crude glycerine* pathway could be expected to improve if the natural gas input for the represented methanol production process were substituted by biogas or by utilising the energy content of the crude glycerine feedstock itself (see section 4.2.1.2 for specific elaborations).

Table 4.1 - WTW GHG emissions of current and near term bio-methanol pathways (g CO_2e/MJ)

Pathway	Step 1: cultivation/ extraction e (c)	Step 2: production process e (p)	Step 3: transport & distribution e (td)	Step 4: end-use e (u)	WTW GHG emissions Σ (E)
Crude glycerin	6.25	22.60	1.74	0.00	30.59
Waste wood via black liquor	1.06	0.20	1.74	0.00	3.00
Farmed wood	5.40	0.17	1.74	0.00	7.32
Waste wood	3.40	0.17	1.74	0.00	5.32
Biogas	20.60	11.70	1.74	0.00	34.04

Figure 4.2 and Table 4.2 show the WTW efficiency ranges of the current and near-term bio-methanol pathways. Thereby, an uncertainty factor of 10% in both directions is incorporated in the ranges represented in the illustration (Figure 4.2) in order to compensate for the implied degree of uncertainty in the WTW model.

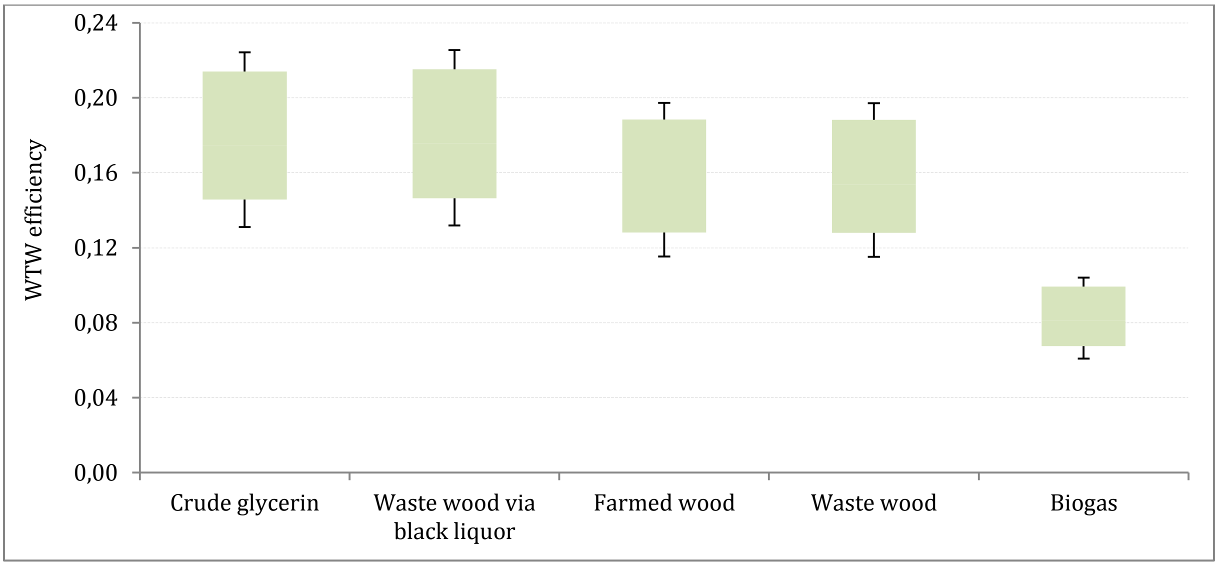


Figure 4.2 - WTW efficiency ranges of current and near term bio-methanol pathways (%)

It can be seen that of all current and near-term bio-methanol pathways the *Waste wood via black liquor* pathway has the highest WTW-efficiency. This is due to both, the high efficiency in collecting and allocating the raw materials for the methanol production, and the relatively high efficiency of the methanol production process itself. However, except for the *Biogas* pathway, most of the pathways perform rather similarly. The main reasons for the low WTW-efficiency of the *Biogas* pathway are the energy losses in the anaerobic digestion of the raw materials to biogas and the subsequent upgrading to biomethane (allocated to step 1). In general, the depicted ranges signify that the ability of ICE to utilise the efficiency-improving characteristics of methanol fuel (see section 3.3) can have a significantly positive impact on the WTW efficiency.

Table 4.2 - WTW efficiencies of current and near term bio-methanol pathways (%)

Pathway	Step 1: cultivation/ extraction η (c)	Step 2: production process η (p)	Step 3: transport & distribution η (td)	Step 4: end-use η(u)			WTW efficiency Π		
				a) min	b) mid	c) max	a) min H	b) mid H	c) max H
Crude glycerin	0.95	0.65	0.98	0.24	0.29	0.34	0.15	0.17	0.20
Waste wood via black liquor	0.94	0.66	0.98	0.24	0.29	0.34	0.15	0.18	0.21
Farmed wood	0.92	0.59	0.98	0.24	0.29	0.34	0.13	0.15	0.18
Waste wood	0.92	0.59	0.98	0.24	0.29	0.34	0.13	0.15	0.18
Biogas	0.42	0.68	0.98	0.24	0.29	0.34	0.07	0.08	0.09

4.2.1.2 - Specific assumptions and concrete explanations

For the pathways shown in Tables 4.1 and 4.2 and Figures 4.1 and 4.2, the respective values of $e(c)$ and $\eta(c)$ account for the efforts and energy inputs which are necessary for collecting, cultivating or extracting the required raw materials and transporting them by truck to a methanol production facility. Thereby, the emissions from the transport effort are rather minor constituents in all pathways. The values of $e(p)$ and $\eta(p)$ quantify the energy balance for the biomass gasification and methanol synthesis of the respective raw materials in state of the art processing plants (see section 3.4.1).

In this analysis it is assumed that bio-methanol should be produced regionally and close to consumption within European boundaries. Therefore, a calculation is produced for the transportation and distribution of an inner-European product. The values for $e(td)$ and $\eta(td)$ are partly based on the source data which states figures for imported fossil methanol. However, the values are changed to account for 600 km sea transport and 50 km distribution on road and rail within the EU. It is believed that these revised assumptions reflect a realistic average of inner-European distances of fuel shipping and distribution since most terminals are located at sea- or river harbours, therefore requiring only low average shipping and trucking distances.

The values for $e(u)$ are zero due to the underlying assumption of carbon-neutrality (see section 4.1 for further explanation). The values for $\eta(u)$ in step 4 (TTW) are calculated on the base of a gasoline-powered mid-size vehicle model of projected EU-average thermal efficiency of 21.8% in the year 2020 [ENS 2012a]. Due to its advantageous fuel characteristics, as described in section 3.3, methanol fuel can increase the end-use performance of the engine, achieving a more efficient combustion than gasoline fuel. Literature suggests that this efficiency increase lies somewhere between 20-40% in modern engines with an increased compression ratio and using DI [Brusstar & Bakenhus 2002].

For conservative estimation however, it must be considered that the extent to which engines can utilise the efficiency-improving properties of methanol fuel are somewhat ambiguous. Therefore three possibilities are accounted for in the analysis: a) the average thermal efficiency of 21.8%, marginally increased by 10%; b) the average thermal efficiency of 21.8%, increased by 20%; c) the average thermal efficiency of 21.8%, increased maximally by 40%.

In what follows, further assumptions and the concrete nature of the respective pathways are described:

- The *Crude glycerine* pathway: crude glycerine is a viscous by-product from the production of bio-diesel and is widely used as a component in a great number of chemical applications. Using residue glycerine as methanol feedstock can improve the environmental performance of both, the production of bio-diesel and, in comparison to an otherwise fossil feedstock, the production of methanol.

Due to a lack of specific data for the transportation of crude glycerin to the methanol production facility, the values for $e(c)$ and $\eta(c)$ in this pathway are calculated by offsetting the weighted average distance of glycerine imports to Dutch bio-methanol producer *BioMCN* with $e(td)$ and $\eta(td)$, the inner European bio-methanol distribution values assumed in this analysis (described above). This is a simplifying yet valid assumption because the two products glycerine and methanol are of similar nature: they are both pumpable liquid products and they have similar energy contents per volume.

Once the glycerine has been collected and transported from the bio-diesel plants to the methanol plant, *e(p)* and *η(p)* account for the energy invested in the purification, evaporation and cracking of the glycerine to eventually obtain syngas from which bio-methanol can be synthesised. As the energy inputs for the represented process are largely based on natural gas, the GHG emissions in *e(p)* are relatively high compared to the other bio-methanol pathways.

- The *wood waste via black liquor* pathway: black liquor is a residue of paper processing in pulp mills. Paper processing involves the separation of cellulose from the other two main components of wood, lignin and hemicellulose, which end up together with most of the processing chemicals in a residue of watery sludge called black liquor. This product contains roughly half of the organic material that was in the wood originally and therefore has a high energy content. It is usually burned in a so-called recovery boiler in order to produce electricity and process heat for the pulp mill, thereby covering a significant part of its energy demand [Ekbom et al., 2005]. Alternatively, by the use of a gasifier unit, the black liquor can be converted to syngas from which methanol can be synthesised. Thus, in this pathway, the raw material for the production of methanol is an already processed and pumpable liquid which is easily collected on-site.

  If the black liquor is used for the production of methanol, consequently another source of energy is needed to produce process heat for the pulp mill. Therefore, residuals from commercial forestry such as branches and tops are collected and burnt in the so-called hog boiler of the pulp mill. Thereby this waste wood substitutes the black liquor which before was used for producing process heat and which now can be allocated to the production of bio-methanol. Thus, at the bottom line, this resembles a net wood waste-to-methanol pathway.

  The waste wood is collected in the course of felling the stem trees for the pulp production and transported to the production facility by use of the same transport infrastructure. *e(c)* and *η(c)* account for the collection, chipping and trucking of the waste wood. Besides rendering accessible the highly convenient black liquor feedstock for methanol production, the burning of wood waste in the hog boiler also increases the efficiency of process heat generation for the pulp mill. This leads to an efficiency improvement of the pulping process which is accounted for in the net values for *e(p)* and *η(p).*

  In countries with a small population but a relatively large paper industry, black liquor-based methanol and derived DME could potentially replace a large part of the of the fuel demand. Olah et al. [2009] state that in Sweden the share could be as high as 28% and in Finland even 50%.

- The *Farmed wood* pathway: this pathway is mainly based on fast-growing woody crops from Short Rotation Forestry (SRF) such as poplar or willow. As opposed to conventional forestry where trees are grown for decades in order to supply the paper and plywood industries, in SRF the trees are harvested after only 4-10 years in order to maximise biomass generation for energetic utilisation. Moreover, this pathway also incorporates perennial grasses such as miscanthus or switch grass which offer similar yields but have lower water requirements. As agricultural activity is limited by the availability of water in large parts of Southern Europe, this is a relevant consideration. SRF plantations generally have less energy inputs as bio-energy crops such as, for instance, rape or wheat because they require less labour and fertilizer. This small need for energy inputs consequently has a favourable impact on the GHG performance of the pathway. *e(c)* and *η(c)* account energy inputs for cultivation, fertilising, harvesting and 50 km road transportation to the methanol plant. *e(p)* and *η(p)* reflect the gasification and synthesis in a state-of-the art facility.

- The *Waste wood* pathway: in this pathway, the gasification of farmed wood is substituted by the gasification of woody waste products. Thereby, in addition to the residuals from commercial forestry activities, other types of wood wastes can be used as feedstock as well, for example, secondary wastes from the timber industry such as sawdust, or forest litter such as dead wood removed from old stands.

  The efforts to collect and transport these raw materials to the methanol production plant are greater than in the farmed wood pathway because they are usually dispersed at lower densities over wider geographical areas. However, the value for *e(c)* is lower than in the farmed wood pathway because no cultivation and fertilizing is taken into account for waste wood. *e(p)* and *η(p)* reflect the same gasification and synthesis process as in the *Farmed wood* pathway.

- The *Biogas* pathway: in this pathway the biogas is produced from maize and barley which are common biogas-feedstocks in the EU and can be cultivated by double cropping on the same land during a single growing season.

  e(c) and *η(c)* account for all efforts associated with the cultivation and harvest of the feedstock, the production of biogas in an anaerobic digester and the upgrading of the biogas to biomethane quality. Subsequently, the upgraded biogas is passed to the natural gas grid where it can be easily stored. In *e(p)* and *η(p)* the virtual biogas is extracted from the natural gas grid and transformed to methanol via steam reforming and subsequent synthesis (see descriptions in section 3.4.1.1).

  The production of bio-methanol from biogas competes with the direct use of upgraded biogas, either in gas-based vehicles or in gas-based CHP plants, which might offer better resource-efficiency and could be a more optimal use from a holistic energy system perspective. This comparison cannot be made in this study but has been partly undertaken by Grandal [2013].

4.2.2 - Novel mid-term bio-methanol pathway

This pathway incorporates the *novel mid-term method* for the production of bio-methanol, integrating SOEC. This concept is described in section 3.4.2.

Section 4.2.2.1 depicts the results of the WTW GHG emissions and efficiency model in comparison to the results of the *current and near-term Farmed wood* pathway described in the previous section. As both pathways depend on the same feedstock, it is therefore possible to directly assess how the integration of SOEC improves the WTW performance in the *novel* concept. Section 4.2.2.2 further explains the specific inputs to the model.

4.2.2.1 - Results

Figure 4.3 and Table 4.3 depict the WTW GHG emissions of the novel medium-term pathway for bio-methanol production based on gasification of farmed wood and integrating SOEC, in comparison to the *current and near-term Farmed wood* pathway described in the previous section:

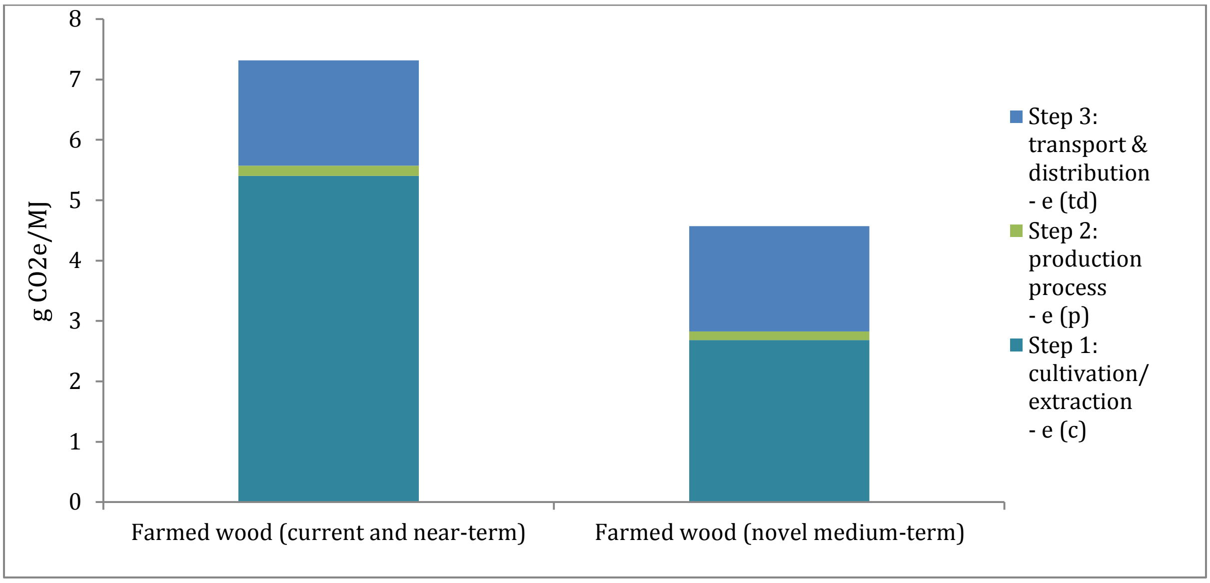


Figure 4.3 - WTW GHG emissions of novel medium-term pathway vs. current and near term pathway (g CO_2e/MJ)

It can be seen that the carbon efficiency improvement through integration of SOEC in the *novel* concept significantly reduces the WTW GHG emissions by roughly 60%. This difference accounts for the significantly reduced energy input which is required per MJ bio-methanol output (accounted in steps 1 and 2) but also for the high electricity input which is required to operate the SOEC (accounted in step 2).

Table 4.3 - WTW GHG emissions of novel medium-term pathway vs. current and near term pathway (g CO_2e/MJ)

Pathway	Step 1: cultivation/ extraction	Step 2: production process	Step 3: transport & distribution	Step 4: end-use	WTW GHG emissions Σ
	e (c)	e (p)	e (td)	e (u)	*E*
Farmed wood (current and near-term)	5.40	0.17	1.74	0.00	7.32
Farmed wood (novel medium-term)	**2.68**	**0.14**	**1.74**	**0.00**	**4.57**

Figure 4.4 and Table 4.4 depict the WTW GHG efficiency range of the *novel medium-term pathway* in comparison to the *current and near-term Farmed wood* pathway described in the previous section. Thereby, an uncertainty factor of 10% in both directions is incorporated in the ranges represented in the illustration (Figure 4.4) in order to compensate for the implied degree of uncertainty in the WTW model.

Figure 4.4 - WTW efficiency range of novel medium-term pathway vs. current and near term pathway (%)

It can be seen that the integration of SOEC in the novel concept significantly increases the WTW efficiency by roughly 25% on average. Furthermore, the depicted ranges signify that the ability of ICE to utilise the efficiency-improving characteristics of methanol fuel (see section 3.3) can be of significantly positive impact on the WTW efficiency.

Table 4.4 - WTW efficiency range of novel medium-term pathway vs. current and near term pathway (%)

Pathway	Step 1: cultivation/ extraction η (c)	Step 2: production process η (p)	Step 3: transport & distribution η (td)	Step 4: end-use η(u)			WTW efficiency Π		
				a) min	b) mid	c) max	a) min H	b) mid H	c) max H
Farmed wood (current and near-term)	0.92	0.59	0.98	0.24	0.29	0.34	0.13	0.15	0.18
Farmed wood (novel medium-term)	**0.96**	**0.71**	**0.98**	**0.24**	**0.29**	**0.34**	**0.16**	**0.19**	**0.22**

4.2.2.2 - Specific assumptions and concrete explanations

Although both pathways are based on the same feedstock, their values in *e(c), e(p), η(c)* and *η(p)* greatly differ, signifying the carbon efficiency improvement effect of SOEC integration: while in the *current and near-term* bio-methanol production concept large parts of the available CO_2 in the syngas must be removed in order to optimize the C/H ratio for the methanol synthesis, in the *novel* concept the addition of SOEC-derived hydrogen to the synthesis reaction enables a much better utilization of the CO_2 which is present in the syngas. As described in section 3.4.2, this improved carbon efficiency theoretically doubles the methanol output which can be produced from the same amount of wood input: from 523 tons per day in the *current and near-term* production concept to 1,053 tons per day in the *novel* concept [Mortensgaard et al. 2011]. This doubling of the carbon efficiency consequently halves the land area which is required for the same bio-methanol output.

Thereby it should be noted that the doubled carbon efficiency does not directly double the WTW efficiency as a significant electricity input is required to operate the SOEC. However, it is a strong indicator, as is reflected in the presented results.

The values of *e(td)* and *η(td)* constitute the same efforts as for the pathways in section 4.2.1: an average distance of 600 km shipping and 50 km road transport to bio-methanol fuelling stations within the EU. In equal measure, the values for *e(u)* in the TTW step are zero due to the underlying assumption of carbon-neutrality. Moreover, the values for *η(u)* are produced by applying an efficiency improvement range of 10-40%, on the base of a gasoline-powered mid-size vehicle model of projected EU-average thermal efficiency of 21.8% [ENS 2012a].

4.2.3 - Long-term renewable methanol pathway

This pathway is based on the on-site capture of concentrated CO_2 emissions and subsequent recycling to methanol using electrolysis-derived hydrogen. This concept is described in section 3.4.3.

Section 4.2.3.1 depicts the results of the WTW GHG emissions model for this pathway in comparison to the results of the *near-term* and *medium-term* bio-methanol pathways described in the previous sections. As this pathway is biomass-independent, it implies only very marginal consumption of natural resources and therefore its specific WTW efficiency is not further highlighted here. Section 4.2.3.2 further explains the specific inputs to the model.

4.2.3.1 - Results

Figure 4.5 and Table 4.5 depict the results of the WTW GHG emissions of the long-term renewable methanol pathway (*CO_2 capture and recycling*) in comparison to the bio-methanol pathways described in the previous sections:

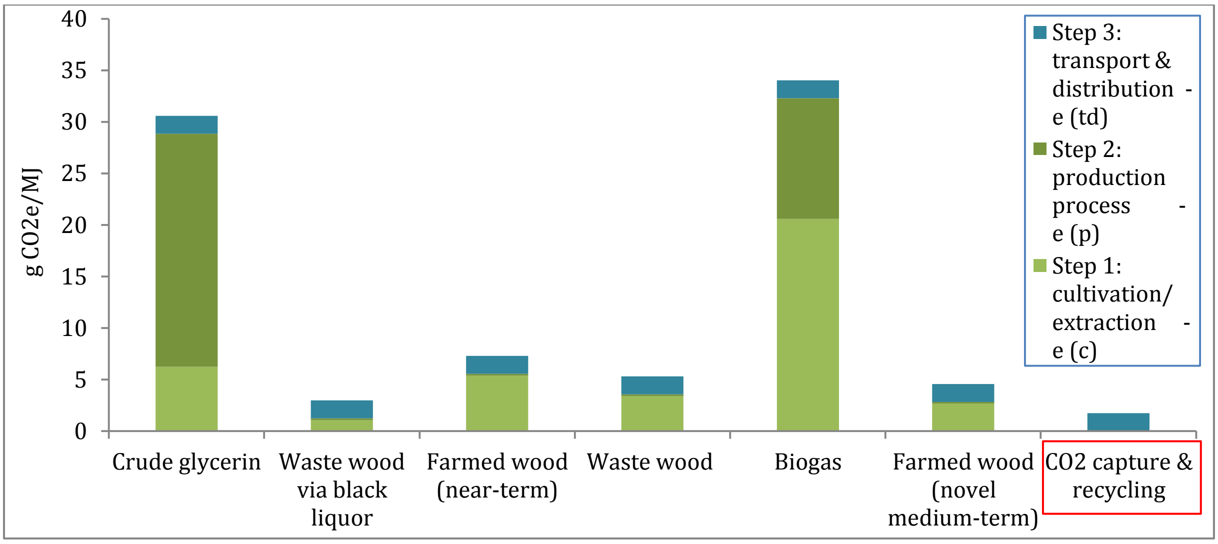


Figure 4.5 - WTW GHG emissions of long-term renewable methanol pathway vs. near- and medium-term bio-methanol pathways (gCO2e/MJ)

It can be seen that the long-term renewable methanol pathway only accounts for very marginal GHG emissions and in this regard is superior to the *near-term* and *medium-term* bio-methanol pathways.

Table 4.5 - WTW GHG emissions of long-term renewable methanol pathway vs. near- & medium-term bio-methanol pathways (g CO_2e/MJ)

Pathway	Step 1: cultivation/ extraction e (c)	Step 2: production process e (p)	Step 3: transport & distribution e (td)	Step 4: end-use e (u)	WTW GHG emissions Σ *E*
Crude glycerin	6.25	22.60	1.74	0.00	30.59
Waste wood via black liquor	1.06	0.20	1.74	0.00	3.00
Farmed wood	5.40	0.17	1.74	0.00	7.31
Waste wood	3.40	0.17	1.74	0.00	5.31
Biogas	20.60	11.70	1.74	0.00	34.04
Farmed wood (novel medium-term)	2.68	0.14	1.74	0.00	4.57
CO_2 capture & recycling (long-term)	**0.00**	**0.00**	**1.74**	**0.00**	**1.74**

4.2.3.2 - Specific assumptions and concrete explanations

e(c) and *e(p)* in this pathway constitute of the on-site capture of concentrated industrial CO_2 emissions and the subsequent electrochemical methanol production process via synthesis at low pressure and low temperature. Thereby, these efforts are based on a carbon-neutral renewable energy input and therefore no GHG emissions are attributed to these steps.

Clearly, this represents an optimal situation of technical and economic availability of renewable electricity. However, the feasibility of this concept is demonstrated by *CRI* who commercially operate such a plant in Iceland which offers highly favourable conditions in terms of available renewable energy (see chapter 3.4.3) [CRI 2013a].

GHG emissions are attributed in e*(td)* for 600 km shipping and 50 km road transport of the methanol product to refuelling stations within the EU. Equally to the pathways described in the previous sections, GHG emissions in *e(u)* are zero due to the underlying assumption of carbon-neutrality.

4.3 – Comparison of renewable methanol- and comparative fossil- and biofuel pathways

As described in the introduction to this chapter, the primary aim of this WTW-analysis is to investigate the potentials of renewable methanol technology in regard to the EU biofuels-policy objective of *Greenhouse Gas Savings* and, to a secondary extent, in regard to the objective of *Security of Supply*. In order to produce a comprehensive assessment, the author includes a number of comparative fossil- and biofuel pathways in the WTW-analysis, thereby creating a base for comparative evaluation.

This comparative evaluation takes place in what follows: section 4.3.1 compares the WTW GHG emissions of the renewable methanol pathways which are described in the previous sections to the chosen comparative pathways which are also described in detail. Section 4.3.2 compares the WTW efficiencies of bio-methanol-pathways to the comparative ethanol and biodiesel pathways, thereby indicating how efficiently biomass resources are generally utilized by these technologies.

4.3.1 - Comparison of WTW GHG emissions of renewable methanol- and comparative fossil- and biofuel pathways

In what follows, section 4.3.1.1 depicts and discusses the differing WTW GHG emissions performances of renewable methanol pathways in comparison to pathways for fossil methanol, gasoline, diesel, ethanol and biodiesel. Thereby the evaluation takes place in view of upcoming regulatory emission savings requirements for biofuels. Moreover, the author introduces the self-conceived concept of *fossil intensity* which integrates the WTW-GHG emissions of fuel pathways and their TTW-efficiency ranges. This enables an improved assessment of the comparative GHG reduction potential of renewable methanol technology. Section 4.3.1.2 explains in detail the specific inputs and assumptions for the comparative fossil- and biofuel pathways

4.3.1.1 - Results

Figure 4.6 illustrates the respective WTW GHG emissions of all investigated renewable methanol- and comparative fossil- and biofuel pathways:

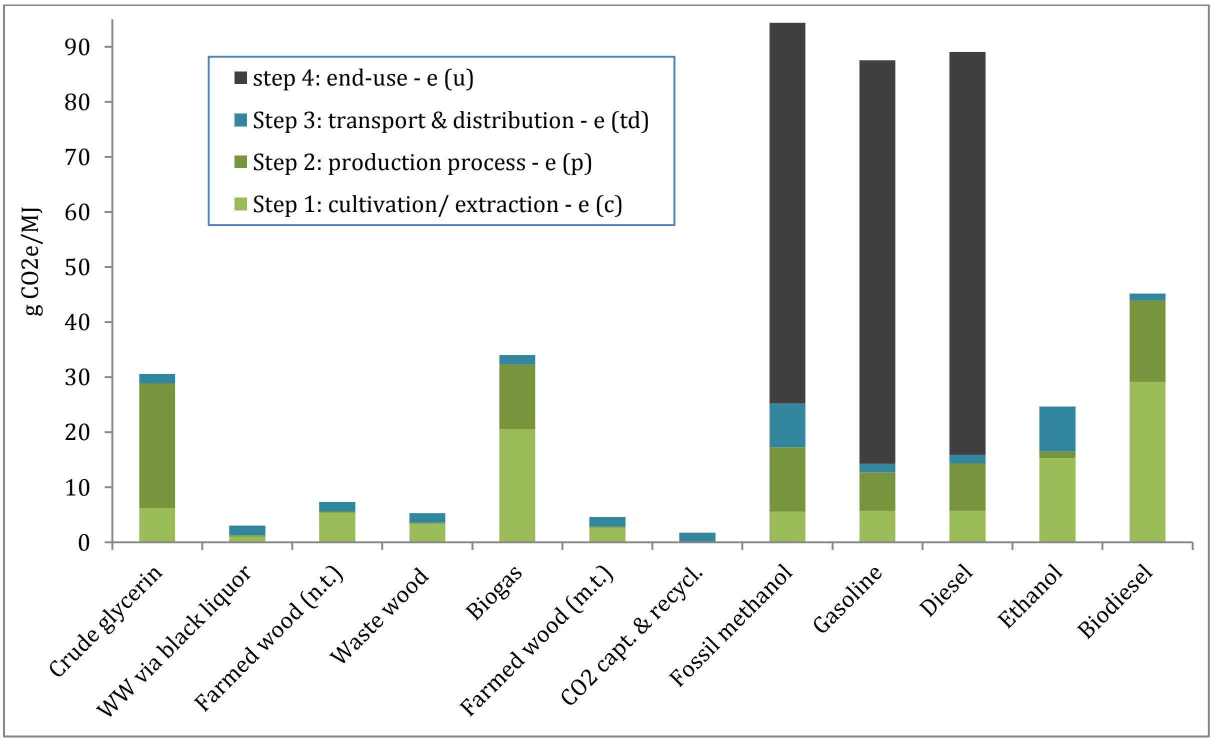


Figure 4.6 - WTW GHG emissions of renewable methanol- and comparative fossil- and biofuel pathways (g CO_2e/MJ)

At first sight it is obvious that all renewable methanol pathways have greatly reduced WTW GHG emissions in comparison to fossil fuel pathways. This is mainly due to the apparent fact that fossil fuels account for very high GHG emissions in *e(u).*

The renewable methanol pathways also account for less WTW GHG emissions than the comparative biofuel pathways for ethanol and biodiesel, except for the *Crude glycerine* and the *Biogas* pathways which are slightly more emitting than the *Ethanol* pathway. Thereby it must be noted that the ethanol pathway represents an ethanol product produced from Brazilian sugarcane which generally accounts for less WTW GHG emissions than European ethanol products which are based on wheat or sugar beet, as is illustrated in Figure 4.7 [F3 2013].

Consequently, if the *Crude glycerine* and the *Biogas* pathways were compared to sugar beet- or wheat-based ethanol pathways, they would seem more favourable in regard to GHG emissions.

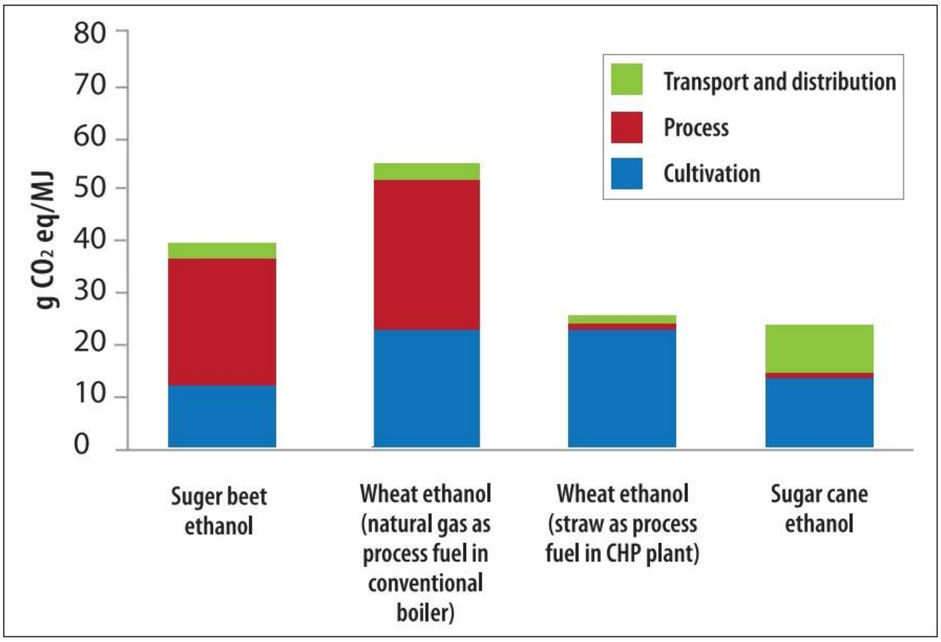


Figure 4.7 – WTW GHG emissions of different ethanol pathways (g CO2e/MJ) [adapted from F3 2013]

Figure 4.8 illustrates only the WTW GHG emissions of the renewable methanol- and comparative biofuel pathways in view of the upcoming emission savings requirements for biofuels in the EU: the EU *Fuel Quality Directive* (*FQD*) requires all biofuels to have WTW GHG emission reductions of at least 35% compared to a reference fossil fuel comparator of 83.8 g CO2eq/MJ. This emissions reductions requirement is to be gradually increased to 50% in 2017 and 60% in 2018 for new plants [EU 2009b]. The red lines in the Figure mark the according maximum emissions levels for biofuels:

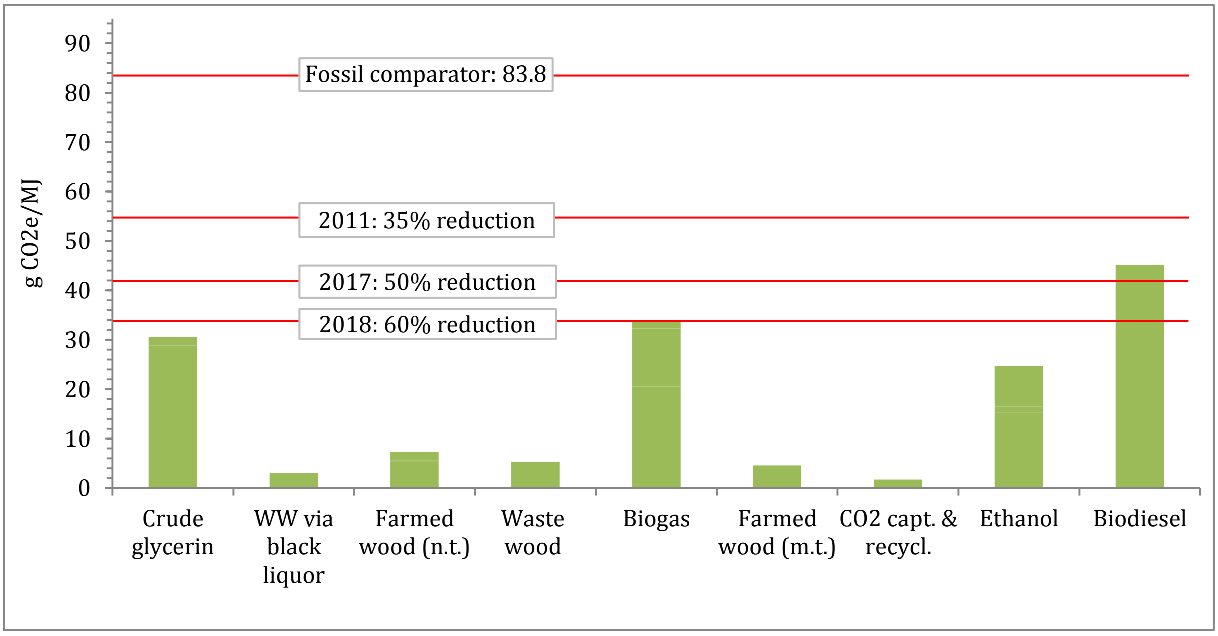


Figure 4.8 - WTW GHG emissions of renewable methanol- and comparative biofuel pathways in view of *FQD* emission savings requirements for biofuels (g CO2e/MJ)

It can be seen that, except for the *Biogas* pathway, all renewable methanol pathways comply with the upcoming regulatory emissions limits. However, the *Biogas* pathway investigated here also implies a relatively favourable prospect in this regard as current R&D activities are expected to yield efficiency improvements in the biogas-to-methanol production process (step 2) in the near future [IRENA 2013].

Moreover, it can be seen that the investigated comparative *Biodiesel* pathway does not comply with the upcoming regulatory emissions limits. As biodiesel is currently the most predominant biofuel in use in the EU, this finding substantiates the apparent need for less-emitting biofuel alternatives such as bio-methanol.

Figure 4.9 illustrates the *fossil intensity* of all investigated fuel pathways: the *fossil intensity* accounts the entire fossil energy input which must be invested during a fuel pathway in order to propel a standard passenger car one km. Thereby, the calculative base is an ICE-based car with an emissions-standard of 95 gCO_2/km, complying with recent EU regulations on GHG emissions from new passenger cars in 2020 [EC 2012a].

This representation is of significance as the illustrated ranges depict the effect which the efficiency-improving fuel properties of alcohols in ICE (see chapter 3) can have on the WTW fossil energy requirement and, consequently, on the overall GHG emissions performance of a vehicle. Moreover, the ranges represented in this illustration incorporate an uncertainty factor of 10% in both directions in order to compensate for the implied degree of uncertainty in the WTW model (see section 2.3 for a detailed elaboration on this issue).

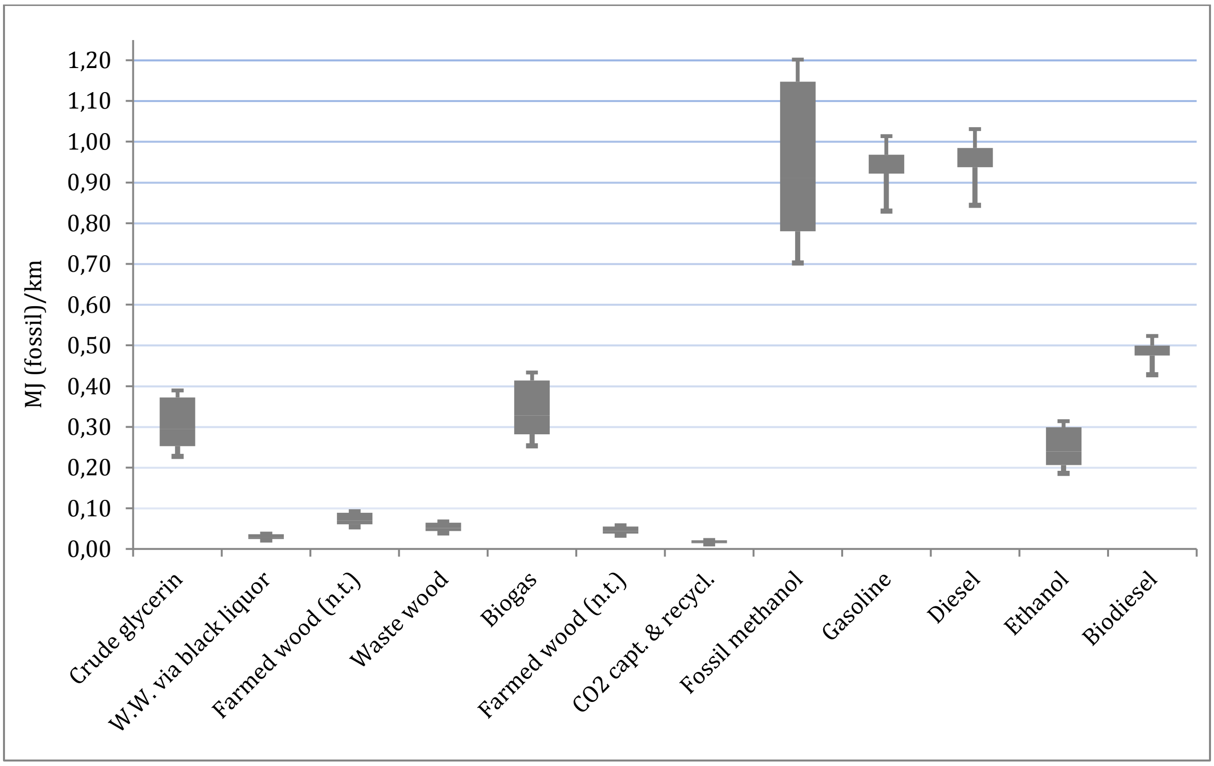


Figure 4.9 - WTW *fossil intensity* of all investigated pathways (MJ$_{\text{(fossil)}}$ / km)

It can be seen that the efficiency-improving fuel properties of methanol have a significant effect on the overall fossil energy requirement. This is most obvious in the case of fossil methanol which performs better than gasoline and diesel if its fuel properties are accounted for. By way of contrast, the depiction of the WTW GHG emissions in Figure 4.6 indicates higher emissions for fossil methanol than for gasoline and diesel as it does not yet account this effect.

However, in the context of this research this effect is of significance primarily to the evaluation of renewable methanol. Table 4.6 therefore depicts the pathway-specific ranges of GHG emission savings of renewable methanol as against the comparative fossil- and biofuels:

Table 4.6 - Pathway-specific GHG reductions of renewable methanol as against comparative fuel pathways, based on *fossil intensity* (%)

Pathway	Fossil methanol	Gasoline	Diesel	Ethanol	Biodiesel
Crude glycerin	0.55 - 0.77	0.62 - 0.73	0.62 - 0.73	0.71 - 0.11	0.25 - 0.47
Waste wood via black liquor	0.96 - 0.98	0.96 - 0.97	0.96 - 0.97	0.83 - 0.91	0.93 - 0.95
Farmed wood (current and near-term)	0.89 - 0.94	0.91 - 0.93	0.91 - 0.94	0.59 - 0.79	0.82 - 0.87
Waste wood	0.92 - 0.96	0.93 - 0.95	0.93 - 0.95	0.70 - 0.85	0.87 - 0.91
Biogas	0.49 - 0.74	0.57 - 0.69	0.58 - 0.70	-0.91 - 0.01	0.17 - 0.41
Farmed wood (novel medium-term)	0.93 - 0.97	0.94 - 0.96	0.94 - 0.96	0.74- 0.87	0.89 - 0.92
CO_2 capture & recycling (long-term)	0.97 - 0.99	0.98 - 0.98	0.98 - 0.98	0.90 - 0.95	0.96 - 0.97

It can be seen that renewable methanol generally achieves great emissions reductions compared to fossil fuels and biodiesel. The same goes for the comparison with ethanol, except for *Crude* *glycerine*- and *Biogas*-based bio-methanol which only saves GHG emissions in the best cases[6] and is expected to be more emitting on average. The highest emissions reductions are clearly achieved by renewable methanol which is based on the long-term pathway. In regard to bio-methanol which is based on near-term pathways, the highest savings are achieved by bio-methanol based on *Black liquor*, followed by bio-methanol based on *waste wood*.

It should be noted that the results which are described here are partly confirmed by Volvo [2008] who have analysed the environmental performance of different biofuels in heavy-duty applications, among them black liquor-based bio-methanol for which a GHG emissions reduction of more than 90% compared to fossil fuels was indicated.

4.3.1.2 - Specific assumptions and concrete explanations on the comparative fossil- and biofuel pathways

- The *Fossil methanol* pathway: this pathway is based on natural gas-based methanol production at remote plants in Western Siberian gas fields and its subsequent import to the EU. Thereby the value in *e(c)* accounts the efforts for the extraction of natural gas. It should be noted however, that generally the energy which must be invested to extract and process the natural gas can vary significantly between regions and fields of origin due to, for instance, differing practices, climatic conditions or gas qualities. The value in *e(p)* accounts for the methanol production in a state-of-the art plant of 600 MW capacity (roughly 900 kt/a). *e(td)* accounts for a shipping distance of 5,000 nm (roughly 9,260km) to the EU and 250 km of methanol distribution to fuelling stations within the EU via road and rail. *e(u)* accounts the standard emissions factor of fossil methanol of 69.1 gCO_2/MJ [CONCAWE 2011a].

- The *Gasoline* pathway: this pathway is based on crude oil which most often can be extracted by utilising the natural pressure in underground reservoirs. In other cases this pressure must be boosted by injecting gas into the reservoir. Most often the crude oil is associated with gases and must be pre-treated before shipping. Thus, for the largest part, the value for *e(c)* accounts for emissions from the efforts to extract and stabilize the crude oil and from the flaring and venting of undesirable hydrocarbons. Production conditions can vary considerably between different regions of origin. Therefore these values represent average emissions and efficiencies for the wide range of crude oil products from regions such as the Middle East, Africa or the FSU, transported to European gasoline refineries in pipelines or large carriers of 200-500 kt capacity [CONCAWE 2011b].

  e(p) accounts for the gasoline refining process in a state-of the art refining plant in Europe. Here, in a complex combination of processing plants, the crude oil is turned into marketable gasoline by physically separating the crude components, cracking heavy hydrocarbon molecules into lighter ones and removing unwanted compounds such as sulphur [EB 2013]. The value in *e(td)* accounts the efforts for transporting the gasoline 750 km to an interim storage within Europe by barge, rail and pipeline. Furthermore, 150 km of subsequent distribution to a gasoline station by

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[6] The best case here refers to a maximum efficiency increase of 40% for bio-methanol fuel vs. a minimum efficiency increase of 10% for ethanol fuel in the ICE (based on an average thermal ICE efficiency of 21.8%). This is however unlikely in the same engine and would require its methanol-specific optimisation.

tank truck are accounted for. *e(u)* accounts the standard emissions factor of gasoline of 73.3 gCO_2/MJ [CONCAWE 2011a].

- The *Diesel* pathway: this pathway is very similar to the gasoline pathway as both fuels are refined from the same crude oil and are distributed in the same manner within Europe. However, the value in *e(p)* is higher because the diesel refining process requires more energy input in comparison. *e(u)* accounts the standard emissions factor of diesel of 73.2 gCO_2/MJ [CONCAWE 2011a]

- The *Ethanol* pathway: this pathway is based on Brazilian sugarcane and is chosen as comparative biofuel pathway over a European alternative because it accounts for less WTW GHG emissions than European ethanol pathways based on wheat or sugar beet (see Figure 4.7), thereby allowing for more conservative comparative results on renewable methanol. Moreover, Brazilian ethanol from sugar cane currently represents the largest share of all foreign ethanol imports to the EU and is bound to increase in the coming decade due to pressure from EU biofuel mandates [EU 2009a-b] and Brazil's large potential for expanding its production [CIFOR 2012; OECD 2012].

  Due to favourable climatic conditions, Brazilian sugarcane has much higher annual yields than European ethanol-crops and, unlike European crops, planting sugarcane on previous pastureland is estimated to increase soil carbon stocks [CONCAWE 2011a]. However, this estimation is not quantified here. The data source states values for a Brazilian *best-practice* scenario in cultivation and production of anhydrous ethanol [CONCAWE 2011a]:

  e(c) accounts the emissions which can be attributed to farming activities and the production of fertilizers. The accruing bagasse is burned to provide process heat and electricity via a steam turbine and is credited accordingly in *e(p)*. Other potential external uses for surplus bagasse are not credited here. The transport to the production facility is accounted for by a weighted average of nearer and more distant fields. *e(p)* furthermore accounts the required energy inputs in a state of the art ethanol plant with a capacity of roughly 34 kt per year*. e(td)* accounts the efforts for the transport of the ethanol to a harbour over a weighted average distance, the subsequent shipping of the ethanol to the EU and its distribution to fuelling stations over an average distance of 500 km via rail and road.

- The *Biodiesel* pathway: this pathway is chosen as a comparative biofuel pathway because with a market share of roughly 75% it is currently by far the most widely used biofuel in the EU (EC 2013b). Thereby the dominating feedstock which is cultivated for its production is rapeseed which has the highest oil yield in the Northern half of Europe and is also represented in this pathway. Rapeseed is usually farmed in rotation with wheat [CONCAWE 2011a].

  The value in *e(c)* accounts for all energy inputs associated with cultivating, harvesting and transporting the rapeseed feedstock to a biodiesel production facility. Thereby the emissions from transporting the feedstock to the bio-diesel plant have a minor impact on the overall GHG emissions of the pathway. The emissions associated with the production of fertilizers are more significant.

The value in *e(p)* accounts for the extraction of the plant oil from the feedstock, its refining and trans-esterification. In this process, the fats in the rapeseed oil are converted into so-called rapeseed methyl ester (RME) through reaction with an alcohol, usually methanol. RME is of lower viscosity and has better fuel properties than the initial rapeseed oil. In this analysis, the rapeseed cake is modelled as stock for animal feed. However, it could also be used as biogas-feedstock which would have different implications for the GHG emissions of the pathway. No credit for a potential utilization of the residue glycerin from the trans-esterification process is included here as the database does not offer the values required for such a calculation. The WTW GHG emissions are greatly determined by N_2O emissions in the cultivation step in *e(c)* due to the high requirement of nitrogen fertiliser. *e(td)* accounts for the distribution of the biodiesel to fuelling stations within Europe over an average distance of 500 km via rail and by trucks.

4.3.2 - Comparison of WTW efficiencies of bio-methanol- and comparative biofuel pathways

In regard to the *Security of Supply* objective of EU biofuels policy, the elaborations in the proceeding chapter have emphasised the feedstock flexibility of renewable methanol technology as a highly advantageous prospect. In the same regard, the maximizing of energy efficiency in the utilisation of biomass resources is of importance as well.

Although comparing biofuel pathways and -technologies which are based on different raw materials and feedstocks on the basis of the same efficiency parameter cannot be a clear and decisive measure of their land-use or preferability, comparing the EROEI of different pathways does however give at least an indication on how efficiently biomass resources are utilized in general. Clearly, this is of particular importance in the context of limited bio-resources for energetic utilisation. Therefore, Table 4.7 depicts the relative WTW EROEI performance of the investigated bio-methanol pathways in comparison to the comparative biofuel pathways for ethanol and biodiesel:

Table 4.7 - WTW EROEI performance of bio-methanol pathways vs. comparative biofuel pathways (%)

Pathway	Ethanol	Biodiesel
Crude glycerin	-0.07 -0.44	0.48 - 0.63
Waste wood via black liquor	-0.07 - 0.45	0.49 - 0.63
Farmed wood (current and near-term)	-0.22 - 0.37	0.41 - 0.58
Waste wood	-0.22 - 0.37	0.41 - 0.58
Biogas	-1.31 - 0.20	-0.11 - 0.20
Farmed wood (novel medium-term)	0.02- 0.49	0.53 - 0.66

It can be seen that all bio-methanol pathways are clearly more energy efficient than the comparative *Biodiesel*-pathway and, except for the *Biogas*-pathway, on average they are also more efficient than the comparative *Ethanol*-pathway. Moreover, the depiction re-emphasises the energy efficiency improvement through integration of SOEC in the *medium-term* pathway.

In sum, although this comparison does not decisively prove land-use efficiency improvements, it clearly shows that, already in the near-term, renewable methanol technology is capable of efficiently utilising biomass resources, particularly of lignocellulosic nature, and in the medium-term the prospects are even more favourable.

These findings are especially relevant in view of dawning resource constraints for the production of 1G biofuels in the EU and, consequently, in regard to the *Security of Supply* objective of EU biofuels policy.

4.4 - Conclusions

The findings of the WTW-analysis in this chapter clearly demonstrate that renewable methanol technology holds significant potential in regard to the EU biofuels policy objective of *Greenhouse Gas Savings*.

The EU *FQD* requires all biofuels to have WTW GHG emission reductions of at least 35% compared to a reference fossil fuel comparator of 83.8 g CO2eq/MJ. This emissions reductions requirement is to be gradually increased to 50% in 2017 and 60% in 2018 for new plants [EU 2009b]. In view of these increasingly strict regulations, the investigated renewable methanol pathways do not only comply but greatly exceed.

The only exceptions in this regard are the *Crude glycerine* and the *Biogas* pathways: while the *Crude glycerine* pathway does indeed comply with the 60% emissions reductions requirement in 2018, it does however not reach the superior emissions reductions above 90% as the pathways which are based on black liquor or on lignocellulosic biomass. However, the GHG emissions of this pathway are expected to be reduced significantly if the fossil energy input for the methanol production process modelled here were to be substituted by a renewable energy input or by utilising the energy content of the crude glycerine feedstock itself. The *Biogas* pathway, which complies with the 50% emissions reductions requirement in 2017 but not with the 60% requirement in 2018, also implies potential for further GHG reductions as the methanol-to-biogas production process is expected to become less energy-intensive in the near future [IRENA 2013].

Furthermore, it is found that biodiesel, which is currently the most predominant biofuel in use in the EU, neither complies with the 50% emissions reductions requirement in 2017 nor with the 60% requirement in 2018. This substantiates the apparent need for less-emitting biofuel alternatives such as renewable methanol. Moreover, although the investigated sugar cane-based ethanol pathway complies with the *FQD* requirements, its emissions performance is inferior to that of the bio-methanol pathways which are based on black liquor or on lignocellulosic biomass. For clarification, compared to the *Ethanol* pathway, the *Black liquor* pathway reduces emissions by 83-91% and the *Waste wood* pathway reduces emissions by 70-85%.

The lowest GHG emissions of all investigated fuel pathways are clearly achieved by renewable methanol which is based on the long-term production method of on-site capture of concentrated CO_2 emissions and subsequent recycling to methanol using electrolysis-derived hydrogen. In the long term, this concept will enable methanol production and vehicle propulsion at near-zero WTW GHG emissions. Although this production concept is in fact already in commercial operation and doubtlessly holds positive prospects, particularly in a future energy system with high penetration of renewable electricity, in the time frame considered for this study it cannot realistically be expected to have large-scale implications for the EU biofuels sector.

By making use of the *fossil intensity* concept which integrates a pathway's WTW-GHG emissions and its respective TTW-efficiency range, the positive effect of the advantageous combustion properties of methanol fuel is reflected in the comparison of the WTW GHG emissions of the pathways. Moreover, a 10% uncertainty factor is incorporated in the production of the results in order to compensate for the implied degree of uncertainty in the WTW model.

The assessment of the novel mid-term pathway for bio-methanol, integrating SOEC, shows a significant reduction of the WTW GHG emissions by roughly 60% compared to the near-term pathway which is based on the same farmed wood feedstock. Moreover, as the integration of SOEC roughly doubles the carbon efficiency, it thereby doubles the methanol output which can be produced from the same amount of wood input. This doubling of the carbon efficiency consequently directly halves the land area which is required for the production of the same bio-methanol output.

In view of the dawning resource constraints for the production of biofuels, it is clear that improving carbon efficiency is of great importance. Therefore, the upgrading of biomass energy inputs by way of electrolysis possesses a highly relevant potential in regard to the *Security of Supply* objective of EU biofuels policy.

Moreover, the feedstock flexibility of renewable methanol technology is seen as a fundamentally favourable prospect with regard to the *Security of Supply* objective in general.

Lastly, the EROEI of the bio-methanol, biodiesel and ethanol pathways are compared. Although comparing biofuel pathways and -technologies which are based on different raw materials and feedstocks on the basis of the same efficiency parameter is not a clear and decisive measure of their land-use or preferability, it does however give an indication on how efficiently biomass resources are utilized in general. This evaluation yields that all bio-methanol pathways are clearly more energy efficient than the comparative *Biodiesel*-pathway and, except for the *Biogas*-pathway, on average they are also more efficient than the comparative *Ethanol*-pathway. Thus, already in the near-term, renewable methanol technology is capable of efficiently utilising biomass resources, particularly of lignocellulosic nature. In the medium-term, the integration of SOEC greatly improves this prospect further.

In sum, the results produced by way of the WTW-analysis method in this chapter imply significantly favourable potentials of renewable methanol technology in regard to the EU biofuels policy objective of *Security of Supply.*

5 - Socio-economic implications of large-scale renewable methanol technology deployment in the EU

This chapter assesses the potentials of renewable methanol technology primarily with regard to the EU biofuels-policy objectives *Security of Supply* and *Employment*. Moreover, it assesses the potential impact on the EU trade balance if renewable methanol technology were to be deployed on a large-scale. Such assessment must take place in view of the existing regulatory framework for biofuels which is briefly recalled at first:

The EU *RED* [EU 2009a] requires all member states to ensure that by 2020 at least 10% of all fuels used in the transport sector stem from renewable resources. As this share currently stands below 6% on an EU average, the *RED* can be viewed as the primary driver of an increasing demand for biofuels in the coming years. Furthermore, as discussed in the proceeding chapter, the EU *FQD* [EU 2009b] requires all biofuels to have WTW GHG emission reductions of at least 35% compared to a reference fossil fuel comparator of 83.8 g CO2eq/MJ. This emissions reductions requirement is to be gradually increased to 50% in 2017 and 60% in 2018 for new plants. Moreover, the *FQD* states a number of sustainability requirements for biofuels to be eligible, for instance the exclusion of feedstock extraction from primary forests, conservation areas or highly bio-diverse grasslands.

Thus, while the *RED* aims at increasing the penetration of biofuels, regardless of their GHG savings potentials, the *FQD* requirements will gain increasing importance post-2017, directly enforcing the use of biofuels with high GHG emissions reductions.

In this context, it is important to also mention the European Commission's (EC) recent call for including ILUC-related GHG emissions in the accounting models and reporting requirements of all biofuels. Moreover, the EC has proposed an absolute 5% limit on food crop-derived biofuels post-2020 [EC 2012b]. This signifies that in order to gain widespread public acceptance for further large-scale implementation of biofuels, critical issues such as ILUC and negative effects on the volatility of food prices must be avoided. The ILUC-proposal is scheduled to be voted on 10th July 2013 [EC 2012c].

The analysis in the following sections is undertaken by establishing two *prospective outlooks A* and *B*, which investigate how bio-methanol technology can be deployed beneficially with regard to *Security of Supply* and *Employment* in the EU*.* Thereby, the potential deployment of bio-methanol is analysed in view of the contrast between limited biomass resources on the one hand, and the strong growth in demand for biofuels on the other hand. Importantly, the analysis thus takes into account the current EU targets and regulatory framework for biofuel sustainability. Hereby, the main focus lies on the time frame running up until 2020 and the utilisation of the *current and near-term* bio-methanol production concept, described in the proceeding chapters.

In section 5.1, firstly the probable 2020 EU biomass demand for bio-energy is identified, in line with projections found in recent scientific literature [AEBIOM 2012; Bentsen & Felby 2012; Ecofys 2012]. Secondly, the potentially exploitable bioenergy resources within the EU are identified and discussed by considering their sustainable and economic feasibility.

Based on these findings, in section 5.2 firstly the quantity of biomass resources required for domestically supplying the projected biofuels demand in 2020 is identified, and reviewed in the context of competing demands for biomass resources from other sectors. Secondly, the potential for job-creation through bio-methanol plants is determined. On this basis, *prospective outlook A* models the potential employment creation should bio-methanol technology be deployed on a full scale in order to meet the entire EU demand for biofuels in 2020.

In section 5.3, *prospective outlook B* models the potential employment creation of bio-methanol technology if it were to substitute solely the biofuel imports to the EU, projected to increase strongly until 2020 by Elbersen et al. [2012] and the OECD [2012]. Furthermore, the potential effect on the EU trade balance by substituting these projected biofuel imports with domestically produced bio-methanol is modelled.

Section 5.4 summarizes and provides conclusions on the produced results regarding the *Security of Supply* of domestic biomass resources for large-scale implementation of bio-methanol technology in the EU, the implied *Employment* creation potential, and trade-balance effects.

5.1 - Supply and demand for bioenergy resources in view of ambitious sustainability criteria

In view of the European renewables targets for 2020 which are formulated in the *RED* [EU 2009a], Elbersen et al. [2012] conclude that more than 50% of all renewable energy supply will need to come from biomass. This is endorsed by AEBIOM [2012] who state that bio-energy will remain by far the most important source of renewable energy in the EU in 2020, covering 56.5% of the entire renewable energy share. Consequently, the demand for biomass in the energy sector can be expected to strongly increase in the coming years. This is illustrated by Bentsen & Felby [2012], who project total the renewable energy supply in the EU as is shown in Figure 5.1, and by Ecofys [2012] who project the concrete biofuels demand in the EU as shown in Figure 5.2:

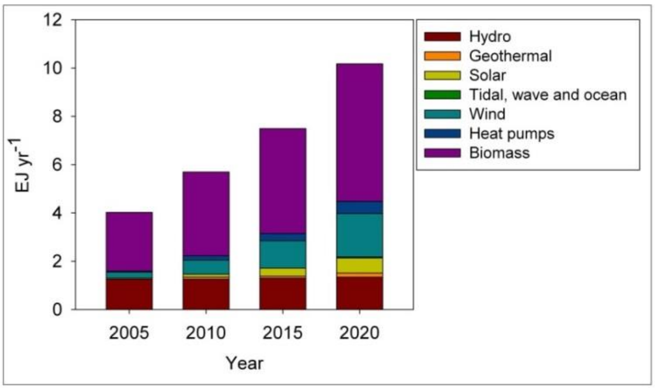


Figure 5.1 - Projections on the renewable energy supply in the EU27, based on stipulations in national renewable energy action plans of member states (EJ/a) [Bentsen and Felby 2012]

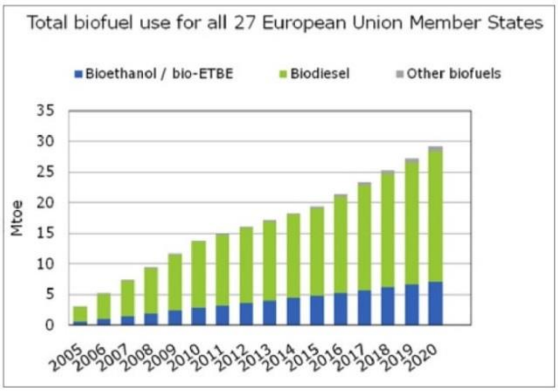


Figure 5.2 - Projected demand for biofuels in the EU up to 2020, based on stipulations in national renewable energy action plans of member states (Mtoe) [Ecofys 2012]

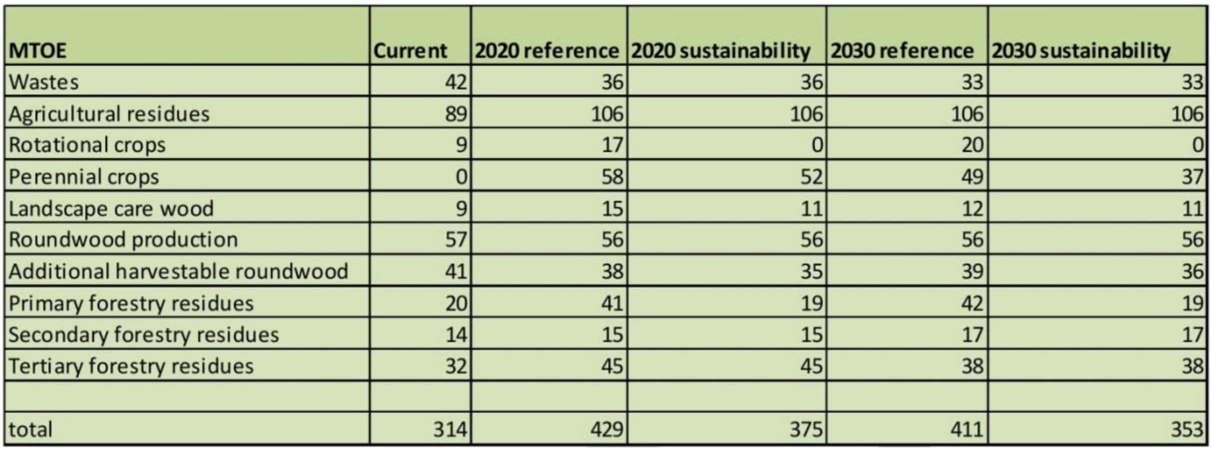
On the supply side, a great number of studies have estimated the availability of biomass and bio-energy resources in the EU over the past few years. However, due to different methodologies and definitions, geographical scopes, and assumptions regarding availability, these studies have produced widely varying results.

For the sake of clarity and validity, the author primarily follows Elbersen et al. [2012] who conducted a comprehensive comparative study of numerous individual assessments of European biomass potentials in the context of the *Biomass Futures* project which has the aim of assessing the role that biomass can play in meeting EU energy policy targets. This study produces qualified projections of European bio-energy supplies and related cost-supply estimates in 2020 and 2030, by analysing biomass availability[7], investigating the member states' national renewable energy action plans, performing sectorial market analyses, and modelling supply and demand within the energy system. Thereby, the biomass potential analyses are classified in two scenarios, a *Reference* and a *Sustainability scenario*, which apply varying sustainability standards and produce accordingly varying results.

Currently, the EU biomass potential for energy is determined to amount to 314 Mtoe and it is estimated that in the year 2020 it will range from 375 to 429 Mtoe, depending on the applied sustainability criteria [Elbersen et al. 2012]. Thus, the biomass potential is expected to increase significantly in the coming years until 2020. Post-2020, the biomass potential is expected to stabilise (see Table 5.1).

All biomass potential can be categorised as either biomass from agriculture, from forestry or from waste. Based on this categorisation it is estimated that currently the largest biomass potential lies in the aggregated group of agricultural residues, such as straw, manure and crop cuttings. However, the largest fraction of this potential is currently not being utilised. The second and third largest potentials stem from round wood production and the waste group. In view of the potential increase towards 2020, the largest contribution in growth stems from the significant increase in energy-cropping on both existing and newly-released agricultural lands with perennial crops. Table 5.1 summarises these projected biomass potentials:

Table 5.1 - EU biomass potentials for energy per aggregated group and scenario in 2020 and 2030 (Mtoe) [Elbersen et al. 2012]



MTOE	Current	2020 reference	2020 sustainability	2030 reference	2030 sustainability
Wastes	42	36	36	33	33
Agricultural residues	89	106	106	106	106
Rotational crops	9	17	0	20	0
Perennial crops	0	58	52	49	37
Landscape care wood	9	15	11	12	11
Roundwood production	57	56	56	56	56
Additional harvestable roundwood	41	38	35	39	36
Primary forestry residues	20	41	19	42	19
Secondary forestry residues	14	15	15	17	17
Tertiary forestry residues	32	45	45	38	38
total	314	429	375	411	353

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[7] An overview on the categorisation of biomass potentials evaluated by Elbersen et al. [2012] can be found in Annex 2 of this study

With regard to their practical exploitability, biomass potentials are to be categorised either as theoretical, technical, economic or sustainable potentials. The figures shown in Table 5.1 represent the estimated sustainable biomass potentials in the EU, according to two different scenarios with varying sustainability requirements.

Firstly, the applied *Reference Scenario* requires all biofuels to reduce WTW GHG emissions by 50% compared to the aforementioned reference fossil fuel comparator of 83.8 g CO2eq/MJ [EU 2009b] in 2020. Thereby, it disallows biomass cropping on either bio-diverse land or land with high carbon stock. However, it excludes ILUC-related GHG emissions. Essentially, this reflects the current minimum sustainability criteria for biofuels appointed in the *RED* and the *FQD* [EU 2009a; EU 2009b].

Secondly, the *Sustainability Scenario* requires all bio-energy carriers in the transport, heat and electricity sectors to reduce GHG emissions by 70% in 2020 and 80% in 2030 compared to the reference fossil fuel comparator. Importantly, thereby ILUC-related GHG emissions are incorporated and accounted for as well. Moreover, besides disallowing biofuel cropping on bio-diverse land or land with high carbon stock, it applies strict guidelines in the forestry sector such as limited intensification of forest exploitation, or setting aside forest areas for biodiversity protection.

Accordingly, as can be seen in Table 5.1, the expected growth in available biomass potential is stronger in the *Reference Scenario* than in the *Sustainability Scenario*. Overall, applying the stricter criteria in the *Sustainability Scenario* causes a potential reduction of domestic biomass supply by roughly 13% compared to the *Reference Scenario*. This reduction is caused in particular by the impossibility of biofuel cropping against the backdrop of the implied 70% GHG emissions reduction requirement by 202. However, growth in sustainable potential is expected nonetheless, largely lying with lignocellulosic perennial crops from SRF.

In order to determine the potential role of bio-methanol fuel in this context, the author positions himself according to the environmentally more ambitious *Sustainability Scenario*. In doing so, a more conservative and environmentally ambitious end-result can be produced which complies not only with the upcoming *FQD* GHG emission savings requirements until and beyond 2018 [EU 2009b], but also mitigates additional ILUC-related GHG emissions. Thereby, the author's projections of the available biomass potential for the production of bio-methanol are in line with the EC proposal to account for ILUC-related GHG emissions in the eligibility evaluation of all biofuels. Consequently, the total biomass potential which can be sustainably exploited for energetic purposes in 2020 amounts to 375 Mtoe, as can be seen in table 5.1..

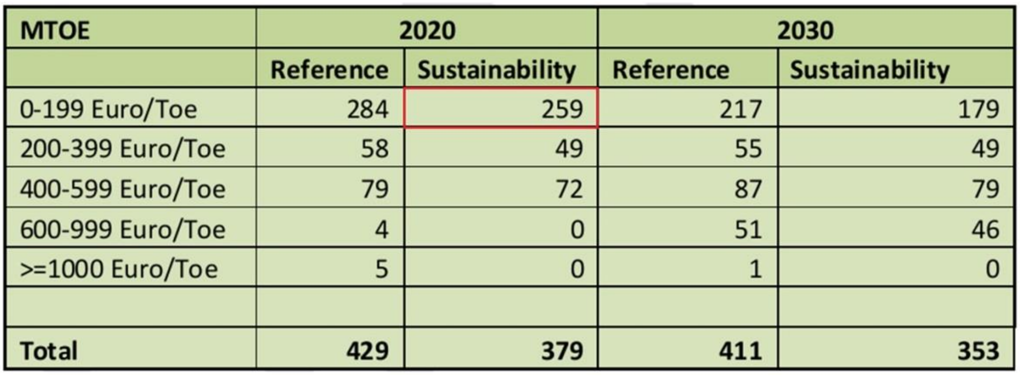
This potential greatly exceeds the final bioenergy demand of roughly 138 Mtoe projected for the EU in the year 2020 by AEBIOM [2012]. Thereby, according to the national renewable energy action plans of the member states, the heat sector is expected to remain the most important sector for bio-energy, accounting for 65% of the total demand. The transport sector and the electricity sector trail with 21% and 14% of the total demand respectively [AEBIOM 2012].

Having identified the sustainably exploitable bioenergy resource potential for 2020, a subsequent cost-supply analysis can give an indication of the economic availability of this potential. Such price indication is vital as the cost of the available biomass feedstock is a highly important economic feasibility factor for deploying bio-methanol technology. [Mortensgaard et al. 2011; Bromberg & Cheng 2010].

Cost-supply modelling by Elbersen et al. [2012], which incorporates sectorial market analyses and reviews of the EU member states' renewable energy action plans, produces the estimation that 259 Mtoe of the sustainably exploitable domestic biomass potential in the EU is available at a price below 200 €/toe (see Table 5.2). At roughly 68%, this is by far the largest fraction of the total.

Clearly, potential producers of bio-methanol would seek to acquire their feedstock primarily in this cheapest price class which consists mostly of waste and residual products from agriculture and forestry. Table 5.2 gives an overview of the available biomass potentials in their respective price classes. It can furthermore be seen that in the *Reference Scenario* more cheaply priced biomass potential is available due to its more lenient sustainability standards. Beyond 2020 prices are generally expected to increase, mainly due to increasing competition for bioenergy resources.

Table 5.2 - Available biomass potential per price class and per sustainability requirements in 2020 and 2030 (Mtoe) [Elbersen et al. 2012]



MTOE	2020		2030	
	Reference	Sustainability	Reference	Sustainability
0-199 Euro/Toe	284	259	217	179
200-399 Euro/Toe	58	49	55	49
400-599 Euro/Toe	79	72	87	79
600-999 Euro/Toe	4	0	51	46
>=1000 Euro/Toe	5	0	1	0
Total	**429**	**379**	**411**	**353**

It can be seen that a potential of 259 Mtoe of cheaply available and sustainably exploitable domestic biomass is available in the EU in 2020, if applying ambitious sustainability criteria. This potential still significantly exceeds the total final bio-energy demand of roughly 138 Mtoe in the year 2020, estimated by AEBIOM [2012]. However, although this demand is so much smaller than the domestic biomass potential, the cost-supply model produces the estimation that imports in 2020 will nonetheless amount to a large 46 Mtoe. This is roughly one third of the entire projected bio-energy demand.

Besides conversion losses in the energetic utilisation of biomass resources, an important reason for this large import share is that the domestic supply of rotational crops does not suffice to supply the projected European demand for biodiesel and 1G ethanol in 2020. This is the case in the *Reference Scenario* under which 66% of the biomass demand for biodiesel and 70% of the demand for ethanol are to be cultivated and refined in Europe while the rest would be imported from outside the EU. However, in the *Sustainability Scenario* this already large import share is fundamentally increased to 100%. This is because none of the production pathways of biodiesel or ethanol based on domestic rotational crops are considered to achieve the required lifecycle GHG emissions savings of 70% in the year 2020 and 80% in 2030 (see Table 5.1).

Thus, if the EU continues to rely on biodiesel and 1G ethanol while aiming to comply with strict GHG emissions reduction criteria for biofuels which account for ILUC, the entire biofuels demand would have to be supplied by imports. In this case, most certainly Brazilian sugar cane-based ethanol, or tropical palm oil- and soybean-based biodiesel would gain paramount importance in supplying the EU biofuels demand.

Although other agricultural products could be cultivated on the released land in the EU instead, potentially increasing EU food security and exports, clearly such a scenario is suboptimal and politically unrealistic from different perspectives. For instance, it would imply much less socio-economic added value from biofuels in the EU and significantly burden the EU trade balance. Furthermore, importing the entire biofuels demand to the EU would simply export the entire EU biofuels footprint elsewhere without mitigating global problems whether climate change or critical land-use change related issues such as increased food price volatility or loss of biodiversity.

However, the *Sustainability Scenario* by Elbersen et al. [2012] serves to illustrate that, despite an abundant domestic biomass potential, a major dilemma exists between the European ambitions to reduce direct and indirect GHG emissions while utilising domestic resources to supply the EU biofuel demand. Essentially, this can be explained by the predominant position of rotational energy crop-based biodiesel and 1G ethanol in the biofuels market.

Against this backdrop, the following sections investigate the potential of bio-methanol technology to mitigate this dilemma by overcoming the resource limits of other biofuels while improving *Security of Supply* and creating positive socio-economic effects through *Employment* creation and trade balance improvement.

5.2 - *Prospective outlook A*: mitigating competing resource demands and creating large-scale employment through bio-methanol

The previous section identifies a cheaply available and sustainably exploitable domestic biomass potential of 259 Mtoe (see Table 5.2) for 2020, most of which falls in to the groups of agricultural residues, lignocellulosic perennial crops and forestry residues. This resource potential would theoretically enable the EU to be self-sufficient with regard to its biofuels targets under strict self-imposed sustainability criteria. However, imports of biofuels and biofuel-feedstock are expected to increase strongly in coming years. In fact, if ambitious and strict sustainability criteria were applied for biofuels, taking ILUC-related GHG emissions into consideration, the entire EU biofuels demand would have to be satisfied by imports in 2020. Mainly, this is due to the EU dependence on rotational energy crops for biodiesel and 1G ethanol.

Renewable methanol technology holds promise to mitigate this dilemma because, unlike biodiesel and 1G ethanol, it can be produced from a wide variety of biomass feedstocks which are sustainably and cheaply available in the EU (see chapters 3 and 4 of this study which discuss the biomass-feedstock flexibility of renewable methanol technology as well as its favourable WTW-performance in terms of GHG emissions and feedstock-use efficiency).

Since the transport sector is expected to account for 21% of the entire final bio-energy demand in the EU in 2020 (138 Mtoe) [AEBIOM 2012], renewable methanol production would have to amount to roughly 29 Mtoe to fully satisfy this demand:

$$138\ \mathit{Mtoe}_{\text{(final bioenergy demand in the EU in 2020)}} * 21\%_{\text{(transport sector share of final bioenergy demand in the EU in 2020)}}$$

$$\approx$$

$$29\ \mathit{Mtoe}_{\text{(projected demand for biofuels in EU in 2020)}}$$

Due to its feedstock-flexibility, it is valid to assume that in 2020 this entire demand of 29 Mtoe of biofuels could be satisfied domestically through bio-methanol. Considering the *current- and near-term concept* of bio-methanol production (see sections 3.4.1 and 4.2.1) and a bio-methanol plant efficiency of 59% as described by Mortensgaard et al. [2011], the primary energy demand for the sufficient production of bio-methanol would require a total of 49 Mtoe of biomass/primary energy:

$$29\ \mathit{Mtoe}_{\text{(projected demand for biofuels in EU in 2020)}} \,/\, 59\%_{\text{(efficiency of bio-methanol plants)}}$$

$$\approx$$

$$49\ \mathit{Mtoe}_{\text{(biomass/primary energy demand required to cover the entire biofuel demand in the EU in 2020 with domestic bio-methanol production)}}$$

This 49 Mtoe of biomass/primary energy demand represents a fraction of 19% of the 259 Mtoe of cheaply available and sustainably exploitable biomass potential available in the EU in 2020, and would not compete with the biomass demands in the heat and electricity sectors which are expected to account for 65% (roughly 90 Mtoe) and 14% (roughly 19 Mtoe) of the total final EU bioenergy demand in 2020 respectively. If applying average conversion efficiencies of 80% for biomass-to-heat and of 40% for biomass-to-electricity[8] [Østergaard 2011; ECF 2010], this yields a summarized biomass/primary energy demand of the heat and electricity sectors in 2020 which amounts to roughly 159 Mtoe:

$$90\ \mathit{Mtoe}_{\text{(final bioenergy demand for heat in 2020)}} \,/\, 80\%_{\text{(assumed biomass-to-heat conversion efficiency)}}$$

$$\approx$$

$$112\ \mathit{Mtoe}_{\text{(biomass/primary energy demand for heat in 2020)}}$$

$$19\ \mathit{Mtoe}_{\text{(final bioenergy demand for electricity in 2020)}} \,/\, 40\%_{\text{(assumed biomass-to-electricity conversion efficiency)}}$$

$$\approx$$

$$47\ \mathit{Mtoe}_{\text{(biomass/primary energy demand for electricity in 2020)}}$$

$$112\ \mathit{Mtoe}_{\text{(biomass/primary energy demand for heat in 2020)}} + 47\ \mathit{Mtoe}_{\text{(biomass/primary energy demand for electricity in 2020)}}$$

$$\approx$$

$$159\ \mathit{Mtoe}_{\text{(summarized biomass/primary energy demand for heat and electricity in 2020)}}$$

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[8] The conversion efficiencies stated here [Østergaard 2011; ECF 2010] are an average assumption across different technologies and cannot reflect the technology-specific detail that would be required for a more precise estimation of primary energy demands in the electricity and heat sectors in 2020. Comprehensive databases and elaborations in this regard can be found in Energinet.dk [2012] and with Nussbaumer & Oser [2004].

Thus, even if the expected 2020 biomass/ primary energy demands of the heat and electricity sectors were to be satisfied as sustainably and cheaply as possible, still enough sustainably exploitable and cheaply available biomass potential would remain to cover the expected biofuels demand roughly twice:

$$259\ Mtoe_{\text{(cheaply available and sustainably exploitable biomass potential in EU in 2020)}} - 159\ Mtoe_{\text{(summarized biomass/primary energy demand for heat and electricity in 2020)}}$$
$$\approx$$
$$2 * 49\ Mtoe_{\text{(biomass/primary energy demand to cover the entire biofuel demand in the EU in 2020 with domestic bio-methanol production)}}$$

Any estimation of such scale is fraught with a degree of uncertainty. However, it illustrates well how domestic resources can suffice to sustainably supply our biofuel demands in 2020 if renewable methanol technology is utilised. Particularly its potential to make use of domestic resources which yet have scarcely been utilised for biofuel production represents a significantly positive potential in regard to the EU biofuels-policy objective of *Security of Supply*. The general finding that the availability of feedstock is not expected to present a barrier to introducing renewable methanol production on a larger scale is moreover confirmed and shared by Law et al. [2013].

Moreover, it should be noted at this point that the estimated 49 Mtoe of biomass/ primary energy required to supply the total EU biofuel demand in 2020 by domestic bio-methanol, is to be regarded as conservative in light of recent technological improvements of biomass gasification technology. In fact, the feedstock conversion efficiency of recent gasification-based bio-methanol plants has been stated as being higher than the 59% used here [MI 2013c; P. Koustrup, personal communication]. Thus, since improved plant efficiency leads to a better utilisation of the available biomass feedstock, the biomass/ primary energy demand to cover the entire biofuel demand in the EU in 2020 with domestic bio-methanol production would be lower than stated above.

Having ascertained that enough cheap and sustainably exploitable biomass is available to meet the EU biofuels demand with bio-methanol in 2020 without negatively affecting the biomass potential available for other energy sectors, it is of interest to highlight the potential *Employment* effects of such a full-scale scenario.

As previously described, positive *Employment* effects are an explicit objective of EU biofuels policy and can therefore be regarded as an essential factor for political support for the development and deployment of renewable methanol technology in the EU. However, it is difficult to estimate these effects. For a start, this difficulty is due to the wide range of employment sectors in which job creation can be claimed and secondly, because little reference data is yet available in scientific literature for bio-methanol.

By way of comparison, various investigations into the employment effects of the well-established European biodiesel and ethanol sectors disagree strongly on the quantity and quality of jobs created [Urbanchuk 2012; IISD 2013]. Generally, such investigations are often criticised because they include newly created agricultural employment which is likely to have existed anyway even in spite of any biofuel industry [IISD 2013].

Generally, it can be assumed that direct jobs within the industry, as well as indirect jobs in related sectors, will be created along the WTT chain of bio-methanol. For instance, in the agricultural and forestry sectors new jobs would not only be created in the cultivation and extraction of dedicated energy plants but also in the collection and pre-treatment of residues and wastes. Naturally, bio-methanol plants require technically skilled labour as well and will create employment, amongst other roles, for chemists and engineers. Furthermore, the logistics and sales of bio-methanol are bound to create jobs, as are bio-methanol-related R&D and project management activities.

Importantly, some of this newly created employment may be offset by employment losses in other sectors. In the case of the bio-methanol scenario at hand, particularly the bioethanol and biodiesel sectors would experience lost jobs as these biofuels are substituted by bio-methanol. In the study at hand, the author accounts for these negative additionalities by offsetting the existing direct and indirect employment of the current biofuels sector against the newly created jobs in the bio-methanol sector of 2020.

In order to produce valid estimations on the potential employment creation of bio-methanol in the EU, the author makes assumptions which are based on elaborations by Bromberg & Cheng [2010] who offer estimations on the direct and indirect job creation of methanol plants. Thereby, direct jobs are those which are created on-site at the production facility. Indirect jobs are, firstly, those jobs which are created in the community, supplying goods, services and other inputs. Secondly, indirect jobs account for those jobs which entail collecting and transporting the biomass feedstock to the production facility. It should be noted that this employment spectrum excludes pure farming and forestry jobs as well as R&D-related jobs and jobs in the TTW stage. This has a positive impact on the quality of the analysis as it leads to more conservative results which are less vulnerable to dissent.

In the following calculations it is assumed that 60 direct jobs are created through each bio-methanol plant. This assumption is based on elaborations by Bromberg & Cheng [2010] who state that, depending on size and output capacity, methanol plants create between 50 to 120 direct jobs. Thereby, the higher end refers to fossil-based megaplants which have an annual methanol output of one million tons or more. However, for the exemplary bio-methanol plant used in the following calculations, 60 direct jobs can be assumed as a fair and conservative estimate due to its dimensions: the author follows the aforementioned *traditional* bio-methanol plant described by Mortensgaard et al. [2011] which has a methanol output capacity of 120.6 MW. If applying an average capacity factor of 0.9 [P. Koustrup, personal communication], this yields an annual amount of roughly 172,000 tons of methanol, or 0.091 Mtoe, and requires a wood-feedstock input of 207.5 MW. Thereby it is based on the *current and near-term* method for the production of bio-methanol via biomass gasification, as described in sections 3.4.1 and 4.2.1 of this study.

Furthermore, the two groups of newly created indirect jobs, as described above, must be estimated as well. Thereby, the number of indirect jobs being created in the community is estimated by applying a multiplier to each of the newly created direct jobs. According to Bromberg & Cheng [2010], this job multiplier lies between 5.3 and 9. The number of indirect jobs entailing the collection and transportation of the biomass feedstock to the production facility is estimated by ascribing 4 newly created jobs in this field to every MW of installed input capacity. Altogether, this results in a creation of 1,208 - 1,430 jobs per methanol plant, as is shown in Table 5.3:

Table 5.3 - Estimated job creation per exemplary bio-methanol plant [own assumption, based on Mortensgaard et al. 2011; Bromberg & Cheng 2010]

Concrete job creation per bio-methanol plant, lower end			Concrete job creation per bio-methanol plant, higher end		
Direct jobs	60	60	Direct jobs	60	60
Indirect jobs in the community	5.3 * 60	318	Indirect jobs in the community	9 * 60	540
Indirect jobs in feedstock collection & transport	4 * 207.5	830	Indirect jobs in feedstock collection & transport	4 * 207.5	830
Sum of jobs per plant	Σ	1,208	Sum of jobs per plant	Σ	1,430

Having established these parameters of job creation, it is now possible to produce qualified estimations of the effects on employment. In the following, *prospective outlook A* models the potential creation of jobs if bio-methanol were to cover the entire projected demand for transport biofuels in the EU in 2020. Covering this demand of 29 Mtoe would require roughly 319 bio-methanol plants of the sort described above:

29 Mtoe (projected demand for biofuels in EU in 2020) / 0.091 Mtoe (Bio-methanol output per plant)
≈
319 (amount of bio-methanol plants needed to satisfy EU biofuels demand in 2020)

Accounting for both the lower end (1,208) and the higher end (1,430) of the job creation range of bio-methanol plants, it can therefore be estimated that a total of 385,649 - 456,522 jobs would be created:

*Lower end: 319 (amount of bio-methanol plants needed to satisfy EU biofuels demand in 2020) * 1,208 (lower end of jobs created per bio-methanol plant)*
≈
385,649 (lower end of jobs created by all bio-methanol plants)

*Higher end: 319 (amount of bio-methanol plants needed to satisfy EU biofuels demand in 2020) * 1,430 (higher end of jobs created per bio-methanol plant)*
≈
456,522 (higher end of jobs created by all bio-methanol plants)

These jobs are offset against the lost jobs in the biodiesel and ethanol sectors. IISD [2013] state that 51,639 jobs existed in the biodiesel sector and 70,272 jobs existed in the ethanol sector in the year 2011. This amounts to a total of 121,911 across both sectors. The author projects the required figures for the year 2013 by accounting average annual growth rates of 18.6% for employment in the biodiesel sector and 29.6% for employment in the ethanol sector. These growth rates are identified by the author through analysis of Urbanchuk [2012] who projects this growth to take place in the biodiesel and ethanol sectors from 2010 to 2020. All in all, the total employment to be offset can be estimated to amount to 158,377 jobs in 2013 across both sectors. Consequently, offsetting the lost jobs in the biodiesel and ethanol industries against the new jobs developing in the bio-methanol sector, results in the creation of 227,272 - 298,145 new jobs by 2020:

Lower end: 385,649 *(lower end of jobs created by all bio-methanol plants)* *- 158,377* *(existing jobs in the EU biodiesel and ethanol sectors)*
≈
227,272 *(lower end of jobs created by supplying the 2020 EU biofuels demand through bio-methanol)*

Higher end: 456,522 *(higher end of jobs created by all bio-methanol plants)* *- 158,377* *(existing jobs in the EU biodiesel and ethanol sectors)*
≈
298,145 *(higher end of jobs created by supplying the 2020 EU biofuels demand through bio-methanol)*

It is important to note that the scientific validity of the author's comparison and offsetting of jobs across all sectors is ensured because the same criteria in the accounting of direct and indirect jobs are applied in the fundamental base data which is referred to [IISD 2013; Bromberg & Cheng 2010]. In particular, this refers to the exclusion of pure farming jobs from the employment estimations. If this were not the case, the calculations at hand would be prone to distortion. Table 5.4 summarizes the results of *prospective outlook A.*

Table 5.4 – Prospective outlook A: job creation by supplying 100% of EU biofuels demand in 2020 through domestic bio-methanol: key assumptions and results

Prospective outlook A: 100% of the EU biofuels demand in 2020 is supplied by bio-methanol	
Bio-methanol demand in the EU in 2020	
Demand for bio-methanol (Mtoe)	29
Bio-methanol plants required	319
Own assumption, based on AEBIOM [2012]; Elbersen et al. [2012]	
Concrete job creation through bio-methanol in the EU in 2020	
Lower end	385,649
Higher end	456,522
Offsetting job creation through bio-methanol against lost employment in the biodiesel and ethanol industries	
Jobs in biodiesel and ethanol sectors in 2013	158,377
Own assumption, based on Urbanchuk [2012]; IISD [2013]	
Newly created jobs through bio-methanol until 2020	
Lower end	227,272
Higher end	298,145

5.3 - *Prospective outlook B*: Creating employment and improving the EU trade balance by substituting biofuel imports with domestic bio-methanol

In the context of achieving the European biofuels quota for 2020 [EU 2009a; EU 2009b], *prospective outlook A*, established in the previous section, illustrates the positive implications of a full-scale implementation of bio-methanol technology with regard to environmental sustainability and employment creation. However, in light of the current political and techno-economic reality, such a full-scale technological transformation of the EU biofuels supply until 2020 seems unrealistic. Therefore, an EU bio-methanol scenario, which seems rather more achievable, is established in the following: *prospective outlook B*.

It investigates the effects on job creation and on the EU trade balance if bio-methanol were to substitute solely the projected imports of biofuels to the EU in the year 2020. Thereby, *prospective outlook B* refers to the import-projections in the aforementioned *Reference* scenario by Elbersen et al. [2012] who estimate that in 2020, 34% of the EU biodiesel demand and 30% of the ethanol demand will be imported. In total, this represents a 33% import share of all biofuels in the EU in 2020.

Prospective outlook B implies that a substantial fraction of the entire biofuel supply is covered by a newly-created European bio-methanol industry without affecting the domestic market share of European biodiesel and ethanol industries. Consequently, no lost jobs in these sectors must be offset against the newly created jobs in the bio-methanol sector. Thereby, *prospective outlook B* applies the same methodological criteria in the calculation of created direct and indirect jobs as *prospective outlook A in* the previous section.

Moreover, it is based on the same assumptions regarding the sufficient availability of sustainably exploitable and cheaply available bio-methanol feedstock. However, it should be noted that *prospective outlook B* does not represent an EU biofuels sector which complies with the ambitious 70% GHG-emissions reductions and sustainability criteria which are applied in *prospective outlook A*. Nonetheless, from an environmental standpoint, it is surely superior to the alternative of importing a large percentage of the EU biofuels supply.

Based on sectorial projections by Panoutsou & Castillo [2011], in what follows the projected biofuel demand of 29 Mtoe in 2020 is estimated to be proportioned in roughly 21.65 Mtoe of biodiesel and 7.35 Mtoe of ethanol. 2G cellulosic ethanol is thereby estimated to play only a marginal role and is therefore not further considered as relevant in this scenario. This estimation is endorsed by OECD [2012] or IISD [2013]. According to the aforementioned import projections by Elbersen et al. [2012], the biodiesel import share of 34% amounts to 7.361 Mtoe to be imported in 2020. For ethanol, the import share of 30% results in 2.205 Mtoe to be imported:

$$\textit{Biodiesel: } 21.65\ \textit{Mtoe}_{\textit{(projected EU biodiesel demand in 2020)}} * 34\%_{\textit{(projected import share of biodiesel supply in 2020)}}$$

$$\approx$$

$$7.361\ \textit{Mtoe}_{\textit{(projected biodiesel imports to the EU in 2020)}}$$

*Ethanol: 7.35 Mtoe (projected EU ethanol demand in 2020) * 30% (projected import share of ethanol supply in 2020)*

≈

2.205 Mtoe (projected ethanol imports to the EU in 2020)

In sum, this amounts to a total of 9.566 Mtoe of biofuel imports to the EU which are to be substituted by domestic bio-methanol:

Total: 7.361 Mtoe (projected biodiesel imports to the EU in 2020) + 2.205 Mtoe (projected ethanol imports to the EU in 2020)

≈

9.566 Mtoe (projected total biofuels imports to be substituted by domestic bio-methanol)

In order to quantify the according demand for bio-methanol production facilities and their implied creation of direct and indirect jobs, the same criteria and assumptions are used as in *prospective outlook A* in the previous section. Thereby, a newly created exemplary bio-methanol plant has an average annual output of roughly 172,000 tons of methanol, or 0.091 Mtoe, and requires a wood-feedstock input of 207.5 MW. It is based on the current and near-term method for the production of bio-methanol via biomass gasification, as described in sections 3.4.1 and 4.2.1 of this study. The implied direct and indirect job creation per bio-methanol plant lies in the range of 1,208 - 1,430 jobs, as is shown in table 5.3.

Based on these criteria and estimates, the quantity of bio-methanol plants which is required to substitute all biofuel imports to the EU in 2020 is calculated to amount to 105 bio-methanol plants:

9.566 Mtoe (total biofuels imports to be substituted by domestic bio-methanol in 2020) / 0.091 Mtoe (Annual bio-methanol output per plant)

≈

105 (amount of bio-methanol plants needed to substitute all biofuels imports to the EU in 2020)

Applying the established criteria for both the lower end (1,208) and the higher end (1,430) of the job creation range of bio-methanol plants, it can therefore be estimated that a total of 127,211 – 150,590 jobs would be created by substituting all biofuel imports to the EU in 2020 with domestically produced bio-methanol:

*Lower end: 105 (amount of bio-methanol plants needed to substitute all biofuels imports to the EU in 2020) * 1,208 (lower end of jobs created per bio-methanol plant)*

≈

127,211 (lower end of jobs created by substituting all biofuels imports to the EU in 2020)

*Higher end: 105 (amount of bio-methanol plants needed to substitute all biofuels imports to the EU in 2020) * 1,430 (higher end of jobs created per bio-methanol plant)*

≈

150,590 (higher end of jobs created by substituting all biofuels imports to the EU in 2020)

Importantly, it should be re-emphasised that if the import projections found in literature were to substantialise in 2020, these newly created jobs along the WTT-chain of bio-methanol would not be created. Moreover, it should be re-emphasised at this point that no offsetting against lost employment in the EU biodiesel and ethanol sectors is necessary in *prospective outlook B* as the total market share of these industries is not directly negatively affected. Therefore it is assumed that no job losses in these sectors are induced by establishing the described bio-methanol sector. Table 5.5 summarizes the resulting job creation if a domestic bio-methanol sector were to fully substitute the projected imports of biofuels to the EU in 2020.

Table 5.5 - Prospective outlook B: job creation by substituting the projected imports of biofuels to the EU in 2020 through domestic bio-methanol: key assumptions and results

Prospective outlook B: biofuel imports to the EU in 2020 are substituted by domestic bio-methanol	
According bio-methanol demand in the EU in 2020	
Demand for bio-methanol (Mtoe)	9,566
Bio-methanol plants required	105
Own assumption, based on AEBIOM [2012]; Elbersen et al. [2012]	
Newly created jobs through bio-methanol in 2020	
Lower end	127,211
Higher end	150,590

Besides investigating the sustainable and economic availability of domestic biomass resources for large-scale implementation of bio-methanol technology and its implied *Employment* creation potential, it is also of interest to investigate how the EU trade balance would be affected if all imported biofuels were to be substituted by domestic bio-methanol. Referring back to the *Security of Supply* objective, this is of particular interest as the domestic bioenergy industry is scheduled to make an increasingly significant contribution to lowering the EU dependence on imported transport fuels in the next decades.

Against this backdrop, the growing EU dependence on biofuel-imports seems particularly unfavourable: the projected 9.566 Mtoe of biofuels to be imported in 2020 represents a large share of roughly 33% of the estimated EU demand whereas in 2010 the net import share of biofuels stood at only roughly 2.5% [EU 2012]. This increasing demand for biofuels imports can be explained primarily by the limited availability of suitable cultivation area for biodiesel and 1G ethanol feedstocks, particularly under the pretext of increasingly ambitious sustainability requirements.

In order to quantify the impact on the EU trade balance of *prospective outlook B*, it is necessary to monetise the projected biodiesel and ethanol imports in 2020. As these imports are domestically substituted, their total monetary value can then be positively credited in the EU balance of payment. For the according monetisation calculations, the author invokes market and price projections by the OECD [2012] which offers a comprehensive analysis on biodiesel and ethanol market trends and prospects over an outlook period until 2021. According to the estimated development of world prices, biodiesel is projected to cost 177$/hl and ethanol is projected to cost 93$/hl in 2020. The evolution of these world prices is illustrated in Figure 5.3:

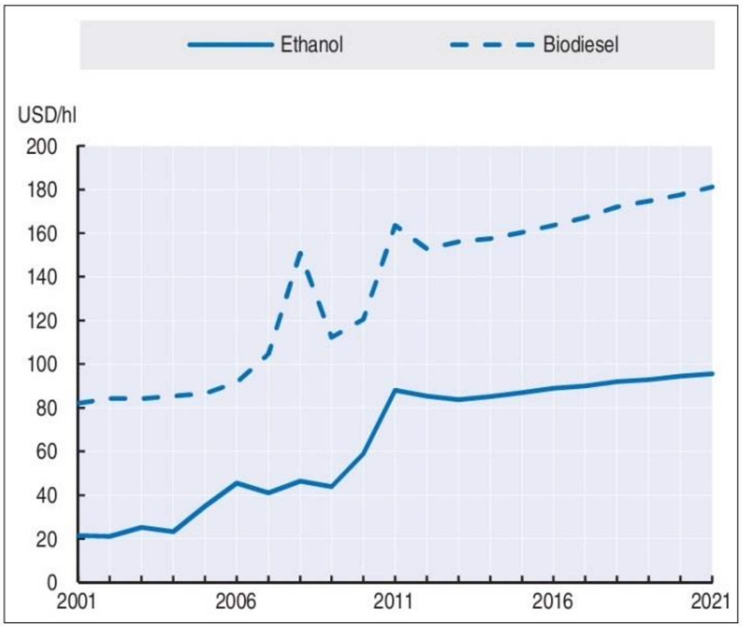

Figure 5.3 - Evolution of world prices of biodiesel and ethanol (USD/hl) over a time period until 2021 [OECD 2012]

Based on these price projections, it is possible to calculate the costs of importing 7.361 Mtoe of biodiesel and 2.205 Mtoe of ethanol, the estimated net biofuel imports to the EU in 2020 [own assumption, based on Panoutsou & Castillo 2011; AEBIOM 2012; Elbersen et al. 2012]. Due to the implied degree of uncertainty in price projections such as the above, the author chooses to apply an additional uncertainty factor of 15% in both price directions.

According to these parameters, the calculations project that the biodiesel import costs to the EU in 2020 lie in a range of 10.8 – 14.5 billion €, whereas the import costs for ethanol lie in a range of 2.3 – 3.2 billion €. In sum, the EU trade balance in 2020 can be expected to be burdened with costs between 13.1 – 17.7 billion € by the projected biofuel imports:

Lower end: 10.8 B€ (lower end of cost of projected biodiesel imports to the EU in 2020) + 2.3 B€ (lower end of cost of projected ethanol imports to the EU in 2020)

≈

13.1 B€ (lower end of total cost of projected biofuel imports to the EU in 2020)

Higher end: 14.5 B€ (higher end of cost of projected biodiesel imports to the EU in 2020) + 3.2 B€ (higher end of cost of projected ethanol imports to the EU in 2020)

≈

17.7 B€ (higher end of total cost of projected biofuel imports to the EU in 2020)

By way of illustration, these expenditures are larger than, for instance, the GDP of the EU member states, Iceland and Malta, which in 2012 stood at roughly 13 billion € and 11.1 billion € respectively [CIA 2013]. If these expenditures to recipients outside the EU were avoided by the net substitution of all biofuel imports through domestic bio-methanol, the EU trade balance in 2020 would be improved by this amount. Table 5.6 summarizes the calculated results:

Table 5.6 - *Prospective outlook B*: EU trade balance effect in 2020 by substituting all biofuel imports with domestic bio-methanol

Prospective outlook B: All biofuel imports to the EU in 2020 are substituted by domestic bio-methanol					
Biodiesel imports to be substituted			Ethanol imports to be substituted		
Total amount	7.361	Mtoe	Total amount	2.205	Mtoe
Total volume in hl	95,193,930	hl	Total volume in hl	39,396,474	hl
Own assumption, based on Panoutsou & Castillo [2011]; AEBIOM [2012]; Elbersen et al. [2012]					
Projected cost of biodiesel imports to be substituted			Projected cost of ethanol imports to be substituted		
Est. 2020 World price	177	$/hl	Est. 2020 World price	93	$/hl
2020 import cost	16,849,325,589	$	2020 import cost	3,663,872,105	$
$/€ exchange rate (avg. 2011-2013)	0.7508	$/€	$/€ exchange rate (avg. 2011-2013)	0.7508	$/€
2020 import cost	12,650,473,653	€	2020 import cost	2,750,835,176	€
Own assumption, based on OECD [2012]					
Cost ranges if adding uncertainty factor to cost projections: -/+ 15%					
Lower end (import cost 15% lower)	10,752,902,605	€	Lower end (import cost 15% lower)	2,338,209,900	€
Higher end (import cost 15% higher)	14,548,044,700	€	Higher end (import cost 15% higher)	3,163,460,453	€
Own assumption					
Total credit to the 2020 EU trade balance by substituting all biofuel imports with domestic bio-methanol					
Lower end			Σ	13,091,112,505	€
Higher end			Σ	17,711,505,153	€

The advantages of utilising a domestic bio-methanol industry in this way is also emphasised by reviewing the above result in relative terms: for instance, according to the CIA [2013], the EU trade deficit in 2011 stood at roughly 34.5 billion €. Consequently, a trade balance improvement of the above-projected dimension could reduce a similar deficit in 2020 by 40-50%. However, it is not expedient to project further trade balance developments in the context of this study.

5.4 - Conclusions

This section summarizes and concludes on the results of the analyses in this chapter, in view of the EU biofuel-policy objectives *Security of Supply* and *Employment*.

In 2020 in the EU, more than enough cheaply available biomass resources, below 200 €/toe, will be available to meet the 10% biofuel requirement through the domestic production of bio-methanol. These biomass resources can be exploited under strict sustainability criteria and GHG-emissions savings requirements of 70%, compared to fossil fuels. These criteria are also in line with the claimed consideration of ILUC-related GHG emissions for biofuels, soon to be voted on by the EC. On the contrary, domestic biodiesel and 1G ethanol production cannot comply with such criteria since their production depends on rotational crop feedstock: in theory, the entire demand for biodiesel and ethanol in 2020 would have to be imported if the EU were to unsheathe strict sustainability criteria which take into account ILUC-related GHG emissions. This serves to illustrate that a dilemma exists between the European ambitions to reduce direct and indirect GHG emissions while utilising domestic resources to supply the EU biofuel demand.

For feedstock-flexible bio-methanol technology on the other hand, enough cheaply available and sustainably exploitable domestic biomass resources exist to supply the entire projected EU biofuels demand in 2020. In this context, a full-scale deployment of bio-methanol technology would not compete with the biomass resource demands of the heat and electricity sectors which are also expected to grow significantly in the coming years. Ergo, the feedstock flexibility of bio-methanol technology can be considered a paramount advantage over other biofuels in terms of *Supply security.*

Although in this regard no precise evaluations are undertaken for the time beyond 2020, the prospects for the further expansion of bio-methanol technology can be considered favourable with respect to sustainably exploitable biomass. This view is based on the high efficiency in the utilisation of biomass-feedstock in state-of-the-art facilities, currently being further improved by R&D activities. Moreover, it is encouraged in view of the *novel mid-term concept* for bio-methanol production, enabling a superior utilisation of biomass-feedstock through the integration of SOEC (see sections 3.4.2 and 4.2.2). Improved feedstock-utilisation by integrating SOEC in the *novel mid-term* concept of bio-methanol production clearly holds the most promise in future RES with high shares of renewable electricity.

In terms of *Employment* creation, the modelling of two *prospective outlooks* suggests that a significant number of jobs can be created by deploying bio-methanol technology in the EU: *prospective outlook A* demonstrates that between 227,000 - 298,000 new jobs would be created if the entire 2020 EU-demand for biofuels were to be supplied by domestically produced bio-methanol. This projection implies that newly-created jobs along the WTT-chain of bio-methanol are offset against lost jobs in the currently predominant biodiesel and ethanol sectors.

However, such a full-scale technological transformation of the EU biofuels supply until 2020 seems unrealistic in light of the current political and techno-economic reality. In order to outline a more realistic and achievable outlook for the role of bio-methanol in the time frame considered, *prospective outlook B* models the employment creation if bio-methanol were only to substitute the projected imports of biofuels to the EU in the year 2020. In this case, between 127,000 - 151,000 new jobs would be created. Importantly, these newly created jobs along the

WTT-chain of bio-methanol are jobs which would otherwise not be created in the EU, if the biofuel import projections found in scientific literature were to substantialise until 2020.

Against the same backdrop, the effect of *prospective outlook B* on the EU trade balance is modelled, signifying the potential monetary savings of substituting all projected biofuel imports with domestically produced bio-methanol. Thereby, *prospective outlook B also* refers to the *Security of Supply* objective since the domestic bioenergy industry is scheduled to make an increasingly significant contribution to lowering the EU dependence on imported transport fuels in the next decades.

Based on the projected world price developments of biodiesel and ethanol until 2020, it is shown that the EU economy could save between 13.1 billion € - 17.7 billion € if domestic bio-methanol were to be utilised to substitute the projected biofuel imports in this way. The economic dimension of this result can be elucidated by comparing it to the current trade deficit of the EU which stands at roughly 34.5 billion €: if a deficit of similar dimension were to exist in 2020, substantialising *prospective outlook B* could potentially reduce this deficit by 40-50%.

6 - Conclusions on the core analyses

In what follows, the relevant findings of the core analyses in chapters 4 and 5 are summarized in order to answer the main Research Question of this study:

Which potentials does renewable methanol technology possess in regard to the EU biofuels-policy objectives of Greenhouse Gas Savings, Security of Supply and Employment?

- With regard to the objective of *Greenhouse Gas Savings*, the findings of the WTW-analysis in chapter 4 clearly demonstrate that renewable methanol technology holds high potentials and favourable prospects:

  The EU *FQD* requires all biofuels to have WTW GHG emission reductions of at least 35% compared to a reference fossil fuel comparator of 83.8 g CO2eq/MJ. This emissions reductions requirement is to be gradually increased to 50% in 2017 and 60% in 2018 for new plants [EU 2009b]. The investigated renewable methanol fuel pathways not only generally comply with these increasingly strict regulations, but far surpass them.

  As such, although the biogas- and crude glycerine-based bio-methanol fuel pathways which are investigated here do not account for as equally significant emissions reductions as the other investigated bio-methanol fuel pathways, they can be expected to further improve in this regard in the near future. This is achieved by substituting fossil process energy inputs with renewable energy inputs in the fuel production step, or by utilising the energy content of the feedstock itself (crude glycerine) and by reducing the energy-intensity of the fuel production step in general (biogas pathway).

  However, the fuel pathways which are based on black liquor and on lignocellulosic biomass reach emissions reductions well above 90% compared to fossil fuels. Moreover, they demonstrate superior GHG emissions savings compared to the investigated biofuel pathways for ethanol and biodiesel: for instance, compared to Brazilian sugar cane-based ethanol, black liquor-based bio-methanol fuel reduces GHG emissions by 83-91%, and bio-methanol which is based on waste wood reduces emissions by 70-85%. Compared to biodiesel, these GHG emissions savings even exceed 90%. In general, biodiesel, which is currently the most predominant biofuel in use in the EU, will neither comply with the 50% emissions reductions requirement in 2017 nor with the 60% requirement in 2018. This substantiates the apparent need for less-emitting, alternative biofuels such as renewable methanol.

  Furthermore, the WTW-analysis shows that the lowest GHG emissions are clearly achieved by renewable methanol which is biomass-independent, based on the long-term production method of on-site capture of concentrated CO_2 emissions and its subsequent recycling to methanol using electrolysis-derived hydrogen. In the long term, this concept will allow for methanol production and vehicle propulsion at near-zero WTW GHG emissions.

On the road towards this very future-oriented concept, the *novel* mid-term method for bio-methanol production, integrating SOEC, and thereby enabling a superior carbon efficiency, demonstrates a further GHG emissions reduction of roughly 60% compared to the *current* production method based on the same feedstock. This signifies that biomass-based renewable methanol technology not only offers a superior GHG emissions reductions potential in the short-term, but also that this prospect will become even more favourable in the medium-term post-2020.

- With regard to the objective of *Security of Supply*, both the WTW-analysis in chapter 4 and the analysis of biomass potentials and socio-economic implications in chapter 5 show that renewable methanol technology possesses high potentials and favourable prospects:

  The feedstock flexibility of renewable methanol technology in general must be seen as a fundamentally favourable prospect with regard to supply security since it enables the utilisation of wastes and other feedstocks which have so far been under-used in the production of biofuels. As such, the EROEI comparison of the bio-methanol, biodiesel and ethanol pathways in the WTW-analysis demonstrates that the pathways for bio-methanol are clearly more energy efficient than the pathway for biodiesel and, except for the biogas-based pathway, on average they are also more energy efficient than the ethanol pathway.

  Thus, already in the short-term, renewable methanol technology is capable of efficiently utilising biomass resources, particularly of lignocellulosic nature. In the medium-term, the above-mentioned integration of SOEC improves this prospect further since the upgrading of biomass inputs by way of electrolysis-derived hydrogen will greatly improve carbon efficiency and thereby reduce the relative biomass inputs required for a given output of bio-methanol fuel. Consequently, this implies positive land-use aspects and is seen as favourable prospect in view of dawning resource constraints for the production of biofuels in general.

  In this context of resource availability, chapter 5 offers an evaluation of supply and demand for biomass resources in the EU in 2020: it suggests that more than enough cheaply available biomass resources, below 200 €/toe, will be available to meet the 10% biofuel requirement through the domestic production of bio-methanol. These biomass resources can be exploited under strict sustainability criteria which imply that existing environmental protection requirements are extended and strengthened with all biomass resources being required to achieve GHG-emissions savings of at least 70% compared to fossil fuels. Thereby, these implied criteria are in line with the claimed consideration of ILUC-related GHG emissions for biofuels, soon to be voted on by the EC.

  In contrast, domestic biodiesel and 1G ethanol production cannot comply with such criteria since their production depends on rotational crop feedstock: in theory, the entire demand for biodiesel and 1G ethanol in 2020 would have to be imported if the EU were to unsheathe such strict sustainability criteria for biofuels. This serves to illustrate that a tension exists between the European ambitions towards sustainable biofuels with reduced direct and indirect GHG emissions while utilising domestic resources to supply the EU biofuel demand.

In avoidance of, and in preference to such an outlook, a full-scale deployment of domestic bio-methanol technology to meet the *RED* target of 10% biofuels in the transport sector would not compete with the biomass resource demands of the heat and electricity sectors which are also expected to grow significantly until 2020. Although in this regard no precise evaluations are undertaken for the time beyond 2020, the prospects for the further expansion of bio-methanol technology can be considered favourable with respect to sustainably exploitable biomass. This view is based on the high efficiency of the utilisation of biomass-feedstock in state-of-the-art facilities (>59%), currently being further improved by R&D activities. Moreover, it is encouraged in view of the aforementioned *novel concept* for bio-methanol production, enabling a superior utilisation of bio-carbon-feedstock through the integration of SOEC. Considering this, the improved feedstock-utilisation through the *novel concept* clearly holds the most promise in future RES with high shares of renewable electricity.

- With regard to the objective of *Employment*, the high potential of renewable methanol technology is demonstrated by modelling two *prospective outlooks* on job creation in chapter 5.

These *prospective outlooks* suggest that a significant number of jobs can be created by deploying bio-methanol technology in the EU: *prospective outlook A* yields that between 227,000 - 298,000 new jobs would be created if the entire 2020 EU-demand for biofuels were to be supplied by domestically produced bio-methanol. This projection implies that newly-created jobs along the WTT-chain of bio-methanol are offset against lost jobs in the currently predominant biodiesel and ethanol sectors.

However, as such a full-scale technological transformation of the EU biofuels supply until 2020 seems beyond reach, a more realistic and achievable outlook is produced in *prospective outlook B:* it models the employment creation if bio-methanol were only to substitute the projected imports of biodiesel and ethanol to the EU in the year 2020. In this case, between 127,000 - 151,000 new jobs would be created along the WTT-chain of bio-methanol. It should be emphasised that these are newly created jobs which would otherwise not exist in the EU if the projected imports of biodiesel and ethanol were to substantialise until 2020.

Against the same backdrop, the effect of *prospective outlook B* on the EU trade balance is modelled, demonstrating the potential monetary savings of substituting all projected biofuel imports with domestically produced bio-methanol. This evaluation refers back to the *Security of Supply* objective since the domestic biofuel industry is scheduled to make an increasingly significant contribution to lowering the EU dependence on imported transport fuels in the next few decades.

Based on the projected world price developments of biodiesel and ethanol until 2020, it is shown that the EU trade balance could be improved by 13.1 - 17.7 billion € if domestic bio-methanol were to substitute for the projected biofuel imports. The economic dimension of this result can be elucidated by comparing it to the current trade deficit of the EU, which stands at roughly 34.5 billion €: if a deficit of similar dimension were to exist in 2020, substantialising *prospective outlook B* could potentially reduce this deficit by 40-50%.

7 - Political recommendations

The analyses of this study demonstrate that renewable methanol technology possesses significant favourable potentials with regard to the three main objectives of EU biofuels policy: *Greenhouse Gas Savings*, *Security of Supply* and *Employment*. In order to unlock these potentials for the benefit of sustainable development in the EU, the technology should be deployed on larger-scales sooner rather than later.

In what follows, three recommendations for political measures offer policy-makers indications on how to activate the deployment of renewable methanol technology in the EU, thereby optimising the sustainability of the biofuels sector in general. In this, the secondary RQ of this study is addressed:

Which political measures could advance the implementation of renewable methanol as a sustainable energy technology in the EU?

The following three recommendations aim to advance the desired deployment of renewable methanol technology in the EU and are described in broad outline in the following sections:

- *Implementing the EC proposal to minimise the climate impacts of biofuel production in the EU (ILUC Proposal).*
- *Implementing a mandatory obligation to make renewable fuels available at gas stations in the EU (Pump Act).*
- *Implementing a mandatory flexible fuel standard for new vehicles produced by car manufacturers in the EU (Open Fuel Standard).*

It should be emphasised that these measures are technology-neutral in the sense that they do not discriminate against biofuels other than renewable methanol, so long as they comply with the requirements from the *ILUC Proposal*. Moreover, as each of these political measures targets different steps along the WTW-chain, these proposals must be seen as fundamentally complementary in view of larger-scale deployment of renewable methanol technology:

While the *ILUC Proposal* targets the sustainability of feedstock cultivation and biofuel production (steps 1 and 2), the *Pump Act* aims to make these biofuels easily available to end-consumers (Step 3). The *Open Fuel Standard* targets the vehicles themselves (step 4), enabling the choice of a wider range of fuels to vehicle holders. Figure 7.1: illustrates the complementariness of these three political measures:

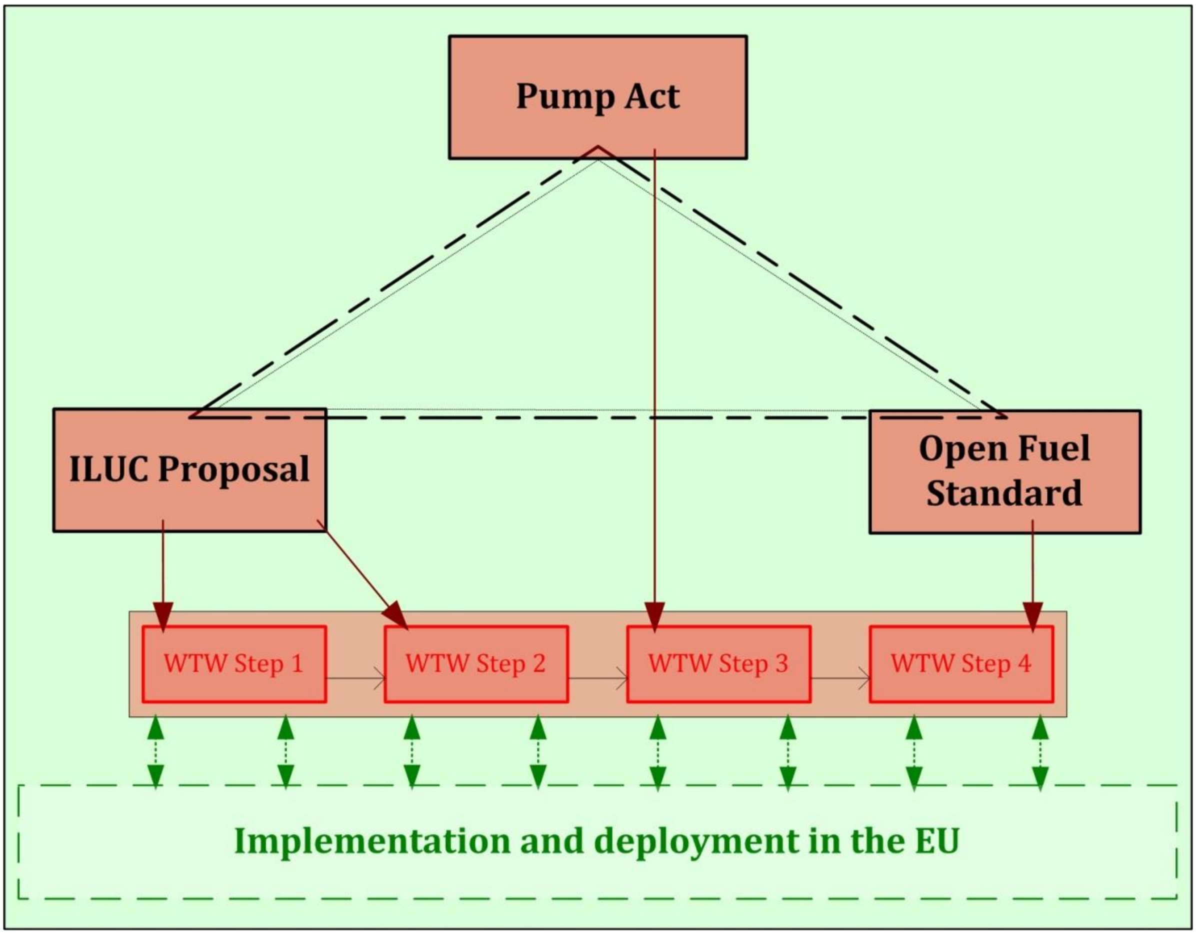

Figure 7.1 – Conceptualisation of complementary political measures to activate the deployment of renewable methanol technology in the EU

7.1 - Implementing the ILUC Proposal

As previously described, ILUC-related GHG emissions have not been mandatorily accounted for in the reporting of lifecycle emissions of biofuels so far. However, it is expected that these emissions are highly significant.

In this context, the evaluation on sustainable biomass potentials in chapter 5, based on estimations and projections by Elbersen et al. [2012], shows that the production of biodiesel and 1G ethanol in the EU would not be able to comply with more stringent GHG emissions criteria; consequently, a tension exists between the ambitions to reduce direct and indirect GHG emissions while utilising domestic resources to supply the EU biofuel demand. It should, however, be re-emphasised that the *Sustainability* scenario by Elbersen et al. [2012], which underlies the analysis in chapter 5, applies different GHG emissions savings criteria for bioenergy resources than are implied in the respective ILUC-emissions parameters in the *ILUC Proposal*. While the *Sustainability* scenario by Elbersen et al. [2012] simply requires a minimum of 70% GHG emissions savings for all bioenergy resources, the current *ILUC Proposal* applies ILUC-factors of 12g CO_2e/MJ for cereal-based ethanol, 13g CO_2e/MJ for sugar-based ethanol and 55g CO_2e/MJ for plant oil-based biodiesel [EC 2012b].

Implementing the *ILUC Proposal* would require certain amendments in the *RED* and the *FQD,* and it is scheduled to be voted on 10th July 2013 [EC 2012c]. Explicitly, the proposal [EC 2012b] aims to:

"limit the contribution that conventional biofuels (with a risk of ILUC emissions) make towards attainment of the targets in the Renewable Energy Directive; improve the greenhouse gas performance of biofuel production processes (reducing associated emissions) by raising the greenhouse gas saving threshold for new installations (...); encourage a greater market penetration of advanced (low-ILUC) biofuels by allowing such fuels to contribute more to the targets in the Renewable Energy Directive than conventional biofuels; improve the reporting of greenhouse gas emissions by obliging Member States and fuel suppliers to report the estimated indirect land-use change emissions of biofuels."

The proposal also aims to protect already existing investments until 2020. Post-2020, those biofuels which do not offer substantial direct and indirect GHG emissions savings and are produced from food crops will not be subsidized any further. In what follows, the most relevant actions implied in the *ILUC Proposal* are summarized:

- Introducing a limit to the contribution of biofuels which are produced from food crops (e.g. cereals, sugars and oil crops) to 5% of the total transport fuel demand.

- Increasing the minimum GHG emission savings criteria for biofuels produced in new production plants (taking effect in the next years) and discouraging further investments in biofuels with low direct and indirect GHG emissions savings.

- Improving the reporting methods of estimated ILUC-related GHG emissions of biofuels, based on the best available scientific evidence. Moreover, it must be ensured that these methods are updated and adapted in accordance with scientific developments.

- Creating an augmented incentive scheme to further promote advanced sustainable biofuels from feedstocks which do not create additional land demands.

While these measures would optimise the sustainability of the EU biofuels production and give a competitive edge to advanced sustainable biofuels such as renewable methanol, implementing the *ILUC Proposal* alone would not necessarily lead to large-scale deployment. The technical infrastructure which is necessary to implement the technology in society also requires political measures of activation. The *Pump Act* and the *Open Fuel Standard* which are elaborated on in what follows, target this issue.

7.2 - Implementing a Pump Act

A pump act should oblige fuel retailers in the EU to supply their customers (vehicle owners) with biofuels. Thereby it would stimulate not just the use of biofuels directly, but indirectly also increase the number of vehicles which use biofuels.

By way of example, a pump act has been successfully implemented in Sweden where in 2005 the parliament introduced the *Pumplagen,* requiring all gas stations selling more than a certain amount of fuel per year, to supply their customers with at least one kind of renewable fuel (biofuels or biogas) [SF 2005]. As accessibility was regarded a major barrier to increasing the consumption of biofuels and reducing GHG emissions in the Swedish transport sector, improving the availability of biofuels was the main aim of the *Pumplagen* [SR 2009]. It was implemented in several stages until in 2009 all Swedish gas stations with annual sales volumes above 1,000 m^3 of gasoline or diesel supplied at least one type of renewable fuel by means of one or several fuel pumps. Consequently, the possibility for vehicle owners to use biofuels greatly increased after the *Pumplagen* was introduced.

The *Pumplagen* is in itself a technology-neutral act. However, E85 has eventually established itself as predominant biofuel, sold at more than 1,700 fuelling stations in Sweden which has consequently developed the largest FFV fleet in the EU today, strongly growing from roughly 700 FFV in 2001 to just below 230,000 FFV in April 2013 [BAFF 2013]. As the predominance of E85 is largely based on imported Brazilian sugarcane-ethanol, the Swedish government announced that the supply and demand for other, domestic, biofuels will be increasingly stimulated in the future [SR 2009]. However, generally the structural development for biofuels induced by the *Pumplagen* should be regarded as highly successful and can be considered as a model for a refined *Pump Act* at the EU level.

A possible implementation plan for a *Pump Act* in the EU is shown in Table 7.1: all gas stations in the EU can be categorized by size with regard to their annual sales output (m^3/a), each category constituting roughly 20% of the total. (P. Koustrup, personal communication). Starting in 2015, the largest gas stations would have to comply with the *Pump Act* and in the following years until 2019, the smaller gas stations would gradually have to follow. Such a gradual approach would grant smaller gas stations more time for undertaking necessary modifications and investments.

Table 7.1 - Possible time plan for the gradual implementation of a *Pump Act* in the EU

Year	Gas stations: fuel sales per year (m^3)	Gas stations: approx. share of total fuel sales (%)	Gas stations: approx. cumulative share of fuel sales (%)
2015	≥ 3000	~ 20	~ 20
2016	2000 - 3000	~ 20	~ 40
2017	1500 - 2000	~ 20	~ 60
2018	1000 - 1500	~ 20	~ 80
2019	0 - 1000	~ 20	~ 100

Thereby, although the implementation of an EU *Pump Act* would advance the large-scale deployment of biofuels in general, by itself it would not necessarily lead to the use only of sustainable domestic biofuels, such as bio-methanol. However, in combination with other targeted measures and particularly in view of an implemented *ILUC Proposal,* this could be achieved.

At the same time, the large-scale deployment of sustainable domestic biofuels should be stimulated by creating a real choice in fuels for vehicle holders themselves. This choice could be created by implementing an *Open Fuel Standard,* described in what follows.

7.3 - Implementing an Open Fuel Standard

An *Open Fuel Standard* should essentially disallow the mass production of cars that can run only on gasoline fuel, and oblige EU vehicle manufacturers to produce FFV which are capable of running on gasoline, methanol, ethanol or any combination of these.

Implementing this measure would enable all biofuels to compete against gasoline, thereby encouraging consumer choice and creating a clear impulse for the large-scale deployment of renewable methanol technology. Moreover, a number of potential favourable impacts can be assumed, for instance:

- The enabled competition between different fuels could lead to lower gasoline prices and would generally reduce the EU dependency on fossil fuel imports and the associated economic vulnerability on volatile petroleum prices. As such, implementing the *Open Fuel Standard* would contribute to the *Security of Supply* objective and would have a positive effect on the EU trade balance.

- The increased demand for domestic biofuels would generate *Employment* on the supply side (see descriptions in chapter 5 of this study). Moreover, it would promote further R&D activities and innovations in the EU transport sector in general.

- Implementing the *Open Fuel Standard* would not involve any direct costs for the governments of EU member states. Moreover, the incremental cost which this measure would cause for car manufacturers has been stated to lie in the relatively cheap range of 50-100 € per vehicle [Stephens 2010; Luft & Korin 2012].

A possible implementation plan for an Open Fuel Standard in the EU is shown in Table 7.2: It illustrates a gradual increase of the mandatory FFV-share in the annual fleet of newly produced vehicles of EU car manufacturers. Starting in 2015 (simultaneously with the *Pump Act*), no less than 20% of newly produced cars would have to be FFV. This share gradually increases to 100% in 2019. Clearly, the development of other sustainable vehicle concepts such as BEV, FCEV, hybrid-systems etc. must not be impeded by this measure and they should therefore fall under the same category as the FFV here[9]:

Table 7.2 - Possible time plan for the implementation of an *Open Fuel Standard* in the EU

Year	Mandatory minimum share of FFV[1] in the newly produced annual vehicle fleet of EU car manufacturers (%)
2015	≥ 20
2016	≥ 40
2017	≥ 60
2018	≥ 80
2019	100

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[9] The specifics of other sustainable vehicle concepts which should be treated equally to FFV under this gradual implementation plan are disputable. However, this notion generally aims to create sufficient space for the further development and deployment of all vehicle concepts which are not propelled by petroleum-products.

Despite the positive prospects of an *Open Fuel Standard* and its potential to encourage the deployment of renewable methanol technology, it seems apparent that if it were to be implemented in the EU, the total demand for biofuels might very well increase beyond what could be supplied sustainably. Such an outlook re-emphasises the fundamental importance of the complementary implementation of the *ILUC Proposal.*

An Open Fuel Standard is in fact currently under active discussion in the U.S. where it has already been proposed as a bill to the House of Representatives. The bill can be found in Annex 3 of this study.

8 - Discussion of results and identification of further research needs

This chapter elaborates on implied uncertainties in the produced results and on the shortcomings of this study in general. Moreover, it points towards further research which should be undertaken to assess the feasibility and applicability of renewable methanol technology in the EU in light of the desired sustainable development in the transport sector.

Section 8.1 discusses the WTW analysis (chapter 4) and recommends further research which should be undertaken in order to refine and confront the knowledge created in the analysis at hand. Section 8.2 discusses the undertaken evaluation of the socio-economic implications of large-scale renewable methanol deployment (in chapter 5). Moreover it specifies different follow-up research activities which should be embarked upon to optimise, challenge and expand the findings of this analysis. Section 8.3 discusses the outlined political recommendations (in chapter 7) and points towards further analyses which are required to concretely assess the effects and barriers to their implementation in the EU.

8.1 - Well-to-Wheels analysis

The WTW analysis proved itself a suitable methodological approach in view of its research objective. In spite of the aforementioned complexity and consequential degree of uncertainty implied in the fundamental base data for the calculations of the WTW model (see section 2.3), the comparative results and conclusions on the *Greenhouse Gas Savings* potential of renewable methanol technology are clear and distinct. However, potential improvements to both the method itself and the choice of investigated pathways should be discussed here.

Since they incorporate avoidable fossil energy inputs in their production step, the investigated bio-methanol pathways which are based on crude glycerine and on biogas do not represent respective best-cases in terms of their GHG emissions and EROEI. Nonetheless, they were modelled because these pathways are of relevance and no other source data was available. For future analyses of a similar kind, identifying more state-of-the-art production procedures for these pathways is, however, recommended.

Moreover, future WTW-analyses of biofuels should aim to identify reliable and up-to-date source data for ILUC-related GHG emissions of their investigated pathways. This consideration would generally optimise the results which were obtained here, not only with regard to 1G biofuels but also with regard to advanced biofuels, particularly those based on farmed wood. Although it would have been desirable to draw on reliable and up-to-date source data in this regard, the exclusion of ILUC-related GHG emissions in this study does not lead to faulty conclusions on the *Greenhouse Gas Savings* potential of renewable methanol technology as such.

While the research focus on renewable methanol technology has indeed produced relevant new knowledge in this respective field, it excludes a greater comparative reflection on other advanced biofuels which might offer high *Greenhouse Gas Savings* and *Security of Supply* potentials as well. As it seems beyond doubt that other advanced biofuels will develop parallel to renewable methanol, for instance 2G ethanol or isobutanol, a comparative evaluation of their performance is of interest and should also be approached by use of the WTW-analysis method, embedded in a larger societal context. The author recommends such research be undertaken in order to produce comprehensive and detailed results on the comparative potentials of different advanced biofuels, particularly in the EU context. The findings of such research could potentially endorse or challenge the conclusions of this study and serve as important additional scientific input for political decision makers, economic investors and other potential stakeholders.

8.2 - Socio-economic implications of large-scale renewable methanol deployment

The conducted evaluation of supply and demand projections for biomass produced the main conclusion that feedstock availability is not expected to present a barrier to introducing renewable methanol technology on a large scale in the EU.

However, the quantitative estimations, particularly in view of competing sectorial demands towards 2020, are naturally imprecise. On the one hand, this is due to the large numbers at play and the rather rough projections found in the source data. On the other hand, the undertaken calculations, required to identifying the sectorial primary energy demands, are based on simplified assumptions.

Although these potential inadequacies in the quantification of available biomass resources do not essentially curtail the demonstrated favourable potentials of renewable methanol technology with regard to *Security of Supply*, a more in-depth and technology-specific evaluation of demands in the heat, transport and electricity sectors would be desirable to sophisticate the produced results concerning relative biomass availability. As this study only quantifies the supply and demand projections up to 2020, such an evaluation should extend its temporal frame towards 2030, particularly as the expected growth for bioenergy carriers in all sectors is eventually likely to be met by physical and economic resource constraints.

With regard to the evaluation of the *Employment* creation potential of renewable methanol technology, the author has sought to produce conservative projections (as is described in section 5.2). However, since there is very little reference data yet available in scientific literature for this technology, the underlying assumptions imply a certain degree of uncertainty. This regards mainly the estimated job creation per bio-methanol plant. Follow-up research efforts should aim to identify clear parameters in this regard in order to provide for optimised employment creation models for renewable methanol technology in the future.

Furthermore, although in order to assure scientific validity the modelled offsetting of newly created jobs in the bio-methanol sector against lost jobs in the ethanol and biodiesel sectors applies the same accounting criteria, nonetheless a natural degree of imprecision in such projections is clearly unavoidable. At the bottom line however, despite the unavoidable degree of imprecision implied in the *prospective outlooks*, the estimated *Employment* creation potential of renewable methanol technology remains high in view of its large-scale deployment.

In similar measure this can be said for the demonstrated positive monetary impact on the EU trade balance if renewable methanol were to substitute the projected biofuel net-imports in 2020. However, in the context of this evaluation it is rather the likelihood of this scenario itself which is debatable, than any potential deviations of the underlying price projections for biofuel imports: a multitude of regionally diverse political and economic factors would have to be considered for a more precise evaluation of import/export relations in 2020. A comprehensive analysis in this regard would not have been purposeful in this study, but it is highly recommended that research in this general direction is undertaken elsewhere in order to further investigate the concrete socio-economic feasibility of renewable methanol technology in the EU.

As such, further research of this kind should take into consideration not just detailed net-import/export relations, but should investigate regional implications for employment and value creation through deployment of renewable methanol technology. This is of particular importance for underdeveloped rural regions of the EU, implied also in the *Employment* objective of EU biofuels policy which aims at economically developing these regions.

Moreover, further research on the economic potentials and feasibility of renewable methanol technology in the EU context should take into detailed consideration important parameters such as the investment and operational costs of renewable methanol plants, the investment costs for upgraded distribution and vehicle infrastructure, and the opportunity costs of alternative fuel technologies. The potential impact of a large-scale penetration of renewable methanol on the general fuel price structure in the EU member states is also an issue of significance, particularly with regard to the acceptance and endorsement of the technology by political decision-makers as well as end-consumers.

8.3 - Political recommendations

While implementing the *ILUC proposal* would optimise the sustainability of the EU biofuel production and grant a competitive edge to advanced sustainable biofuels such as renewable methanol, its implementation is nonetheless likely to create initial adverse economic impacts on the existing biofuels industry in the EU. It is therefore necessary to review the opposing discourse currently taking place. The joint position paper of five European biofuel industry associations states the following perceived errors and disadvantages of the *ILUC proposal* [REA 2013]:

"The ILUC factors in the proposal are based on very uncertain science and need further research. (…) It is highly desirable to address the problem of land use changes (like deforestation or the ploughing of peatland) and fight the undernourishment in many developing regions of the world (…) The proposal of the Commission will not help to solve those problems, instead there are numerous problems arising from it: the 5% cap is a setback from the already achieved biofuel share; Lost trust in investment protection; Demonizing 1st generation biofuels will undermine the acceptance of 2nd generation biofuels and reduce the interest of potential investors; It is unclear when advanced biofuels will be feasible (…)"

It is also stated that the *ILUC Proposal* endangers thousands of jobs across the current biofuel supply chain, puts committed investments of several billion € at risk and jeopardises climate change agreements and renewable energy targets. Moreover, it stresses that numerous benefits of 1G biofuels are ignored in the current political debate, for instance the generally increased agricultural productivity which is driven by the demand for 1G biofuels.

On the one hand, it is indeed of great importance to minimise adverse economic effects and to mitigate the arising conflicts in view of the *ILUC Proposal.* The author strongly recommends that comprehensive and diversified research efforts are undertaken in this direction. On the other hand, threatened organisations will naturally almost never advocate substantial technological changes, despite their potentially advantageous social and environmental implications (see section 2.2.).

This study cannot aim to mitigate conflicts in this regard but only to raise societal awareness to the scientifically demonstrated potentials of renewable methanol technology. Based on the findings of this research, the author therefore remains in strong favour of implementing the *ILUC Proposal* in order to activate the transition to advanced biofuels such as renewable methanol.

The proposed *Pump Act* is guided by the *Pumplagen* which has been an important driver for the increased use of biofuels in Sweden. Consequently, in order to effectively and successfully implement a *Pump Act* at EU level, at first it would be advisable to analyse the experiences from the Swedish example. A follow-up report on the *Pumplagen* by the Swedish *Committee on Transport and Communications* gives indications on some of the economic consequences that the act has had on fuel suppliers and business operators [SR 2009]:

Generally, the *Pumplagen* required the owners of gas stations to invest in new infrastructure and therefore implied more economic risk and constraint for the owners of smaller gas stations than for large petrol companies. Critics have claimed that the *Pumplagen* has led to shut-downs of many smaller gas stations, particularly in rural areas. The report by the *Committee* on the other hand states that, although it may have been a contributing factor in some of these cases, it is not possible to conclude that the majority of the observed shut-downs can be attributed to the *Pumplagen.* This development is rather a result of general structural rationalisations of petrol companies, and similar trends are observable in other member states of the EU.

Regardless, this discussion serves to show that it would be advisable to develop appropriate financing schemes (grants, subsidies, tax rebates etc.) for the infrastructural investments enforced by an EU *Pump Act,* particularly for smaller gas stations which are often the only accessible refuelling points in rural areas. It is therefore recommended that scientific research is undertaken in this regard which should aim to develop according economic mechanisms in due consideration of the differing starting situations in the EU member states and the differing costs of infrastructural investments across alternative fuel technologies.

Moreover, the Swedish example shows that, although the *Pumplagen* was an intentionally technology-neutral act, ethanol eventually established itself as predominant renewable fuel above all other alternatives. This is due to a number of factors ranging from differing investment costs for various types of pumps to the fuel compatibility of the vehicle fleet itself. Thus, although the *Pumplagen* as such was a technology-neutral act, its consequences have not been.

While the simultaneous implementation of the other political measures proposed in this study may be able to partly mitigate such a development, it is recommended that research be undertaken which considers additional regulatory measures with the aim of preventing such disproportion and imbalance in view of an EU *Pump Act*. This research must also be conducted in due consideration of differing situations in the EU member states.

The proposed implementation of an *Open Fuel Standard* in the EU raises a number of critical issues which are indeed challenging and require further investigation. For instance, in spite of the apparent impulse for the domestic development of advanced biofuels such as renewable methanol, a strong and sudden demand increase for alcohol fuels and biofuels in general would likely follow from this political measure, too great to be supplied by domestic produce. Consequently, the biofuels demand in the EU would likely have to be supplied by major imports.

This is clearly undesirable not only in light of the *Supply Security* objective, but also with regard to *Greenhouse Gas Savings* and sustainability issues. Thereby, it would also undermine the tenability and validity of implementing the *ILUC Proposal.* Moreover, it is likely that this initial supply/demand conflict would be reflected by high end-consumer prices for biofuels, hence impeding their further market penetration. Thus, although eventually a large and firmly established domestic advanced biofuels sector could contribute to mitigating such problematic developments, the implementation of an *Open Fuel Standard* in the EU initially calls for additional regulatory measures to prevent these problems from substantialising in the first place. It is recommended that interdisciplinary research activities approach these issues soon, in order to provide useful scientific input for near-term decision making at the EU level.

Generally, upcoming research on the feasibility of an *Open Fuel Standard* in the EU must regard a wide range of important economic issues, most of which could not be considered in this study, for example issues of investment risks and planning security across entire value chains of different fuel technologies. Moreover, there are important economic effects outside the biofuels sphere which must be considered. For instance, the effect of potentially increased fossil methanol prices on other sectors, particularly the chemical sector which is highly dependent on methanol as feedstock in a wide range of industrial applications (see section 3.1). Such potential price increases are likely as an FFV mandate would generally also increase the demand for fossil methanol in the transport sector.

As the WTW analysis in chapter 4 shows that fossil methanol can save WTW GHG emissions compared to gasoline and diesel, this is not necessarily a negative outlook to begin with, particularly as potential synergies between fossil and renewable methanol production are apparent: feeding adequate biomass feedstock together with natural gas to conventional methanol plants could, firstly, reduce the GHG footprint of fossil-based methanol production facilities and, secondly, could gradually introduce renewable methanol production into the existing industrial set-up while building up expertise. Moreover, the economics of integrated plants are potentially less exposed to fluctuating price volatilities of their products. Despite these synergies, however, emissions reductions would be suboptimal and it is disputable whether such developments are feasible and sustainable with regard to the critical aspiration of eventually becoming independent from fossil fuels altogether.

It is apparent that the context in which this research effort has taken place is far-reaching, touching on numerous technical, economic and political dimensions. This re-emphasises and confirms the author's analytical approach of embedding the undertaken investigations in a larger context of interrelated systems, not just within the energy system but also within society itself. Therefore, the findings of this study may serve as point of departure for future research of a similar kind and it may provide a suitable analytical framework from a sustainable energy planning perspective.

9 - Sources

AEBIOM 2012: European Biomass Association. *European Bioenergy Outlook 2012.* pp. 9, 14.-24, 29-62, 86-93. Accessed on 27.04.2013. www.aebiom.org

AFS 2013: Air Fuel Synthesis. Webpage-info on pilot plant and R&D activities. Accessed on 11.05.2013. http://www.airfuelsynthesis.com/

Bentsen and Felby 2012: Niclas Bentsen; Claus Felby. *Biomass for energy in the European Union - a review of bioenergy resource assessments.* pp. 1-4, 7. Accessed on 09.05.2013. http://www.biotechnologyforbiofuels.com/content/5/1/25

BAFF 2013: BioAlcohol Fuel Foundation. *Bought flexifuel vehicles - Total per year.* Accessed on 01.06.2013. http://www.baff.info

BFE 2013: Blue Fuel Energy. *Integration of Blue Fuel and MegaMethanol.* Information on company homepage. Accessed on 10.05.2013. http://bluefuelenergy.com

BioMCN 2013a: BioMCN. *GHG performance of BioMCN's biomethanol*. Internal document of BioMCN.

BioMCN 2013b: BioMCN. *Bio-methanol*. Online resource on bio-methanol product. Accessed on 06.04.2013. http://www.biomcn.eu/our-product/bio-methanol.html

BioMCN 2013c: BioMCN. *BioMCN signs agreement for biogas*. Online resource on company homepage. Accessed on 08.05.2013. http://www.biomcn.eu/news/news/150-biomcn-signs-agreement-for-biogas.html

BP 2013: British Petroleum. BP Energy Outlook 2030. p.21. Accessed on 08.04.2013. http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/BP_World_Energy_Outlook_booklet_2013.pdf

Braungart & McDonough 2002: Michael Braungart; William McDonough. *Cradle to Cradle: Remaking the Way We Make Things.* North Point Press. New York

Bromberg & Cheng 2010: L. Bromberg ; W.K. Cheng. *Methanol as an alternative transportation fuel in the US*. Massachusetts Institute of Technology. pp.3-4, 27-39, 66-68. Accessed on 09.05.2013. http://www.afdc.energy.gov/pdfs/mit_methanol_white_paper.pdf

Bromberg & Cohn 2008: L. Bromberg. D.R. Cohn. *Effective Octane and Efficiency Advantages Of Direct Injection Alcohol Engines.* pp. 2, 15-18. MIT Press. Accessed on 22.03.2013. http://www.psfc.mit.edu/library1/catalog/reports/2000/08ja/08ja002/08ja002_full.pdf

Brusstar & Bakenhus [2002]: Matthew Brusstar; Marco Bakenhus. *Economical, High-Efficiency Engine Technologies for Alcohol Fuels.* Accessed on 09.05.2013. http://www.nord-com.net/stoni/docs/SuTCAF.pdf

CIFOR 2012: Center for International Forestry Research. *Transformations in EU biofuels markets under the Renewable Energy Directive and the implications for land use, trade and forests.* p 6. Accessed on 15.04.2013. http://www.cifor.org/publications/pdf_files/OccPapers/OP-78.pdf

CHEMREC 2008: *The magic of syngas - the link from feedstock to synthetic product.* Accessed on 15.03.2013. http://www.chemrec.se/Syngas_the_link_from_feedstock_to_synthetic_product.aspx

CIA 2013: The Central Intelligence Agency. *CIA World Factbook: Europe*. Accessed on 19.05.2013. https://www.cia.gov/library/publications/the-world-factbook/geos/ee.html

Clausen et al. 2010: Lasse Clausen; Niels Houbak; Brian Elmegaard. *Technoeconomic analysis of a methanol plant based on gasification of biomass and electrolysis of water.* pp.15-18. accessed on 08.05.2013. http://peer.ccsd.cnrs.fr/docs/00/67/36/69/PDF/PEER_author_10.1016%252Fj.energy.2010.02.034.pdf

Coelho et al. 1999. Suani Coelho; Marly Bolognini; Carlos Paletta. *The current situation of PROALCOOL the Brazilian Alcohol Program.* Accessed on 28.05.2013. http://cenbio.iee.usp.br/download/publicacoes/situation_PROALCOOL.pdf

CONCAWE 2011a: Joint Research Centre-EUCAR-CONCAWE collaboration: *Well to Wheels Analysis on Future Automotive Fuels and Powertrains in the European Context, Version 3c. WTT Appendix 1. Description of individual processes and detailed input data.* 2011. pp. 21, 24, 34, 46, 53, 73-74, 68, 86, 102. Publications office of the European Union. Luxembourg. Accessed on 09.04.2013. http://iet.jrc.ec.europa.eu/about-jec/downloads

CONCAWE 2011b: Joint Research Centre-EUCAR-CONCAWE collaboration: *Well to Wheels Analysis on Future Automotive Fuels and Powertrains in the European Context, Version 3c. WELL-to-TANK Report.* Version 3c. 2011. pp. 19-27, 36-38, 54-71, 85. Publications office of the European Union. Luxembourg. Accessed on 09.04.2013. http://iet.jrc.ec.europa.eu/about-jec/downloads

CONCAWE 2011c: Joint Research Centre-EUCAR-CONCAWE collaboration: *Well to Wheels Analysis on Future Automotive Fuels and Powertrains in the European Context, Version 3c. WTT Appendix 2. Description of detailed energy and GHG balance of individual pathways.* 2011. pp. 13, 22, 36, 62. Publications office of the European Union. Luxembourg. Accessed on 09.04.2013. http://iet.jrc.ec.europa.eu/about-jec/downloads

CRI 2013a: Carbon Recycling International. Webpage-info on CRI's commercial activities. Accessed on 10.04.2013. http://www.carbonrecycling.is/

CRI 2013b: Carbon Recycling International. Webpage-info on renewable methanol product. Accessed on 20.04.2013. http://cri.is/index.php?option=com_content&view=article&id=4&Itemid=3&lang=en

EB 2013a: Encyclopaedia Britannica. Online resource. *Petroleum refining.* Accessed on 15.04.2013. http://global.britannica.com/EBchecked/topic/454440/petroleum-refining/81778/Conversion-to-light-fuels

EB 2013b: Encyclopaedia Britannica. Online resource. *Compression ratio.* Accessed on 22.04.2013. http://global.britannica.com/EBchecked/topic/130313/compression-ratio

EC 2008: European Commission Joint Research Center. *Biofuels in the European Context: Facts and Uncertainties.* Accessed on 15.05.2013. http://ec.europa.eu/dgs/jrc/downloads/jrc_biofuels_report.pdf

EC 2012a: European Commission. *Proposal for a Regulation of the European Parliament and of the Council Amending Regulation (EC) No 443/2009 to Define the Modalities for Reaching the 2020 Target to Reduce CO2 Emissions From New Passenger Cars.* COM(2012) 393 final. p. 4. Accessed on 29.03.2013. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2012:0393:FIN:en:PDF

EC 2012b: European Commission. *New Commission proposal to minimise the climate impacts of biofuel production.* 17.10.2012. IP/12/1112. Accessed on 29.01.2013. http://europa.eu/rapid/press-release_IP-12-1112_en.htm and http://ec.europa.eu/clima/policies/transport/fuel/docs/com_2012_595_en.pdf

EC 2012c: European Commission: *Basic information on Ordinary legislative procedure 2012/0288 (COD).* Accessed on 22.05.2013. http://www.europarl.europa.eu/oeil/popups/printficheglobal.pdf?id=612634&l=en

EC 2013a: European Commission. *Clean Power for Transport: A European alternative fuels strategy.* Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. p. 4. Accessed on 29.01.2013. http://ec.europa.eu/danmark/documents/alle_emner/transport/130124_com(2013)17-communication_en.pdf

EC 2013b: European Commission. *Renewable energy progress report.* Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the regions. Accessed on 19.04.2013. http://ec.europa.eu/energy/renewables/reports/reports_de.htm

EC 2013c: European Commission*. Reducing emissions from transport.* Online resource on EU climate action. Accessed on 21.04.2013. http://ec.europa.eu/clima/policies/transport/index_en.htm

ECF 2010: European Climate Foundation. *Biomass for heat and power – opportunity and economics.* p. 9. Accessed on 03.05.2013. http://www.europeanclimate.org/documents/Biomass_report_-_Final.pdf

Ecofys 2010: *Indirect effects of biofuel production - Unraveling the numbers.* Accessed on 29.04.2013. http://www.theicct.org/sites/default/files/ICCT_ILUC_workshop_Ecofys_Sep2010.pdf

Ecofys 2012: *Assessing grandfathering options under an EU ILUC policy*. p. 8. Accessed on 17.05.2013. http://www.ecofys.com/files/files/ecofys_2012_grandfathering%20iluc_02.pdf

EEA 2012: European Environment Agency. *Sectoral trends and projections of EU GHG emissions.* Accessed on 14.05.2013. http://www.eea.europa.eu/data-and-maps/figures/sectoral-trends-and-projections-of-1

EIA 2013: U:S: Energy Information Administration. *International Energy Outlook 2011.* Accessed on 02.04.2013. http://www.eia.gov/forecasts/ieo/liquid_fuels.cfm

Ekbom et al. 2005: Tomas Ekbom; Niklas Berglin; Sara Lögdberg. *Black Liquor Gasification with Motor Fuel Production – BLGMF II.* Accessed on 10.05.2013. http://www.nykomb-consulting.se/pdf/BLGMF_II.pdf

Elbersen et al. 2012: Berien Elbersen; Igor Startisky; Geerten Hengeveld; Mart-Jan Schelhaas; Han Naeff. *Atlas of EU biomass potentials - Spatially detailed and quantified overview of EU biomass potential taking into account the main criteria determining biomass availability from different sources.* Biomass Futures Project: Biomass role in achieving the Climate Change & Renewables EU policy targets. IEE 08 653 SI2. 529 241. pp. 10-13, 63-70. Accessed on 10.05.2013. www.biomassfutures.eu

EMSH 2013: E.M.SH Ng-Tech. Online shop for flex-fuel conversion kits for gasoline engines. Accessed on 8.05.2013. http://emsh-ngtech.com/

Energinet.dk 2012: *Technology Data For Energy Plants - Generation of Electricity and District Heating, Energy Storage and Energy Carrier Generation and Conversion.* Accessed on 03.05.2013. http://www.energinet.dk/SiteCollectionDocuments/Danske%20dokumenter/Forskning/Technology_data_for_energy_plants.pdf

ENS 2012a: Danish Energy Agency. *Alternative drivmidler i transport-sektoren 2.0.* Excel calculation model. Worksheet *Std benzin motor*. Accessed on 20.03.2013. http://www.ens.dk/da-DK/KlimaOgCO2/Transport/Alternativedrivmidler/Sider/Forside.aspx

ENS 2012b: Danish Energy Agency. *Alternative drivmidler i transport-sektoren 2.0.* Excel calculation model. Worksheet *Lastbil Gas*. Accessed on 20.03.2013. http://www.ens.dk/da-DK/KlimaOgCO2/Transport/Alternativedrivmidler/Sider/Forside.aspx

ENS 2012c: Danish Energy Agency. *Alternative drivmidler i transport-sektoren 2.0.* Downloadable Excel calculation model. Worksheet *Std diesel motor*. Accessed on 26.03.2013. http://www.ens.dk/da-DK/KlimaOgCO2/Transport/Alternativedrivmidler/Sider/Forside.aspx

ESRL 2013: Earth System Research Laboratory Global Monitoring Division. *Trends in Atmospheric Carbon Dioxide - April 2013.* Accessed on 09.05.2013. http://www.esrl.noaa.gov/gmd/ccgg/trends/index.html

EU 2009a: Parliament of the European Union. *Renewables Directive*. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. p. 55. Accessed on 07.03.2013. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF

EU 2009b: Parliament of the European Union. *Fuel Quality Directive.* Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC. p.96. Accessed on 05.05.2013. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0088:0113:EN:PDF

EU 2012: European Union. *Energy in Figures – Statistical Pocketbook 2012. Accessed on 19.05.2013.* http://ec.europa.eu/energy/observatory/statistics/statistics_de.htm

EUROSTAT 2012*:* Statistical pocketbook by the European Commission. *Energy, transport and environment indicators*. pp. 33, 51. Accessed on 12.04.2013. http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-DK-12-001/EN/KS-DK-12-001-EN.PDF

EUROSTAT 2013: European Union. *Glossary: Biofuels.* Accessed on 26.05.2013. http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Glossary:Biofuels.

F3 2013: The Swedish Knowledge Centre for Renewable Fuels. *Fact sheet: EU sustainability criteria for biofuels*. Accessed on 31.05.2013. http://www.f3centre.se/sites/default/files/fact_sheet_eu_sustainability_criteria_130107.pdf

Ford 2013: *Fact Sheet: Ford Taurus Vehicle History*. Accessed on 28.05.2013. http://media.ford.com/article_display.cfm?article_id=13482
Grandal 2012: Rune Grandal. *Reducing biomass consumption in a 100 % renewable energy system by efficiently integrating wind, solar and wave power.* Master's Thesis at the University of Southern Denmark. Faculty of Engineering.

Graves et al. 2010: Christopher Graves; Sune D. Ebbesen; Mogens Mogensen; Klaus S. Lackner. *Sustainable hydrocarbon fuels by recycling CO2 and H2O with renewable or nuclear energy.* In: Renewable and Sustainable Energy Reviews 15 (2011) 1–23. p. 1. Accessed on 11.04.2013. http://www.sciencedirect.com/science/article/pii/S1364032110001942

Gustafson 2013: Cole Gustafson*. History of Ethanol Production and Policy*. Accessed on 01.05.2013. http://www.ag.ndsu.edu/energy/biofuels/energy-briefs/history-of-ethanol-production-and-policy

Hamelinck & Faaij 2001: Carlo Hamelinck; André Faaij. *Future prospects for production of methanol and hydrogen from biomass.* Utrecht University. Accessed on 08.05.2013. http://www.costa-due.nl/Achtergrond%20informatie/7%20Algemeen/Report%20Methanol%20and%20Hydrogen.pdf

Hamilton 1995: Bruce Hamilton. *Automotive Gasoline*. Accessed on 09.03.2013. http://blizzard.rwic.und.edu/~nordlie/cars/gasoline.html

Hedegaard 2008: Karsten Hedegaard. *Life cycle assessment of an advanced bioethanol technology in the perspective of constrained biomass availability.* Environmental Science and Technology, 21(42), pp. 7992-7999.

Hvelplund 2005: Frede Hvelplund. *Erkendelse og forandring. Teorier om adaekvat erkendelse og teknologisk forandring med energieksempler fra 1974-2001*. Institute for Development and Planning, Aalborg University.

Hvelplund 2012: Frede Hvelplund. Presentation *Energy policy and Innovative Democracy.* Energy and Environmental Policies lecture on 06.02.2012. Institute for Development and Planning, Aalborg University.

ICCT 2013: The International Council on Clean Transportation. *EU vote on cars CO2: 95 g/km in 2020, 68-78 g/km in 2025.* Accessed on 10.05.2013. http://www.theicct.org/blogs/staff/eu-vote-cars-co2

IEA 2012a: International Energy Association. *World Energy Outlook 2012.* Executive summary. p.4. Accessed on 08.03.2013. http://www.iea.org/publications/freepublications/publication/English.pdf

IEA 2012b: International Energy Association. *Key World Energy Statistics 2012.* p.33. Accessed on 02.04.2013. http://www.iea.org/publications/freepublications/publication/kwes.pdf

IEA 2012c: International Energy Association. *Railway Handbook 2012 - Energy Consumption and CO2 Emissions.* p. 27. Accessed on 09.05.2013. http://www.uic.org/com/IMG/pdf/iea-uic_2012final-lr.pdf

IHS 2013: IHS online press. *Driven By China, Global Methanol Demand Rises 23 Percent in Two Years, Unprecedented Demand Growth Expected for 2012 to 2022.* Accessed on 03.05.2013 http://press.ihs.com/press-release/country-industry-forecasting/driven-china-global-methanol-demand-rises-23-percent-two-

IISD 2013: The International Institute for Sustainable Development. *Biofuels—At What Cost? A review of costs and benefits of EU biofuel policies.* pp. 1-5, 71-76. Accessed on 14.05.2013. http://www.iisd.org/gsi/sites/default/files/biofuels_subsidies_eu_review.pdf

IPCC 2007: Intergovernmental Panel on Climate Change. *Fourth Assessment Report*. p.212. Accessed on 09.04.2013. https://www.ipcc-wg1.unibe.ch/publications/wg1-ar4/ar4-wg1-chapter2.pdf

IRENA 2013: IEA-ETSAP & IRENA. The International Energy Agency's energy technology systems analysis programme in cooperation with the International Renewable Energy Agency. *Production of Bio-methanol.* Technology Brief 108. Accessed on 30.03.2013. www.irena.org/Publications

ISE 2012: Fraunhofer Institut für Solare Energiesysteme. *100% Erneuerbare Energien für Strom und Wärme in Deutschland.* Accessed on 04.02.2013. http://www.ise.fraunhofer.de/de/veroeffentlichungen/veroeffentlichungen-pdf-dateien/studien-und-konzeptpapiere/studie-100-erneuerbare-energien-in-deutschland.pdf

Johnson 2012: Dewey Johnson. *Global methanol market review*. Power point presentation for PEMEX in June 2012. Accessed on 20.04.2013. http://www.ptq.pemex.com/productosyservicios/eventosdescargas/Documents/Foro%20PEMEX%20Petroqu%C3%ADmica/2012/PEMEX_DJohnson.pdf

Law et al. 2013: Karen Law; Jeffrey Rosenfeld; Michael Jackson. *Methanol as a Renewable Energy Resource - White Paper*. Accessed on 08.04.2013. http://www.ourenergypolicy.org/methanol-fuel-blending-and-materials-compatibility-report-2/

Luft & Korin 2012: Gal Luft; Anne Korin. *Petropoly: The Collapse of America's Energy Security Paradigm.* pp. 26-28. ISBN-10: 1478324864. CreateSpace Independent Publishing Platform.

Lund 2008: Henrik Lund. *Choice Awareness and Renewable Energy Systems*. pp. 39-49. Aalborg University.

Lund et al. 2011: Lund, H. (Edt.), Hvelplund, F.; Mathiesen, B. V.; Østergaard, P. A.; Christensen, P.; Connolly, D.; Schaltz, E.; Pillay, J. R.; Nielsen, M. P; Felby, C.; Bentsen, N. S.; Tonini, D.; Astrup, T.; Meyer, N. I.; Heussen, K.; Lind, M.; Morthorst, P. E.; Andersen, F. M.; Münster, M.; Hansen, L. P.; Wenzel, H.; Hamelin, L.; Pöyry, J. M.; Karnøe, P. *Coherent Energy and Environmental System Analysis (CEESA).* Department of Development and Planning, Aalborg University, ISBN 978-87-91404-15-3, Accessed on 03.03.2013. www.ceesa.dk/Publications

Malins 2012: Chris Malins. *A model-based quantitative assessment of the carbon benefits of introducing iLUC factors in the European Renewable Energy Directive.* Accessed on 09.05.2013. http://www.theicct.org/sites/default/files/publications/Malins_gcbb1207.pdf

Mercedes-Benz 2013: *Exponat-Details - Mercedes-Benz Weltrekordwagen T 80*. Accessed on 28.05.2013. http://wiki.mercedes-benz-classic.com/index.php/Exponat-Details?id=83&lang=de

METHANEX 2006: *Technische Informationen und Sicherheitsmerkblatt für den Umgang mit Methanol.* 09/2006. Accessed on 17.04.2013. http://www.methanex.com/products/documents/TISH_german.pdf

METHANEX 2013: Methanex Investor Presentation. 03/2013. Accessed on 25.04.2013. http://www.methanex.com/investor/documents/MXPresentation26Mar2013_FINAL_005.pdf

MI 2013a: Methanol Institute. *Applications for Methanol*. Online Information source on methanol. Accessed on 22.04.2013. http://www.methanol.org/Methanol-Basics/Methanol-Applications.aspx

MI 2013b: Methanol Institute. Methanol Gasoline Blends: *Alternative Fuel for Today's Automobiles and Cleaner Burning Octane for Today's Oil Refinery Methanol Blending.* Technical Product Bulletin. Accessed on 28.04.2013. http://www.methanol.org/Energy/Transportation-Fuel/Fuel-Blending-Guidelines/Blenders-Product-Bulletin-(Final).aspx

MI 2013c: Methanol Institute. Online source for information on the global methanol industry. Accessed on 28.04.2013. http://www.methanol.org/

MMSA 2012: Methanol Market Services Asia. *Global Methanol Supply and Demand Balance, 2005-2010E.* Accessed 25.04.2013. http://www.methanol.org/Methanol-Basics/Resources/MMSA-Global-Methanol-Supply-and-Demand.aspx

Mortensgaard et al. 2011: Aksel Mortensgaard; Jesper Lebæk; Hans Over Hansen; John Bogild Hansen; Allan Schroder Petersen; Ivan Loncarevic; Claus Torbensen; Per Sune Koustrup; Anders Korsgaard; Svend Lykkemarjk Christensen; Morgens Mogensen; Aksel Hauge Pedersen; Martin Wittrup Hansen; Jacob Bonde. *GreenSynFuels.* Final project report. EUDP project journal number: 64010-0011. pp. 8-13, 40-42, 64-65, 74-76, 85. Accessed on 04.02.2013. http://www.hydrogennet.dk/fileadmin/user_upload/PDF-filer/Partnerskabet/Strategier/GreenSynFuels_report_final.pdf

Müller 2003: Jens Müller. *A Conceptual Framework for Technology Analysis*, in: John Kuada, ed., *Culture and Technological Transformation in the South – Transfer or Local Innovation*. pp. 1-30. Samfundslitteratur. Copenhagen.

Murphy & Hall 2010: David Murphy; Charles Hall. *Year in review - EROI or energy return on (energy) invested.* pp. 102-118. Annals of the New York Academy of Sciences Volume 1185.

Nowell 1994: Gregory Nowell. *On the Road with Methanol: The Present and Future Benefits of Methanol Fuel*. Accessed on 18.03.2013. http://www.afdc.energy.gov/pdfs/2474.pdf

Nussbaumer & Oser 2004: Thomas Nussbaumer; Michael Oser. *Evaluation of Biomass Combustion based Energy Systems by Cumulative EnergyDemand and Energy Yield Coefficient.* Accessed on 03.05.2013. http://www.ieabcc.nl/publications/Nussbaumer_IEA_CED_V11.pdf

OECD 2012: The Organisation for Economic Co-operation and Development. *OECD-FAO Agricultural Outlook 2012*. pp. 88-89, 114. Accessed on 18.05.2013. http://www.oecd.org/site/oecd-faoagriculturaloutlook

Olah et al. 2009: George Olah; Alain Goeppert; Surya Prakash. Beyond Oil and Gas: The Methanol Economy. Second and Updated and Enlarged Edition. pp. 180-200, 235-259. WILEY-VCH Verlag, Weinheim.

Østergaard 2011: Poul Alberg Østergaard. Presentation *Energy Conversion Technologies,* on 05.10.2011. p. 20/slide 39. Institute for Development and Planning, Aalborg University.

Panoutsou & Castillo 2011: Calliope Panoutsou; Arturo Castillo. *Outlook on Market Segments for Biomass Uptake by 2020.* Biomass Futures Project: Biomass role in achieving the Climate Change & Renewables EU policy targets. IEE 08 653 SI2. 529 241. Accessed on 17.05.2013. www.biomassfutures.eu

REA 2013: Renewable Energy Association. Position paper by: Asociación de Productores de Energías Renovables Biocarburantes – Spain; Associação Portuguesa de Produtores de Biocombustíveis – Portugal; Krajowa Izba Biopaliw – Poland; Renewable Energy Association – United Kingdom; Verband der Deutschen Biokraftstoffindustrie – Germany. *National Associations refuse Commission's proposal on iLUC.* Accessed on 01.06.2013. http://www.r-e-a.net/images/upload/news_165_130423_National_Associations_refuse_Commissions_proposal_on_iLUC.pdf

Reed and Lerner 1973: T.B. Reed; R.M. Lerner. *Methanol: A versatile Fuel for Immediate Use.* In: Science, Vol. 182. Pp. 1299-1304. Accessed on 26.04.2013. http://driveonwood.com/sites/default/files/pdf/Science1.pdf--Science1.pdf

RENEW 2008: SYNCOM Forschungs- und Entwicklungsberatung. *Renewable Fuels for advanced Powertrains.* pp. 147-148. Accessed on 24.05.2013. www.renew-fuel.com

SAE 1993: Society of American Engineers. *Test Standard Paper J1681*. Accessed on 28.05.2013. http://papers.sae.org/

Searchinger 2010: Timothy Searchinger. *Biofuels and the need for additional carbon.* Accessed on 02.04.2013. http://iopscience.iop.org/1748-9326/5/2/024007/fulltext/

SF 2005: Svensk Författningssamling. *Communication 2005/06:134, Act (2005:1248) on the obligation to supply renewable fuel - the Pump Act* (Swedish language). Accessed on 28.05.2013. https://lagen.nu/2005:1248

Shere 2013: Jeremy Shere. *Ford, Edison, and Alcohol Fuel.* Accessed on 09.05.2013. http://renewablebook.com/chapter-excerpts/biofuel-chapter-excerpt

Siemons et al. 2004: Siemons, R.; Vis M.; van den Berg, D.; McChesney, I.; Whiteley, M.; Nikolaou, N. *Bio-energy's Role in the EU Energy Market: A View of Developments until 2020*. Report to the European Commission. Accessed on 10.05.2013. http://www.edis.sk/ekes/bioenergy_role_2000_2010_2020.pdf

SR 2009: The Swedish Parliament. *The Act on the Obligation to Supply Renewable Fuels– A follow-up report. pp 1-10.* Accessed on 22.05.2013. http://www.riksdagen.se

Stein et al. 2012: Stein, R.; Polovina, D.; Roth, K.; Foster, M. *Effect of Heat of Vaporization, Chemical Octane, and Sensitivity on Knock Limit for Ethanol - Gasoline Blends*. SAE International Technical Paper. Accessed on 27.04.2013. http://papers.sae.org/2012-01-1277

Stephens 2010: Tom Stephens. Speech by then-Vice Chairman of General Motors in February 2010, announcing the company's investments on flex-fuel vehicles. *GM seeking more U.S. ethanol fuelling stations.* Accessed on 01.06.2013. http://www.reuters.com/article/2010/02/16/gm-ethanol-idUSN1619509020100216

UN 1987: United Nations. *Report of the World Commission on Environment and Development: Our Common Future (Brundtland Report).* Accessed on 05.04.2013. http://www.un-documents.net/our-common-future.pdf

UN 1992: United Nations. *Framework Convention on Climate Change.* Accessed on 09.05.2013. http://unfccc.int

Urbanchuk 2012: John Urbanchuk. *Contribution of biofuels to the global economy.* p.18. Accessed on 14.05.2013. http://www.mvo.nl/Portals/0/duurzaamheid/biobrandstoffen/nieuws/2012/05/Global_Economic_Impact_of_Biofuels_FINAL.pdf

VOLVO 2008: VOLVO Group Global. *Climate issues in focus.* Accessed on 31.05.2013. http://www.volvogroup.com/sitecollectiondocuments/vghq/volvo%20group/volvo%20group/our%20values/environment/renewable%20fuels/climate_issues_in_focus_eng.pdf

Ward & Teague 1996: Peter Ward; Jonathan Teague. *Fifteen years of fuel methanol distribution.* Accessed on 28.05.2013. http://www.methanol.org/Energy/Resources/Alternative-Fuel/CEC-1996-ISAF-Fuel-Meoh-Paper.aspx

WEC: World Energy Council. *Global Transport Scenarios 2050*. Accessed on 02.04.2013. http://www.worldenergy.org/documents/wec_transport_scenarios_2050.pdf

Winterkorn 2013: Martin Winterkorn. Speech by Volkswagen CEO in March 2013, announcing the company's drawback from hydrogen-FCV's. *Hydrogen Fuel-Cell Cars Not Viable, Says Volkswagen CEO.* Accessed on 09.05.2013. http://www.greencarreports.com/news/1083046_hydrogen-fuel-cell-cars-not-viable-says-volkswagen-ceo

Zubrin 2013: Robert Zubrin. *Methanol Wins An Open Wager.* Accessed on 22.05.2013. http://www.openfuelstandard.org/2011/12/methanol-wins-open-wager.html

Annex 1 - Pathway-specific data inputs for the WTW analysis

Calculation of e(c) and e(p) for bio-methanol from crude glycerin (near-term pathway)			Sources
Collection and transport: e(c)	6,249	gCO2e/MJ	CONCAWE 2011a: 102; P.Koustrup, personal communication
e (c)	6,249	gCO2e/MJ	
Gasification and synthesis: e(p)	22,600	gCO2e/MJ	BioMCN 2013
e(p)	22,600	gCO2e/MJ	
Calculation of η(c) and η(p) for bio-methanol from crude glycerin (near-term pathway)			Sources
Collection and transport: η(c)	0,949	%	CONCAWE 2011a: 102; P.Koustrup, pers.comm. 16.04.2013
η (c)	0,949	%	
Gasification and synthesis: η(p)	0,650	%	T. Ekbom, personal communication
η(p)	0,650	%	

Table Annex 1 - Input values for the calculation of GHG emissions and efficiencies in the near-term bio-methanol pathway based on crude glycerine

Calculation of e(c) and e(p) for bio-methanol from waste wood via black liquor (near-term pathway)			Sources
Waste collection and chipping: e(c)	0,550	gCO2e/MJ	CONCAWE 2011c: 36
Transport to production facility: e(c)	0,510	gCO2e/MJ	CONCAWE 2011c: 36
e (c)	1,060	gCO2e/MJ	
Gasification and synthesis of black liquor: e(p)	0,200	gCO2e/MJ	CONCAWE 2011c: 36
e(p)	0,200	gCO2e/MJ	
Calculation of η(c) and η(p) for bio-methanol from waste wood via black liquor (near-term pathway)			Sources
Waste collection and chipping: η(c)	0,952	%	CONCAWE 2011c: 36
Transport to production facility: η(c)	0,990	%	CONCAWE 2011c: 36
η (c)	0,943	%	
Gasification and synthesis of black liquor: η(p)	0,658	%	CONCAWE 2011a: 86
η(p)	0,658	%	

Table Annex 2 - Input values for the calculation of GHG emissions and efficiencies in the near-term bio-methanol pathway based on waste wood via black liquor

Calculation of e(c) and e(p) for bio-methanol from farmed wood (near-term pathway)			Sources
Wood farming and and chipping: e(c)	4,700	gCO2e/MJ	CONCAWE 2011c: 36
Transport to production facility: e(c)	0,700	gCO2e/MJ	CONCAWE 2011c: 36
e (c)	5,400	gCO2e/MJ	
Gasification and synthesis: e(p)	0,172	gCO2e/MJ	CONCAWE 2011c: 36; Mortensgaard et al. 2011: 85
e(p)	0,172	gCO2e/MJ	
Calculation of η(c) and η(p) for bio-methanol from farmed wood (near-term pathway)			Sources
Wood farming and and chipping: η(c)	0,926	%	CONCAWE 2011c: 36
Transport to production facility: η(c)	0,990	%	CONCAWE 2011c: 36
η (c)	0,917	%	
Gasification and synthesis: η(p)	0,592	%	Mortensgaard et al. 2011: 85
η(p)	0,592	%	

Table Annex 3 - Input values for the calculation of GHG emissions and efficiencies in the near-term bio-methanol pathway based on farmed wood

Calculation of e(c) and e(p) for bio-methanol from waste wood (near-term pathway)			Sources
Wood collection and chipping: e(c)	0,700	gCO2e/MJ	CONCAWE 2011c: 36
Transport to production facility by road and sea: e(c)	2,700	gCO2e/MJ	CONCAWE 2011c: 36
e (c)	3,400	gCO2e/MJ	
Gasification and synthesis: e(p)	0,172	gCO2e/MJ	CONCAWE 2011c: 36; Mortensgaard et al. 2011: 85
e(p)	0,172	gCO2e/MJ	
Calculation of η(c) and η(p) for bio-methanol from waste wood (near-term pathway)			Sources
Wood collection and chipping: η(c)	0,943	%	CONCAWE 2011c: 36
Transport to production facility: η(c)	0,971	%	CONCAWE 2011c: 36
η (c)	0,916	%	
Gasification and synthesis: η(p)	0,592	%	Mortensgaard et al. 2011: 85
η(p)	0,592	%	

Table Annex 4 - Input values for the calculation of GHG emissions and efficiencies in the near-term bio-methanol pathway based on waste wood

Calculation of e(c) and e(p) for bio-methanol from biogas (near-term pathway)			Sources
Cultivation of maize and barley: e (c)	17,420	gCO2e/MJ	CONCAWE 2011c: 15
transport: e(c)	0,260	gCO2e/MJ	CONCAWE 2011c: 15
production and upgrading: e(c)	2,920	gCO2e/MJ	CONCAWE 2011c: 15
e (c)	20,600	gCO2e/MJ	
Reforming and synthesis: e(p)	11,700	gCO2e/MJ	CONCAWE 2011c: 36
e(p)	11,700	gCO2e/MJ	
Calculation of η(c) and η(p) for bio-methanol from biogas (near-term pathway)			Sources
Cultivation of maize and barley: η(c)	0,909	%	CONCAWE 2011c: 15
manure transprt: η(c)	0,999	%	CONCAWE 2011c: 15
productin and upgrading: η(c)	0,461	%	CONCAWE 2011c: 15
η (c)	0,419	%	
Reforming and synthesis: η(p)	0,683	%	CONCAWE 2011a: 36
η(p)	0,683	%	

Table Annex 5 - Input values for the calculation of GHG emissions and efficiencies in the near-term bio-methanol pathway based on biogas

Calculation of e(c) and e(p) for bio-methanol from farmed wood, integrating SOEC (medium-term pathway)			Sources
Collection e(c)	2,334	gCO2e/MJ	CONCAWE 2011c: 36
Transport to production facility: e(c)	0,348	gCO2e/MJ	CONCAWE 2011c: 36
e (c)	2,682	gCO2e/MJ	
Gasification and synthesis: e(p)	0,144	gCO2e/MJ	own assumption, based on Mortensgaard et al. 2011: 85 and CONCAWE 2011c: 36
e(p)	0,144	gCO2e/MJ	
Calculation of η(c) and η(p) for bio-methanol from farmed wood, integrating SOEC (medium-term pathway)			Sources
Collection η(c)	0,971	%	CONCAWE 2011c: 36
Transport to production facility: η(c)	0,985	%	CONCAWE 2011c: 36
η (c)	0,957	%	
Gasification and synthesis: η(p)	0,708	%	Mortensgaard et al. 2011: 85
η(p)	0,708	%	

Table Annex 6 - Input values for the calculation of GHG emissions and efficiencies in the medium-term bio-methanol pathway based on farmed wood

Calculation of e(c) and e(p) for renewable methanol from CO2 capture and recycling (long-term pathway)			Sources
CO2 capture and MeOH synthesis e(c), e(p)	0,000	gCO2e/MJ	CRI 2013
e(c) + e(p)	0,000	gCO2e/MJ	
Calculation of η(c) and η(p) for renewable methanol from CO2 capture and recycling (long-term pathway)			Sources
CO2 capture and MeOH synthesis η(c), η(p)	0,700	%	Graves et al. 2010: 70
η(c) * η(p)	0,700	%	

Table Annex 7 - Input values for the calculation of GHG emissions and efficiencies in the long-term renewable methanol pathway based carbon emissions recycling

Calculation of e(td) for methanol, 600km sea transport and 50 km road and rail transport (all pathways)			Sources
Handling, loading	0,190	gCO2e/MJ	CONCAWE 2011a: 102
Sea transport	0,326	gCO2e/MJ	CONCAWE 2011a: 102
Depot:	0,850	gCO2e/MJ	CONCAWE 2011a: 102
Distribution by rail and road, 50km	0,378	gCO2e/MJ	CONCAWE 2011a: 102
e (td)	1,744	gCO2e/MJ	
Calculation of η(td) for methanol, 600km sea transport and 50 km road and rail transport (all pathways)			Sources
Handling, loading	0,997	%	CONCAWE 2011a: 102
Sea transport	0,996	%	CONCAWE 2011a: 102
Depot:	0,995	%	CONCAWE 2011a: 102
Distribution by rail and road, 50km	0,997	%	CONCAWE 2011a: 102
η(td)	0,985	%	

Table Annex 8 - Input values for the calculation of transport emissions and efficiencies for the inner-EU distribution of methanol fuel

Calculation of e(c) and e(p) for fossil methanol, based on natural gas and shipped 5000 nm to EU / 250 km road and rail distribution within EU (comparative pathway)			Sources
NG extraction and processing e(c)	5,600	gCO2e/MJ	CONCAWE 2011c: 36
e (c)	5,600	gCO2e/MJ	
Reforming and synthesis: e(p)	11,700	gCO2e/MJ	CONCAWE 2011c: 36
e(p)	11,700	gCO2e/MJ	
MeOH handling and loading: e(td)	0,190	gCO2e/MJ	CONCAWE 2011a: 102
Sea trasnsport 5000 nm	5,030	gCO2e/MJ	CONCAWE 2011a: 102
Depot in EU: e(td)	0,850	gCO2e/MJ	CONCAWE 2011a: 102
Distribution and dispensing: e(td)	1,890	gCO2e/MJ	CONCAWE 2011a: 102
e(td)	7,960	gCO2e/MJ	
Calculation of η(c) and η(p) for fossil methanol, based on natural gas and shipped 5000 nm to EU / 250 km road and rail distribution within EU (comparative pathway)			Sources
NG extraction and processing η(c)	0,962	%	CONCAWE 2011c: 36
η (c)	0,962	%	
Reforming and synthesis: η(p)	0,683	%	CONCAWE 2011a: 34
η(p)	0,683	%	
MeOH handling and loading: η(td)	0,997	%	CONCAWE 2011a: 102
Sea transport 5000 nm: η(td)	0,941	%	CONCAWE 2011a: 102
Depot in EU: η(td)	0,995	%	CONCAWE 2011a: 102
Distribution and dispensing: η(td)	0,969	%	CONCAWE 2011a: 102
η(td)	0,904	%	

Table Annex 9 - Input values for the calculation of GHG emissions and efficiencies in the comparative fossil methanol pathway

Calculation of e (c), e(p) and e(td) for gasoline, refined and distributed within EU, based on average EU crude oil basket (comparative pathway)			Sources
Crude oil extraction and processing e(c)	4,830	gCO2e/MJ	CONCAWE 2011a: 21
Crude oil transportation: e (c)	0,880	gCO2e/MJ	CONCAWE 2011a: 21
e (c)	5,710	gCO2e/MJ	
Refining to gasoline e(p)	7,000	gCO2e/MJ	CONCAWE 2011a: 24
e(p)	7,000	gCO2e/MJ	
Gasoline transport by barge, rail and pipeline e(td)	0,700	gCO2e/MJ	CONCAWE 2011a: 24
Gasoline depot e(td)	0,110	gCO2e/MJ	CONCAWE 2011a: 24
Gasoline distribution e(td)	0,750	gCO2e/MJ	CONCAWE 2011a: 24
e(td)	1,560	gCO2e/MJ	
Calculation of η (c), η(p) and η(td) for gasoline, refined and distributed within EU, based on average EU crude oil basket (comparative pathway)			Sources
Crude oil extraction and processing η(c)	0,945	%	CONCAWE 2011a: 21
Crude oil transportation: (c)	0,989	%	CONCAWE 2011a: 21
η(c)	0,935	%	
Refining to gasoline η(p)	0,926	%	CONCAWE 2011a: 24
η(p)	0,926	%	
Gasoline transport by barge, rail and pipeline: η(td)	0,989	%	CONCAWE 2011a: 24
Gasoline depot: η(td)	0,998	%	CONCAWE 2011a: 24
Gasoline distribution: η(td)	0,986	%	CONCAWE 2011a: 24
η(td)	0,973	%	

Table Annex 10 - Input values for the calculation of GHG emissions and efficiencies in the comparative gasoline pathway

Calculation of e (c), e(p) and e(td) for diesel, refined and distributed within EU, based on average EU crude oil basket (comparative pathway)			Sources
Crude oil extraction and processing e(c)	4,830	gCO2e/MJ	CONCAWE 2011a: 21
Crude oil transportation: e (c)	0,880	gCO2e/MJ	CONCAWE 2011a: 21
e (c)	5,710	gCO2e/MJ	
Refining to diesel: e(p)	8,600	gCO2e/MJ	CONCAWE 2011a: 21
e(p)	8,600	gCO2e/MJ	
Diesel transport by barge, rail and pipeline e(td)	0,700	gCO2e/MJ	CONCAWE 2011a: 21
Diesel depot e(td)	0,110	gCO2e/MJ	CONCAWE 2011a: 21
Diesel distribution e(td)	0,750	gCO2e/MJ	CONCAWE 2011a: 21
e(td)	1,560	gCO2e/MJ	
Calculation of η (c), η(p) and η(td) for diesel, refined and distributed within EU, based on average EU crude oil basket (comparative pathway)			Sources
Crude oil extraction and processing η(c)	0,945	%	CONCAWE 2011a: 21
Crude oil transportation: η(c)	0,989	%	CONCAWE 2011a: 21
η(c)	0,935	%	
Refining to diesel: η(p)	0,909	%	CONCAWE 2011a: 21
η(p)	0,909	%	
Diesel transport by barge, rail and pipeline: η(td)	0,990	%	CONCAWE 2011a: 21
Diesel depot: η(td)	0,998	%	CONCAWE 2011a: 21
Diesel distribution: η(td)	0,986	%	CONCAWE 2011a: 21
η(td)	0,974	%	

Table Annex 11 - Input values for the calculation of GHG emissions and efficiencies in the comparative diesel pathway

Calculation of e (c), e(p) and e(td) for ethanol from sugarcane, imported from Brazil (comparative pathway)			Sources
Cultivation: e(c)	14,450	gCO2e/MJ	CONCAWE 2011a: 68
Road transport: e (c)	0,850	gCO2e/MJ	CONCAWE 2011a: 68
e (c)	15,300	gCO2e/MJ	
Ethanol plant: e(p)	1,200	gCO2e/MJ	CONCAWE 2011a: 68
e(p)	1,200	gCO2e/MJ	
Shipping to EU: e(td)	7,690	gCO2e/MJ	CONCAWE 2011a: 68
Distribution and retail e(td)	0,440	gCO2e/MJ	CONCAWE 2011a: 68
e(td)	8,130	gCO2e/MJ	
Calculation of η (c), η(p) and η(td) for ethanol from sugarcane, imported from Brazil			Sources
Cultivation η(c)	0,943	%	CONCAWE 2011a: 68
Road transport: η(c)	0,990	%	CONCAWE 2011a: 68
η(c)	0,934	%	
Ethanol plant: η(p)	0,562	%	CONCAWE 2011a: 68
η(p)	0,562	%	
Shipping to EU: η(td)	0,909	%	CONCAWE 2011a: 68
Distribution: η(td)	0,990	%	CONCAWE 2011a: 68
η(td)	0,900	%	

Table Annex 12 - Input values for the calculation of GHG emissions and efficiencies in the comparative ethanol pathway

Calculation of e (c), e(p) and e(td) for biodiesel from rapeseed (comparative pathway)			Sources
Cultivation: e(c)	28,960	gCO2e/MJ	CONCAWE 2011a: 46
Road transport: e(c)	0,170	gCO2e/MJ	CONCAWE 2011a: 53
e(c)	29,130	gCO2e/MJ	
Plant oil extraction: e(c)	4,460	gCO2e/MJ	CONCAWE 2011a: 69
Plant oil refining: e(c)	0,720	gCO2e/MJ	CONCAWE 2011a: 73
Esterification: e(c)	9,590	gCO2e/MJ	CONCAWE 2011a: 74
e(p)	14,770	gCO2e/MJ	
Distribution: e(td)	1,270		CONCAWE 2011c: 22
e(td)	1,270	gCO2e/MJ	
Calculation of η (c), η(p) and η(td) for biodiesel from rapeseed (comparative pathway)			Sources
Cultivation η(c)	0,602	%	CONCAWE 2011a: 46
Road transport: η(c)	0,998	%	CONCAWE 2011a: 53
η(c)	0,601	%	
Plant oil extraction: η(c)	0,566	%	CONCAWE 2011a: 69
Plant oil refining η(c)	0,949		CONCAWE 2011a: 73
Esterification: η(c)	0,850	%	CONCAWE 2011a: 74
η(p)	0,457	%	
Distribution: η(td)	0,980		CONCAWE 2011c: 22
η(td)	0,980	%	

Table Annex 13 - Input values for the calculation of GHG emissions and efficiencies in the comparative biodiesel pathway

Annex 2 - Categorization of biomass potentials in the base study by Elbersen et al. [2012]

Sector	Biomass category	Biomass type detail	General definition	Specific definition
Biomass from agriculture	Energy crops	Woody/lignocellulosic biomass	Biomass from agricultural production activities	Solid (lignocellulosic& woody) energy crops (for generating electricity & heat, 2nd generation biofuels)
	Energy crops	Sugar, starch, oil	Biomass from agricultural production activities	Crops for biodiesel & bioethanol (1st generation: sugar/starch & oil crops)
	Energy crops	wet biomass	Biomass from agricultural production activities	Energy maize and maize residues (for biogas)
	Agricultural primary residues	Dry manure	Biomass from agricultural production activities	Dry manure (poultry, sheep & goat manure)
	Agricultural primary residues	Wet manure	Biomass from agricultural production activities	Pig and cattle manure
	Agricultural primary residues	Solid agricultural residues	Biomass from agricultural cultivation, harvesting and maintenance activities	Other solid agricultural residues (prunings, orchards residues)
	Agricultural primary residues	Solid agricultural residues	Biomass from permanent (semi-natural) grasslands	Grass
	Agricultural primary residues	Solid agricultural residues	Biomass from agricultural cultivation and harvesting activities	Straw/stubbles (cereals, sunflower, RAPE)
Biomass from forestry	Forestry biomass	Woody biomass	Biomass from forestry: forests and other wooded land, incl. tree plantations and short rotation forests (SRF)	Stem wood production
	Forestry biomass	Woody biomass	Biomass fr. forests and other wooded land incl. tree plantations)	Volume of additionally harvested wood realistically available for bioenergy
	Primary forestry residues	Woody biomass	Cultivation and harvesting / logging activities in forests and other wooded land. Biomass from trees/hedges outside forests incl. landscape elements	Available volume of felling residues (branches and roots) and woody residues from landscape maintenance activities outside forests.
	Secondary forestry residues	Woody biomass	Biomass coming from wood processing, e.g. industrial production	Bioenergy potential of wood processing residues (e.g., woodchips, sawdust, black liquor)
Biomass from waste	Primary residues	Biodegradable waste	Biomass from road side verges	Biomass residues/solid biomass resulting from maintenance activities (e.g. from grass and woody cuttings from road side verges)
	Secondary residues	Solid and wet agricultural residues	Processing of agricultural products, e.g. for food and feed	Processing residues (e.g. pits from olive pitting, shells/husks from seed/nut shelling and slaughter waste).
	Tertiary residues	Biodegradable waste	Biomass coming from private households and/or private residential gardens	Organic household waste incl. woody fractions, e.g. food leftovers, waste paper, discarded furniture)
	Tertiary residues	Organic waste from industry and trade	Biomass from industry and trade, excl. forest industry	Organic waste from industry and trade incl. woody fractions, e.g. bulk transport packaging, recovered demolition wood (excluding wood which goes to non-energy uses),
	Waste biomass	Biodegradable waste	From industry and private households	Sewage sludge

Table Annex 14 - Categorization of biomass potentials in the base study by Elbersen et al. [2012]

Annex 3 - Open Fuel Standard Bill

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112TH CONGRESS
1ST SESSION

H. R. 1687

To amend chapter 329 of title 49, United States Code, to ensure that new vehicles enable fuel competition so as to reduce the strategic importance of oil to the United States.

IN THE HOUSE OF REPRESENTATIVES

MAY 3, 2011

Mr. SHIMKUS (for himself, Mr. ENGEL, Mr. BARTLETT, and Mr. ISRAEL) introduced the following bill; which was referred to the Committee on Energy and Commerce

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A BILL

To amend chapter 329 of title 49, United States Code, to ensure that new vehicles enable fuel competition so as to reduce the strategic importance of oil to the United States.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE.

This Act may be cited as the "Open Fuel Standard Act of 2011".

SEC. 2. OPEN FUEL STANDARD FOR MOTOR VEHICLES.

Chapter 329 of title 49, United States Code, is amended by inserting after section 32905 the following new section:

“§ 32905A. Open fuel standard for motor vehicles.

“(a) REQUIREMENTS.—Except as provided in subsection (c), each manufacturer’s fleet of covered vehicles for a particular model year shall be comprised of—

“(1) not less than 50 percent qualified vehicles beginning in model year 2014;

“(2) not less than 80 percent qualified vehicles beginning in model year 2016; and

“(3) not less than 95 percent qualified vehicles beginning in model year 2017 and each subsequent year.

“(b) ADDITIONAL DEFINITIONS.—As used in this section—

“(1) the term ‘covered vehicle’ means a passenger automobile, and includes a light-duty motor vehicle;

“(2) the term ‘qualified vehicle ’ means covered vehicle that—

“(A) has been warranted by its manufacturer to operate solely on natural gas, hydrogen, or biodiesel;

“(B) is a flexible fuel vehicle;

''(C) is a plug-in electric drive vehicle;

''(D) is propelled solely by fuel cell that produces power without the use of petroleum or a petroleum-based fuel; or

''(E) is propelled solely by something other than an internal combustion engine, and produces power without the use of petroleum or a petroleum-based fuel;

''(3) the term 'flexible fuel vehicle' means a vehicle that has been warranted by its manufacturer to operate on gasoline, E85, and M85;

''(4) the term 'E85' means a fuel mixture containing 85 percent ethanol and 15 percent gasoline by volume;

''(5) the term 'M85' means a fuel mixture containing 85 percent methanol and 15 percent gasoline by volume;

''(6) the term 'biodiesel' means diesel fuel which has been produced from a non-petroleum feedstock and which meets the standards of ASTM D6751–03;

''(7) the term 'plug-in electric drive vehicle' has the meaning given such term in section 508(a)(5) of the Energy Policy Act of 1992 (42 U.S.C. 13258(a)(5)); and

"(8) the term 'light-duty motor vehicle' means a light-duty truck or light-duty vehicle as such terms are defined in section 216(7) of the Clean Air Act (42 U.S.C. 7550(7)) of less than or equal to 8,500 pounds gross vehicle weight rating.

"(c) TEMPORARY EXEMPTION FROM REQUIREMENTS.—

"(1) APPLICATION.—A manufacturer may request an exemption from the requirement described in subsection (a) by submitting an application to the Secretary, at such time, in such manner, and containing such information as the Secretary may require by regulation. Each such application shall specify the models, lines, and types of automobiles affected.

"(2) EVALUATION.—After evaluating an application received from a manufacturer, the Secretary may at any time, under such terms and conditions, and to such extent as the Secretary considers appropriate, temporarily exempt, or renew the exemption of, a light-duty motor-vehicle from the requirement described in subsection (a) if the Secretary determines that unavoidable events not under the control of the manufacturer prevent the manufacturer of such automobile from meeting its required production volume of qualified automobiles, including—

"(A) a disruption in the supply of any component required for compliance with the regulations; or

"(B) a disruption in the use and installation by the manufacturer of such component.

"(3) CONSOLIDATION.—The Secretary may consolidate applications received from multiple manufacturers under subparagraph (A) if they are of a similar nature.

"(4) CONDITIONS.—Any exemption granted under paragraph (2) shall be conditioned upon the manufacturer's commitment to recall the exempted automobiles for installation of the omitted components within a reasonable time proposed by the manufacturer and approved by the Secretary after such components become available in sufficient quantities to satisfy both anticipated production and recall volume requirements.

"(5) NOTICE.—The Secretary shall publish in the Federal Register—

"(A) notice of each application received from a manufacturer;

"(B) notice of each decision to grant or deny a temporary exemption; and

"(C) the reasons for granting or denying such exemptions.

"(d) RULEMAKING.—Not later than 1 year after the date of enactment of this Act, the Secretary shall promulgate regulations as necessary to carry out this section.".

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There are far, far better things ahead than any we leave behind.

C.S. Lewis