TRANSPORT BIOFUEL FUTURES IN ENERGY-ECONOMY MODELING

– A REVIEW

Report from an f3 project

Authors:

Martin Börjesson

Maria Grahn

Erik Ahlgren

Chalmers University of Technology

THE SWEDISH KNOWLEDGE CENTRE
FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This report is the result of a cooperation project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). The f3 Centre is a nationwide centre, which through cooperation and a systems approach contributes to the development of sustainable fossil-free fuels for transportation. The centre is financed by the Swedish Energy Agency, the Region Västra Götaland and the f3 Partners, including universities, research institutes, and industry (see www.f3centre.se).

This report has been subject to review and commenting by Anna Krook Riekkola (Luleå University of Technology) and Bengt Johansson (Lund University).

This report shoud be cited as:

Börjesson, M., Grahn, M. & Ahlgren, E. O. (2013) *Transport Biofuel Futures in Energy-Economic Modeling – A Review*. Report No 2013:10, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se.

SUMMARY

The high oil dependence and the growth of energy use in the transport sector have increased interest in alternative fuels as a measure to mitigate climate change and improve energy security. More ambitious energy and environmental targets and larger use of alternative energy in the transport sector increase system effects over sector boundaries, and while the stationary energy sector (e.g., electricity and heat generation) and the transport sector earlier to large degree could be considered as separate systems with limited interaction, integrated analysis approaches now grow in importance.

In recent years, the scientific literature has presented an increasing number of energy-economic systems analysis modeling studies treating the transport sector as an integrated part of the energy system and/or economy. Many of these studies provide important insights regarding transport biofuels. To clarify similarities and differences in approaches and results, the present work reviews and synthesizes studies within this field. The work investigates what future role comprehensive energy-economy modeling studies portray for transport biofuels in terms of their potential and competitiveness. This includes a mapping of what future transport biofuel utilization and market shares the studies describe as well as an analysis of what factors influence this.

The work summarizes and analyzes input data and transport biofuel-related results of 29 peer-reviewed scientific journal articles presenting studies based on different energy-economic models. About half of the studies apply a global perspective and about half a regional or national perspective. Regarding the regional and national studies, this work primarily focuses on Europe. Examples of models and model frameworks that are used in the studies included in the review are PRIMES, MARKAL, TIMES, AIM/Enduse, POLES, GCAM, GET and REDGEM70. The studies apply medium-term to long-term perspectives, with time horizons in most cases ending between 2040 and 2100.

In the reviewed model results, the future market shares of transport biofuels range from low to high levels. Most of the studies show low to intermediate market shares, with levels below 40% at the end of the studied time horizons for climate policy scenarios (without sector specific polices). Biofuels are to a higher degree seen in medium-term than in long-term model results. In the latter case, many of the models instead favor hydrogen or electricity-based transport options as competition for limited amounts of biomass increases with more stringent emission targets. Although transport biofuels do not tend to dominate the transport sector at the end of the modeled time horizons, compared to today's level most of the reviewed studies show a significant increase in transport biofuel use.

Differences in transport biofuel utilization in model results depend in many cases on quantitative assumptions regarding more or less uncertain input data. While this highlights difficulties with quantitative long-term modeling of energy-economic systems, it also demonstrates the relevance of the same: without making quantitative statements regarding numerous parameters, not much can be said about what future contribution of transport biofuels that is effective from an overall perspective. Factors influencing transport biofuel utilization in the model results include assumptions on biomass potential, climate ambition/policies, technology representation in the transport sector as well as in the stationary energy sector, oil price, and energy policies in addition to greenhouse gas-related constraints or penalties. The way these factors influence the results are not straightforward and the relative importance of each factor also varies depending on conditions.

The preferred biofuel characteristics in the model results generally include low-cost feedstock (wood waste, etc.) and low costs associated with distribution and vehicle technology. The latter aspects commonly imply a liquid fuel. Fuels based on biomass gasification and the Fischer Tropsch process are frequently mentioned in the studies, but also other options are highlighted. However, many of the studies treat biofuel in aggregate and, therefore, do not provide information on the appropriateness of different options. Besides transport biofuels, energy efficient vehicle technologies, such as plug-in hybrids and, in the longer term, fuel cell vehicles, are an essential part in many of the model scenarios meeting future stringent climate targets.

SAMMANFATTNING

Det höga oljeberoendet och den stigande energianvändningen i transportsektorn har ökat intresset för alternativa drivmedel som en åtgärd för att mildra klimatförändringar och förbättra energisäkerheten. Mer ambitiösa energi-och miljömål och en större användning av alternativ energi i transportsektorn ökar systemeffekterna över sektorsgränser, och medan den stationära energisektorn (t.ex. el- och värmeproduktion) och transportsektorn tidigare i stor utsträckning kunde betraktas som separata system med begränsad interaktion, blir integrerade analysangreppssätt nu viktigare.

Under senare år har den vetenskapliga litteraturen presenterat ett ökande antal energiekonomiska modellbaserade systemanalysstudier vilka behandlar transportsektorn som en integrerad del av energisystemet och/eller ekonomin. Många av dessa studier ger viktiga insikter om biodrivmedel. Detta arbete sammanställer och granskar studier inom detta område i syfte att tydliggöra likheter och skillnader i tillvägagångssätt och resultat. Arbetet undersöker vilken framtida roll energiekonomiska modellstudier, med en omfattande representation av energisystemet, skildrar för biodrivmedel gällande deras potential och konkurrenskraft. Detta inkluderar en kartläggning av vad studierna beskriver gällande framtida biodrivmedelsanvändning och marknadsandelar för biodrivmedel samt en analys av vilka faktorer som påverkar detta.

Arbetet sammanfattar och analyserar indata och biodrivmedelsrelaterade resultat av 29 expertgranskade vetenskapliga artikelstudier baserade på olika energiekonomiska modeller. Ungefär hälften av studierna har ett globalt perspektiv och ungefär hälften ett regionalt eller nationellt perspektiv. Avseende de regionala och nationella studierna fokuserar detta arbete huvudsakligen på Europa. Exempel på modeller och modellramverk som används i de studier som ingår i genomgången är: PRIMES, MARKAL, TIMES, AIM/Enduse, POLES, GCAM, GET och REDGEM70. Studierna tillämpar ett medellångt till långt tidsperspektiv, med modelltidshorisonter som i de flesta fall sträcker sig till mellan 2040 och 2100.

Framtida marknadsandelar för biodrivmedel varierar från låga till höga nivåer i de genomgångna modellresultaten. De flesta av studierna visar på låga till medelhöga marknadsandelar, med nivåer under 40 % i slutet av den studerade tidshorisonten för scenarier med klimatpolitiska mål (men utan sektorsspecifika styrmedel). Biodrivmedel ses i högre grad i modellresultat som avser medellång sikt än i modellresultat som avser lång sikt. I det senare fallet väljer många av modellerna istället vätgas eller elbaserade transportalternativ då konkurrensen om en begränsad mängd biomassaresurser ökar med strängare utsläppsmål. Även om biodrivmedel inte tenderar att dominera transportsektorn i slutet av den modellerade tidshorisonten visar de flesta av de studierna på en betydande ökning av biodrivmedelsanvändningen jämfört med dagens nivå.

Skillnaderna på biodrivmedelsanvändning i modellermas resultat beror i många fall på kvantitativa antaganden gällande mer eller mindre osäkra indata. Medan detta belyser svårigheterna med kvantitativ långsiktig modellering av energi-ekonomiska system, visar det också på betydelsen av densamma: utan att göra kvantitativa antaganden gällande ett flertal parametrar kan inte heller mycket sägas om vilket framtida inslag av biodrivmedel som är effektivt från ett övergripande perspektiv. Faktorer som påverkar biodrivmedelsanvändningen i modellresultaten inkluderar antaganden om biomassapotential, klimatambition/styrmedel, teknikrepresentation inom transportsektorn såväl som inom den stationära energisektorn, oljepris, och energipolitiska styrmedel (utöver växthusgasrelaterade). På vilket sätt dessa faktorer påverkar resultatet är inte alltid självklart och den relativa betydelsen av respektive faktor varierar också beroende på förutsättningar.

Egenskaper för biodrivmedel som prioriters i modellresultaten inkluderar i regel råvara med låg kostnad (träavfall, etc.) och låga kostnader kopplat till drivmedelsdistribution och fordonsteknik. De senare aspekterna innebär ofta ett flytande drivmedel. Drivmedel baserade på biomassaförgasning samt Fischer-Tropsch-processen nämns återkommande i studierna, men även andra alternativ uppmärksammas. Många av studierna behandlar emellertid biodrivmedel endast i aggregerad form och kan därför inte ge någon information om lämpligheten avseende olika biodrivmedelsalternativ. Förutom biodrivmedel utgör energieffektiva fordonstekniker, exempelvis plug-in hybrider och på längre sikt bränslecellsfordon, en viktig del i många av de modellscenarier som klarar stränga framtida klimatmål.

CONTENTS

ABBREVIATIONS IX

1 INTRODUCTION 10

2 GLOBAL STUDIES 12

2.1 STUDIES AND MODEL APPROACHES 12

2.2 MODEL RESULTS 18

3 REGIONAL AND NATIONAL STUDIES 27

3.1 STUDIES AND MODEL APPROACHES 27

3.2 MODEL RESULTS 33

4 DISCUSSION 41

5 CONCLUSIONS 43

REFERENCES 44

APPENDIX: MODEL TYPES AND CONCEPTS 49

A.1 MODEL TYPES 49

A.2 MODEL CONCEPTS 52

ABBREVIATIONS

BECCS	Bio-energy with carbon capture and storage
BtL	Biomass-to-liquid
CCS	Carbon capture and storage
CGE	Computational general equilibrium
CO_2	Carbon dioxide
DME	Dimethyl ether
EtOH	Ethanol
EV	Electric vehicle (battery-powered)
FCV	Fuel cell vehicle
FT	Fischer Tropsch
GHG	Greenhouse gas
H2	Hydrogen
HEV	Hybrid electric vehicle
HDV	Heavy duty vehicle
LDV	Light duty vehicle
MeOH	Methanol
PHEV	Plug-in hybrid electric vehicle
ppm	Parts per million
SNG	Synthetic natural gas

1 INTRODUCTION

The high oil dependence and the growth of energy use in the transport sector have increased interest in alternative fuels as a measure to mitigate climate change and improve energy security. Local and regional air pollution problems also contribute to the interest in finding alternatives to conventional petrol and diesel based on crude oil. Alternatives to conventional diesel and petrol include biofuels, hydrogen, electricity or synthetic fuels from, e.g., coal or natural gas.

Biofuels currently only contributes to a small share of the energy supply to the transport sector; while the global use of transport biofuels is about 2.5 EJ, the total final fuel use in the sector is about 100 EJ (OECD/IEA, 2012). Ethanol accounts for about 80% of the global transport biofuel supply, while the rest is mainly biodiesel (Worldwatch Institute, 2011). However, several governments and intergovernmental organizations have policy targets aiming at a future increase in transport biofuel use. In the EU, the share of fuels from renewable sources in the transport sector should amount to at least 10% of the total transport fuel use by 2020 (EC, 2009). In Sweden, the government has declared that the vehicle fleet should be independent of fossil fuels by 2030 and that Sweden should have no net emissions of greenhouse gases (GHGs) by 2050 (Swedish Government, 2009; SOU, 2013).

While the stationary energy sector (e.g., electricity and heat generation) and the transport sector earlier to large degree could be considered as separate systems with limited interaction, more ambitious energy and environmental targets and an increased utilization of alternative energy carriers in the transport sector can be expected to have system effects over sector boundaries. This is due to several reasons. One such reason is resource competition, e.g., in terms of biomass resources which can be used both for biofuel production and/or heat/power production. All different types of biomass use compete at some level, ultimately due to land scarcity. Further, system interactions also come into play by the possibilities of plants co-producing several outputs, such as biofuels, heat and electricity. Electric cars, as well as hydrogen production based on electrolysis, also affect the electricity generation system by increasing demand and, possibly, by evening out the load curve and allowing more intermittent generation in the system. Interaction over sector boundaries is also a factor from an environmental and climate economic perspective; both the stationary energy sector and the transport sector give rise to GHG emissions and fill up a common (politically and/or environmentally set) emission quota. Since economical resources are limited, a system-wide allocation strategy is imperative.

Methodological approaches in which individual parts of the energy- and transport system are investigated separately have been, and still are, common in environmental and energy systems planning and analysis. However, as dynamic interactions over sector boundaries increase in impact, an expanded systems view in which the co-evolution of an integrated energy and transport system is analyzed increase in relevance. In recent years, a growing number of energy-economic systems analysis modeling studies treating the transport sector as an integrated part of the energy system and/or economy have emerged in the scientific literature.

Several comprehensive energy-economy systems modeling studies include transport biofuels in the scope of the analysis. Thus, important insights regarding the potential future role of transport biofuels, with potential system wide effects taken into account, can be provided. The interpretation and implications of the model results presented in the literature can, however, be complex. Methodological approaches and assumptions made, as well as model results and conclusions, show similarities but also differences and the influencing factors are numerous. Certainly, the chosen system boundaries can have a large significance for outcomes and conclusions. This could include choices of geographical region and scale of study (e.g., national or global), time horizon studied and technology options and energy policies included. While different approaches and types of results can complement each other and highlight different aspects involved, diverging pictures can also be confusing and difficult to grasp.

There are several research modeling studies applying a system-wide perspective on the future role of transport biofuels; however, synthesis studies of this field are rare. To clarify similarities and differences in approaches and results of modeling studies that provide insights on transport biofuel futures, the present work seeks to review and synthesize studies carried out within this field. Questions of investigation are:

- What future role do comprehensive energy-economy modeling studies portray for transport biofuels in terms of their future potential and competitiveness?
    - What future utilization levels for transport biofuels do the studies depict as likely/cost-effective?
    - What factors influence differences in results?
    - What overall insights can be made based on the aggregate results of the studies?

We focus the review on modeling studies with comprehensive systems approaches treating the transport sector as an integrated part of national or international energy systems and/or economies and apply a geographical scope from national to global level. For regional and national studies, we primarily focus on Europe. Further, we focus on studies applying a medium-term to long-term time horizon and which have been published in the scientific literature in recent years (here limited to peer-reviewed journal articles). The studies should be of relevance from a transport biofuel perspective and, preferably, focus on the transport sector. The review does not seek to cover all studies done within the area, but a large number of studies should be covered to enable the formation of justifiable general insights. System modeling studies on plant scale or on a local geographical system level are not considered.

The report is divided according to geographical scope of the reviewed studies. Section 2 presents the model approaches and results of global modeling studies and section 3 presents the same for regional and national modeling studies, with focus on Europe. In Section 4, a discussion of the work and its results is given, and Section 5 presents conclusions. In the Appendix, a background on different types of energy-economic model types and modeling concepts is provided.

2 GLOBAL STUDIES

Global energy-economic systems modeling can be an important tool in the analysis on how to achieve a more environmentally friendly future transport and energy system. Regarding transport biofuels, it can give significant insights to what future market penetration level that is feasible, cost-effective and/or likely on a global level. In this section, the approach and results of a number of recent studies, applying different global systems models, are looked into. Section 2.1 introduces the selected studies and the model approaches applied in these. Section 1.1 presents and analyses the transport and biofuel related results of each of the studies.

2.1 STUDIES AND MODEL APPROACHES

2.1.1 Selected studies

The bulk of recently published modeling studies utilizing a global approach and analyzing questions related to future use of transport biofuels are based on bottom-up, optimization energy system modeling. In the models used in these studies, fossil energy resources are generally described by an, over the studied time period, accumulated available resource base and related extraction costs. Renewable options such as biomass are also limited but their availability are generally linked to a model year, i.e. a maximum potential use of biomass per year is assumed. The models are to different degree regionalized; while some model see the world as one global region with, e.g., unlimited possibilities of trade and allocation of emission reductions between countries and continents, others are disaggregated into different geographical world regions. In the latter case, this allows for the inclusion of model features such as restrictions in trade between regions, regional caps for CO_2 emissions and regional targets for transport biofuel use. In global models, energy prices are to large degree decided endogenously as a function of the final demand for a certain resource, although the studies also at times include sensitivity analyses of different energy price developments. Table 1 summarizes selected global modeling studies that will be closer looked into as well as some of their respective model features.

Takeshita and Yamaji (2008) and Takeshita (2012) develop and utilize the REDGEM70 model. REDGEM70 is a bottom-up type, global energy systems linear optimization model which is regionally disaggregated into 70 regions. The model has a long-term time horizon reaching from 2000 to 2100. REDGEM70 considers a number of energy conversion technologies as well as carbon capture and storage (CCS) in power generation, oil refinery and in production of synthetic fuels. The model includes several technologies for production of alternative transport fuels, e.g., hydrogen, methanol, dimethyl ether (DME), and Fischer-Tropsch (FT), bioethanol and biodiesel. The comparably high regional disaggregation level enables capturing of trade flows between world regions and associated distribution and infrastructural costs. Takeshita and Yamaji (2008) examine the potential role of FT synfuels in competition with other fuel options and Takeshita (2012) assesses co-benefits of CO_2 reduction and reduction air pollutants from road vehicles.

Table 1. Selected global modeling studies and their related model features.

Reference	Model – Regionalization	Model characteristics	End-year
Takeshita & Yamaji (2008); *Takeshita (2012)*	REDGEM70 – 70 regions	Optimization, Partial Equilibrium, Perfect Foresight, Bottom-Up	2100
Turton (2006)	ECLIPSE – 11 regions	Optimization, General Equilibrium, Perfect Foresight, Hybrid, Endogenous Technology Learning, Elastic Demand	2100
Azar et al. (2003); *Grahn et al. (2009ab);* *Hedenus et al. (2010)*	GET – 1; 6/10; 1 region(s)	Optimization, Partial Equilibrium, Perfect Foresight, Bottom-Up	2100
Gielen et al. (2002; 2003)	BEAP – 12 regions	Optimization, Partial Equilibrium, Perfect Foresight, Bottom-Up, Elastic demand	2040
Gül et al. (2009)	GMM (MARKAL) – 6 regions	Optimization, Partial Equilibrium, Perfect Foresight, Bottom-Up, Endogenous Technology Learning	2100
Fulton et al. (2009), *IEA (2008)*	ETP (MARKAL) + MoMo (model-linking) – 22 regions (MoMo)	Optimization (ETP)/Simulation (MoMo), Partial Equilibrium, Perfect Foresight, Bottom-Up, Endogenous Technology Learning, Elastic Demand	2050
Anandarajah et al. (2013)	TIAM-UCL (TIMES) – 16 regions	Optimization, Partial Equilibrium, Perfect Foresight, Bottom-Up, Endogenous Technology Learning, Elastic demand	2100
Akashi & Hanaoka (2012)	AIM/Enduse[Global] – 32 regions	Optimization, Partial Equilibrium, Dynamic recursive, Bottom-Up	2050
van Ruijven & van Vuuren (2009)	TIMER – 26 regions	Simulation, System Dynamics, Bottom-Up, Endogenous Technology Learning	2050
Kitoues et al (2010)	POLES – 12 regions	Simulation, Partial Equilibrium, Recursive, Bottom-up, Endogenous Technology Learning , Elastic Demand	2100
Kyle & Kim (2011)	GCAM– 14 regions	Simulation, Partial equilibrium, Dynamic-recursive (myopic), Elastic Demand	2095

Turton (2006) describe a sustainable automobile transport scenario by analysis with the integrated assessment model ECLIPSE. ECLIPSE incorporates the energy systems model ERIS with macro-economic and passenger transport demand models and further linked to the climate model MAGICC. The ERIS model is a bottom-up optimization model for study of the global energy system. The model has been developed to include non-CO_2 GHG emissions, forest sinks and CCS. Furthermore, endogenous technology learning is applied for a number of technologies, meaning that the cost of a technology in the model is dependent on the level of its application. In the study, multiple sustainable development objectives are taken into account, including continued economic growth with reduced income disparities between different world regions, climate change mitigation and security of energy supply.

GET is an energy system model for the study of long-term development of the global energy system under carbon constraints. GET is a bottom-up model based on linear optimization driven by exogenously given energy demands in four different stationary end-use sectors as well as transportation demands divided into different transport modes. Published studies to a high degree focus on the cost-effective fuel choices in the transport sector and system-wide effects associated with this. The model was originally developed by Azar et al. (2003) and has subsequently been further developed and used by Grahn et al. (2009ab) and Hedenus et al. (2010). Grahn et al. (2009a, 2009b) regionalized the model, and Hedenus et al. (2010) added detail to the representation of the heat sector in the model.

A further example of a bottom-up optimization global energy system model is the BEAP model, developed by Gielen et al. (2002; 2003). The model is utilized to study the optimal use of biomass for GHG emissions reductions. The BEAP model is based on mixed integer programming, in which the development of the system is decided through maximization of the sum of the consumers' and producers' surplus. Focusing on biomass systems, the BEAP model covers the global energy, food and materials system and divides the world in 12 regions. The regions are characterized by natural resource availability, labor costs, and technology availability. Trade of resources, energy carriers, food products and materials between the regions are possible but results in increased transportation causing additional emissions and costs.

MARKAL is a well-established energy system model framework which can be combined with different databases and, in such way, form different model applications. MARKAL models are of bottom-up, optimization type and generally based on linear programming. Gül et al. (2009) utilize a global 6-world region MARKAL model, denoted the Global Multi-regional MARKAL model (GMM). In this case, the bottom-up energy system model is linked to the climate change model MAGICC (in a similar manner as Turton, 2006). GMM has a detailed representation of alternative fuel chains. In terms of biofuel, it includes biodiesel, FT-diesel, ethanol, methanol, DME and synthetic natural gas (SNG) derived from biomass. Also for hydrogen, several options are represented, including production based on biomass gasification. Gül et al. (2009) utilize the model to analyze the long-term prospects of alternative fuels in personal transport, focusing on biofuels and hydrogen.

Fulton et al. (2009) present transport-related results and modeling from the IEA study "Energy Technology Perspectives" (IEA, 2008) in which a combination of the MARKAL based IEA-ETP model and the IEA Mobility Model (MoMo) is utilized. MoMo is a spreadsheet model aimed at estimating and projecting travel indicators, energy consumption, pollutant emissions and GHGs generated for worldwide mobility. In this context, the MoMo model is used to generate transport energy demand projections that are then fed into the IEA-ETP optimization model framework.

The ETSAP-TIAM model is a TIMES based model describing the global energy system. TIMES (an acronym for The Integrated MARKAL- EFOM System) is an update of the MARKAL modeling framework. The basics of the two modeling frameworks are the same, i.e. also TIMES models can be described as bottom-up energy system models based on optimization. Compared to MARKAL, TIMES includes several enhanced features, e.g., a more flexible seasonal and diurnal time division. Several studies have in recent years utilized the ETSAP-TIAM for investigation of different aspects of future developments of the global energy system, examples include Remme and Blesl (2011), Føyn et al. (2011) and Labriet et al. (2012). Anandarajah et al. (2013) give special focus to the road transport sector (using a version of the model referred to as TIAM-UCL) and investigate the role of hydrogen and electricity to decarbonize the transport sector. The analysis uses a multi-cluster global endogenous technology learning approach where key components (fuel cell, electric battery and electric drive train), to which learning is applied, are shared across different vehicle technologies such as hybrid vehicles (HEVs), plug-in hybrid vehicles (PHEVs), fuel cell vehicles (FCVs) and battery-powered electric vehicles (EVs).

In a similar manner as MARKAL and TIMES, the AIM/Enduse model framework has been utilized combined with different databases and in different studies to analyze national energy systems as well as the global energy system. The model is of an optimization type and selects technologies through linear programming algorithms that minimize the total system cost given fixed service demands. Akashi and Hanaoka (2012) examine the technological feasibility of large cuts in GHG emissions. The global version of AIM/Enduse model, AIM/Enduse[Global], which is used in this study, splits the world into 32 regions over a time horizon from 2005 to 2050. In contrast to earlier mentioned global models, the AIM/Enduse[Global] does not apply perfect foresight but is a dynamic recursive model indicating that technology and fuel selection occur one model year at a time, influenced by previous model years (installed capacities, etc.) but uninformed of future developments regarding, e.g., energy prices and technology costs.

The above described models rely largely on optimization in the choice of future fuel and technologies. Other models apply more of a simulatory approach and also seek to incorporate other aspects in technology choices made. Van Ruijven and van Vuuren (2009) explore the energy system impacts of different future hydrocarbon prices, using the global energy model TIMER. The TIMER model, which is part of the integrated assessment model IMAGE, describes the long-term dynamics of the production and consumption of energy carriers in 26 global regions. Here, costs combined with preferences are used in sectoral multinomial logit models in the selection of technologies. The multinomial logit model allocates a larger share in investments for technologies that have lower costs than other technologies, but with small price differences also some investments are made into more expensive options (this is in contrast to a strict linear programming optimization model for which, if no other constraints apply, the lowest cost option takes it all).

Also the POLES model can be described as utilizing a simulating approach. POLES have been used in various studies at both national and international level. Kitoues et al. (2010) present a long-term assessment of the worldwide energy system in scenarios ranging from a baseline to a very low GHG stabilization using the POLES model. The POLES model is a recursive simulation model of the global energy system. Integrating a detailed regional, sectorial and technological specification, the POLES model allows assessments of GHG mitigation policies. Explicit technological description is used for secondary fuels production as well as on the demand side for buildings and vehicles. Econometric functions allow evolving consumption patterns to be taken into account. These functions include both behavioral changes and investment decisions.

The GCAM model (previously known as MiniCAM) is a long-term, global, technologically detailed, partial-equilibrium integrated assessment model that includes representations of energy, agriculture, land-use and climate systems. The model calculates equilibrium for energy goods and services, agricultural goods, land and GHG emissions. Using the GCAM model, Kyle and Kim (2011) assess global light-duty vehicle (LDV) transport and the implications of vehicle technology advancement and fuel-switching on GHG emissions and primary energy demands by simulating five different technology scenarios. In each respective scenario it is assumed that by 2050, all LDVs (globally) consists of: (1) ICEVs fuelled with liquid hydrocarbon fuels; (2) advanced, fuel-efficient ICEVs fuelled with liquid hydrocarbon fuels; (3) natural gas fuelled vehicles; (4) EVs; (5) FCVs.

2.1.2 Example of input and scenario assumptions

Global modeling studies often apply climate policy scenario set-ups in which, e.g., targets for a future atmospheric concentration level of CO_2 is exogenously determined and, in such way, the model is forced to choose low-carbon options. The use of biofuels in the transport sector is often contrasted to other potential low-carbon transport options, which generally are based on either hydrogen or electricity. Table 2 summarizes some model input data related to transport sector technology representation and scenario assumptions made in each of the global studies; namely climate ambition, biomass potential and fuel and technology representation in road transport. These are not the only input data of importance for the biofuel-related results generated from the models, but they exemplify model choices that are made in this regard.

While many studies present a number of different model scenarios with different input data and assumptions, here we focus mainly on the scenarios with stringent climate polices. Most of the studies apply a stabilization target for atmospheric CO_2 concentration, but some studies instead apply an exogenous CO_2 penalty cost. In the latter case, the resulting emission or CO_2 stabilization level is an output of the model (for comparison purposes, this output has been included in the table within brackets). The scenarios include climate ambitions from medium (such as 550 ppm CO_2 concentration) to high levels (such as 400 ppm). Also the assumed biomass potential, i.e. the maximum amount of biomass that can be used for energy purposes per year in the models, varies between the studies.

The representation of fuels and technologies in the transport sector is of importance for the outcome of the models and also how the outcome should be interpreted. Many of the studies treat biofuels in aggregate and thus only include a single generic biofuel fuel option, even though this “biofuel” might be denoted biomass-to-liquid (BtL), synthetic fuel, methanol, or simply “biofuel”. Other studies include a range of biofuel options. As is clear from Table 2, the studies have also chosen different degree of representation regarding non-biofuel low carbon transport fuels as well as vehicle technologies.

Table 2. Climate ambition, biomass potential and fuel and technology representation in road transport for selected studies. Blanks indicate that info were unclear or could not be obtained.

Reference	Climate policy or target	Max biomass per yr	Technology representation road transport		
			Biofuels	Other low carbon options	Vehicle technologies
Takeshita and Yamaji (2008)	550 ppm	300 EJ (2050); 250 EJ (2100) $^{a)}$	Biodiesel, EtOH, biogas, FT- liq., DME, MeOH, H2	H2	ICEV, HEV, FCV
Takeshita (2012)	400 ppm	300 EJ (2050); 250 EJ (2100) $^{a)}$	Biodiesel, EtOH, biogas, FT- liq., DME, MeOH, H2	H2, Electricity	ICEV, HEV, EV, PHEV, FCV
Turton (2006)	550 ppm	235 EJ (2050); 320 EJ (2100)	H2, alcohol, FT- liq.	H2	ICEV, HEV, FCV
Gül et al.(2009)	450 ppm	195 EJ	Biodiesel, FT-diesel, EtOH, MeOH, DME, bio-SNG, H2	H2, Electricity	ICEV, HEV, EV, PHEV, FCV
Azar et al. (2003)	400 ppm	200 EJ	MeOH, H2	H2	ICEV, FCV
Grahn et al. (2009b)	450 ppm	205 EJ	BtL , H2	H2	ICEV, FCV
Hedenus et al. (2010)	400 ppm	200 EJ	Synthetic fuel , H2	H2, Electricity	ICEV, HEV, EV, PHEV, FCV
Gielen et al. (2003)	80 \$/tCO_2 cost (75% CO_2 red.)	Depends on land prices calculated by the model.	MeOH, FT-gasoline, EtOH	No	ICEV
Akashi and Hanaoka (2012)	Cost incr. from 0 to 600 \$/tCO_2 in 2000-2050 (50% CO_2 red.)	364 EJ	“Biofuel”	H2, Electricity	ICEV, HEV, EV, PHEV, FCV
Van Ruijven and van Vuuren (2009)	100 \$/tCO_2 cost (10-45% CO_2 red.)		“Biofuel”	H2	ICEV
Kitoues et al (2010)	400 ppm	200 EJ	“Biofuel”, H2	H2 Electricity	ICEV, HEV, EV, PHEV, FCV
Anandarajah et al. (2013)	Global mean temp. not rise more than 2°C	Probably about 100-150 EJ $^{b)}$	Biodiesel, EtOH, H2	H2 Electricity	ICEV, HEV, EV, PHEV, FCV
Fulton et al. (2009) *IEA (2008)*	450 ppm	Not clear (results = 150 EJ)	Biodiesel, EtOH, BtL (BtL biodiesel, LC ethanol)	H2 Electricity	ICEV, HEV, EV, PHEV, FCV
Kyle and Kim (2011)	Cost incr. from 10 to 400 \$/tCO_2 in 2020-2095 (450 ppm)		BtL, biomass-based gas	H2, Electricity	ICEV, HEV, EV, PHEV, FCV

a) Supporting info from Takeshita (2009)
b) Supporting info from Erb et al. (2009)

2.2 MODEL RESULTS

2.2.1 Biofuel utilization

The reviewed global model studies provide different insights about the future potential and competitiveness of biofuels in the transport sector. Table 3 presents the main transport biofuel related results of the climate policy scenarios of each respective study and summarizes transport biofuel utilization and market shares. In addition, comments on sensitivity analyses, developments in the stationary energy sector and other factors that could be of relevance for the biofuel results are given in the table. The resulting transport biofuel market shares and the total utilization over the studied time horizons are also visualized in Figure 1 and Figure 2, respectively. For a few of the studies, the appropriate quantitative data could not be obtained and these studies are thus not represented in the figures. In most cases, the market shares presented refer to the transport sector as a whole (all transport modes); however, sometimes it refers to road transport sector and sometimes to the passenger car transport (as indicated). Hydrogen produced trough biomass gasification is included in the biofuel market shares of Table 3 and transport biofuel utilization figures in Figure 2, but is reported separately in Figure 1. Several of the presented levels have been read from graphs presented in the studies and small errors compared to the original results might therefore exist.

Note that although all presented results refer to a climate policy scenario, i.e. a scenario in which GHG emissions are constrained in some way (with an emission cap or a monetary penalty for emissions), they show large differences in the stringency of the targets and policies applied (see also Table 2).

As can be seen in Table 3 and Figure 1-Figure 2, the resulting transport biofuel utilization and market shares range from small to large. However, for the bulk of scenarios, the transport biofuel share stays below 40% and several scenarios show very low levels (0-10%). Studies showing biofuel market shares above 40% not only rely on “regular” biofuels but also on hydrogen based on bioenergy with carbon capture and storage (BECCS). Even though market shares for transport biofuels in most of the scenarios stay at low-medium levels, many of the scenarios show a quite significant increase in biofuel use in absolute terms compared to today’s level of 2.5 EJ (out of the total final transport sector fuel use of about 100 EJ; OECD/IEA, 2012). Thus, the results suggest an increase in transport biofuel use compared to today’s level but, at the same time, transport biofuels do not tend to dominate the future transport sector.

Many of the studies only include a single aggregate biofuel option and, thus, provide no insights in regard to which biofuel type is preferable. Among the studies that do point out specific biofuel options, Takeshita and Yamaji (2008) and Takeshita (2012) highlight FT liquids (synthetic diesel, gasoline and kerosene) as one advantageous alternative, partly due to its potential to fuel the aviation sector. Akashi and Hanaoka (2012) and Turton (2006) point out bio-hydrogen combined with BECCS and Turton (2006) also favor bio-alcohol over FT liquids. Fulton et al. (2009) mention ethanol as well as FT liquids.

Table 3. Transport biofuel related results of global climate policy scenarios.

Reference	Transport and biofuel results for climate policy scenario	Comments and sensitivity
Takeshita and Yamaji (2008)	The utilization of FT products in the transport sector amounts to 21 EJ in 2050 and 78 EJ in 2100. About half of this is FT-Kerosene used in aviation. FT production is combined with BECCS after 2070. Petroleum products continue to have a dominating position in the transport sector throughout the century. *Biofuel share 2050: 10%; (transport)* *Biofuel share 2100: 23% (transport)*	High bio potential; Medium CO_2 reduction. In the stationary sector, H_2 produced from biomass accounts for a significant part of the energy use. Likewise to the FT synfuel production, H_2 production is combined with BECCS after 2070. High total final transport energy demand (340 EJ in 2100) lowers biofuel share, although the biofuel use in absolute terms is high.
Takeshita (2012)	Electricity and biomass-derived FT products gain market shares starting from 2040. In 2050, use of FT products from biomass in road transport is about 2 EJ and, in 2100, 13 EJ. At the end of the century, remaining parts is petroleum products (68 EJ), electricity (39 EJ) and a small amount of H_2 (1 EJ). *Biofuel share 2050: 2% (road transport)* *Biofuel share 2100: 11% (road transport)*	High bio potential; High CO_2 reduction. The share of plug-in hybrids in light-duty vehicles reaches 90% in 2100. CCS and fuel switching are mentioned as important CO_2 reduction measures in the stationary sectors.
Turton (2006)	Oil and gas dominate transport fuel supply in first half of the century, but then a large increase in biofuels is seen. In 2100, biomass-to-alcohol accounts for about 55 EJ, or 26%, of transport sector final energy use; biomass-to-H_2 accounts for about 86 EJ, or 41% of transport sector final energy use. H_2 is produced primarily with BECCS. *Biofuel share 2050: 6% (transport)* *Biofuel share 2100: 67% (transport)*	High bio potential; Medium CO_2 reduction. A large increase in nuclear is allowed in the scenario. This makes nuclear dominate the electricity system (nuclear electricity generation amounts to 220 EJ in 2100). Direct thermal needs are supplied mainly by a combination of gas, H_2 and electricity (rather than biomass or coal). Electric vehicles are unavailable in the model.
Gül et al. (2009) a) *a) supporting info from Gül (2008)*	Biofuel production (for all sectors, but primarily transport) peaks at 31 EJ around 2075 and then decreases to 14 EJ in 2100. H_2 becomes the main transport fuel and FCVs dominate the personal transport sector. Favored H_2 production technology is coal-based production with CCS, but also H_2 production from nuclear and wind power via electrolysis are major sources. *Biofuel share 2050: 25% (of vehicle km in personal road transport)* *Biofuel share 2100: 7% (of vehicle km in personal road transport)*	Low bio potential; High CO_2 reduction. With medium CO_2 reduction (550 ppm) no dip in biofuel production is seen at the end of the century. Biofuel production is 34 EJ in 2100. High total energy demand; Primary energy demand is close to 1700 EJ in 2100. Nuclear accounts for 400 EJ of this (about 150 EJ electricity) and (none-bio) renewables 400 EJ.
Azar et al. (2003)	Oil remains the only fuel in transport (excluding trains) until 2040–2050 when a transition to H_2 begins. In 2100, H_2 is the only fuel used in transport. H_2 is produced from fossil fuels with CCS and from solar energy. No transport biofuels enters the scenario. *Biofuel share 2050: 0% (transport)* *Biofuel share 2100: 0% (transport)*	Low bio potential; High CO_2 reduction. Higher H_2 related costs, larger biomass potential or restrictions for bio-industrial heat gives a transient period with biofuels. Nuclear is restricted to current levels and a conservative potential for CCS is assumed. Electric vehicles are unavailable in the model.

Grahn et al. (2009b)	With regional CO_2 emission caps (RC), the biofuel utilization peaks at 2050 with 15 EJ and goes down to 8 EJ in 2100. Total transport fuel use adds up to 223 EJ in 2100. Of this 56% is non-biomass based H_2 and remaining parts are primarily natural gas and petroleum products. A global CO_2 cap gives lower biofuel utilization (3 EJ in 2100). *Biofuel market share 2050: 9% (transport) - RC* *Biofuel market share 2100: 4% (transport) - RC*	Low bio potential; High CO_2 reduction. Sensitivity analysis shows that biofuel usage peak at medium CO_2 reduction targets and that higher biomass supply potential increases biofuel use in results. If HEVs, PHEVs and BEVs are included, biofuel use decreases. In the study, nuclear is restricted to current levels and a conservative potential for CCS is assumed.
Hedenus et al. (2010)	Around 2040 biofuel PHEVs are introduced in LDV transport and dominate this sector after 2070. For heavy vehicles a shift from diesel ICE to H_2 FCVs occurs around 2050. In 2100, 27 EJ of biofuel is used. Total final energy use in transport is 194 EJ. H_2 accounts for about half of the supply and electricity about 20%. Natural gas and petroleum products account for the remaining part. Solar thermal energy dominates both the electricity sector and H_2 production. *Biofuel share 2050: 10% (transport)* *Biofuel share 2100: 14% (transport)*	Low bio potential; High CO_2 reduction. Nuclear and CCS are unavailable in the base scenario. Alternative scenarios in which nuclear and CCS dominate the electricity sector, the biofuel utilization in 2100 is 52 EJ (26%) and 81 EJ (35%), respectively. Compared to other GET model versions (Azar et al., 2003) and Grahn et al., (2009b) the use of biomass for high temperature industrial heat is restricted.
Gielen et al. (2003)[b] *b) supporting info from Grahn et al. (2007)*	Use of biofuels (ethanol, methanol and synthetic diesel/gasoline) and natural-gas-based methanol increase over time. In 2020, approximately 50 EJ gasoline/diesel, 39 EJ biofuels, and 22 EJ methanol (based on natural gas) is used in the transport sector. *Biofuel share 2020: 35% (road transport)* *(Biofuel share 2050: 70% (road transport))*	High bio potential; High CO_2 reduction. Majority of the biomass used is allocated for the production of transportation fuels. Less stringent CO_2 reduction scenarios reduce biofuel utilization. The model lacks low-carbon options in the transport sector other than biofuels (such as electricity or H_2).
Akashi and Hanaoka (2012)	HEV passenger cars are introduced on a large scale after 2015 and reach more than 60% of the market by 2035 (share of pkm). FCVs are rapidly deployed after 2035. In 2050, the transport biofuel use (excluding H_2) is about 50 EJ. H_2 produced from biomass with BECCS amounts to 13 EJ. The remaining part, 75 EJ, is mainly petroleum products (although small amounts of natural gas and electricity are also seen). *Biofuel share 2050: 45% (transport)*	High bio potential; Medium/High CO_2 reduction. Wind, solar, biomass, and hydro together account for about 75 % of the total power generation in 2050. Increase in nuclear capacity is restricted (an increase of about 150% from 2005 is allowed). In the results, a major shift from coal to gas occurs in industry (no biomass).
van Ruijven & van Vuuren (2009)	Exogenously forced low, medium and high fossil fuel price scenarios are tested. In the high price scenario with climate policy, the biofuel use is 50 EJ in 2030 but decreases as more fuel efficient vehicles and H_2, produced from coal with CCS, are introduced. In 2050, the use of biofuels is about 27 EJ (23%), and the remaining part is primarily H_2. Lower fossil fuel prices give somewhat higher use of biofuels, significantly less use of H_2 and higher use of petroleum products. *Biofuel share 2050: 23%-27 (transport)*	Medium/High CO_2 reduction. Exogenous prices imply that there will be no response in oil prices due to less oil demand. The authors point out that this is only likely if the high oil prices are caused by depletion. If not, the analysis represents an initial effect which will be partly cancelled out by price decreases in the longer run. Nuclear and CCS are allowed large shares in electricity generation.

Kitoues et al. (2010)	About 10% of the total biomass use is used for production of biofuel and H_2 throughout the studied time horizon (should correspond to about 10-12 EJ at the end of the century). In 2050-2100, electric and plug-in vehicles account for almost 60% of the total light vehicle stock and, in 2100, H_2 fuelled cars (both ICE and FC) have a 35% market share. H_2 production is primarily based on nuclear. *Biofuel share: not clear (but low)*	Low bio potential; High CO_2 reduction. Biomass (with CCS) and other renewables account for around 65% of the electricity generation. Remaining part is primarily based on nuclear and natural gas. About 80% of the total biomass use is in electricity generation at the end of the century.
Anandarajah et al. (2013)	Biofuels play a minor role. H_2 accounts in 2050 for around 20% of transport energy consumption. Electricity plays a major role and is used in both plug-in hybrid vehicles and battery electric vehicles. H_2 is mainly produced from centralized large coal plants with CCS in the medium term while in the longer term, electrolysis plays a key role. *Biofuel share: not clear (but low)*	Low bio potential; High CO_2 reduction. Bioenergy is prioritized for use in the power generation and industry, often in combination with CCS. With more biomass available, deployment of bio-CCS is increased. If CCS is not an available option, use of biomass as heating fuel and biomass use in industry increase (rather than biofuel production).
Fulton et al. (2009) *IEA (2008)*	For the so-called BLUE map scenario, about 29 EJ biofuel is used in transport. Further, 13 EJ H_2, 12 EJ electricity and about 57 EJ petroleum products are used. For the next 10-15 years, cane ethanol from Brazil is mentioned as a low-cost biofuel option, while over time, lingo-cellulosic ethanol and FT fuels are highlighted. Biofuel share 2050: 26% (transport)	Low bio potential; Medium/High CO_2 reduction. In 2050, around 25% substitution of liquid fossil fuels by biofuels is seen in several different climate policy scenarios. CCS and nuclear account for about half of the electricity generation in 2050. Other important sources are solar, wind and hydro.
Kyle and Kim (2011)	In scenarios dominated by liquid hydrocarbons in LDV transport, biomass accounts for about 10% of LDV primary energy supply, or about 7 EJ in 2050 and 10 EJ in 2095. Other primary energy carriers to the sector include crude oil, unconventional oil, coal and natural gas. CCS is applied. Biofuel share 2050: <10% (LDV transport) Biofuel share 2095: <10% (LDV transport)	High CO_2 reduction. Study focuses on primary energy supply rather than final energy use. Input data or results for stationary energy system are not explicit.

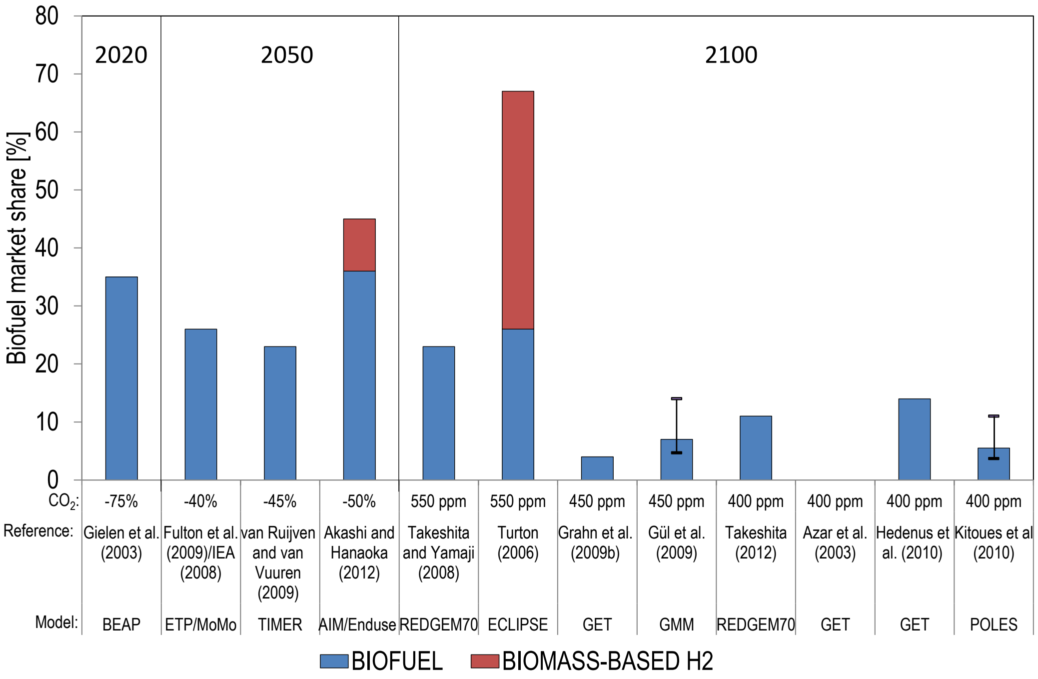

Figure 1. Biofuel market shares for model end-year (indicated) for some of the reviewed global studies. For Gül et al. (2009) and Kitoues et al. (2010), shares have here been calculated with an assumed total final transport energy use of 200 EJ and ranges indicating shares for 100-300 EJ total final energy (due to lack of data).

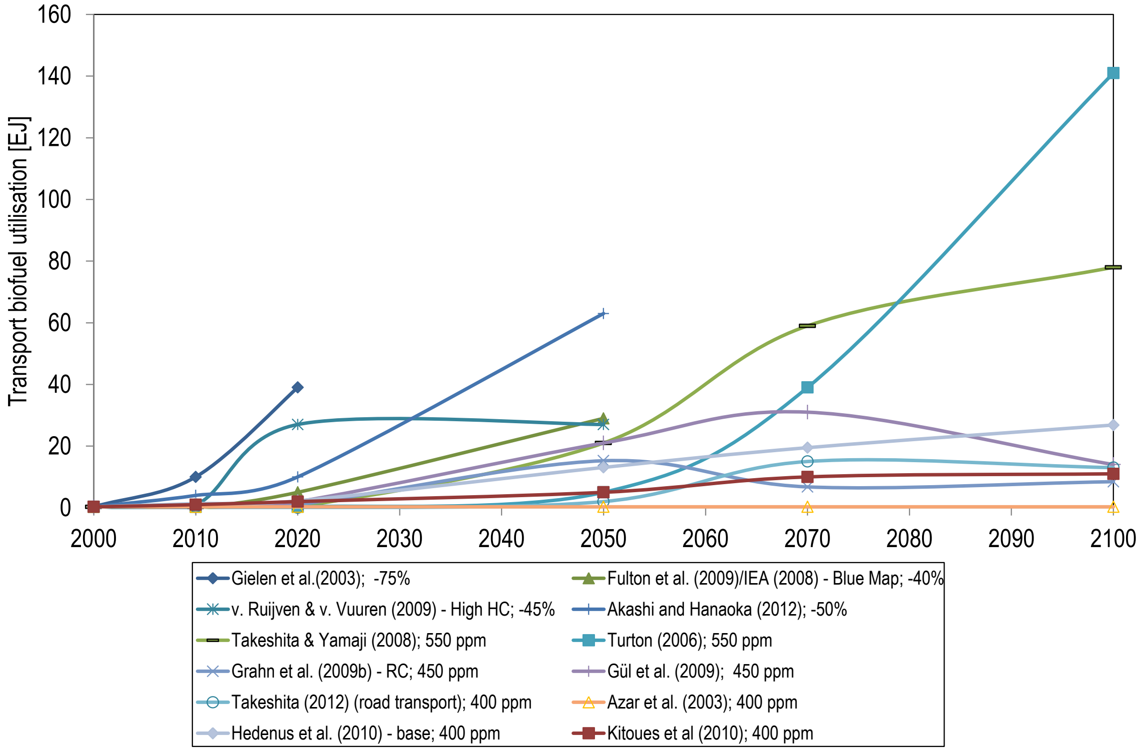

Figure 2. Transport biofuel utilization over modeled time horizons.

2.2.2 Factors influencing biofuel utilization

By comparisons of the scenario results, from different studies as well as sensitivity analyses within studies, a number of factors that often are of importance for the biofuel utilization in the global model results can be identified. Important factors for global model studies include biomass potential, climate ambition and technology model representation for the transport sector as well as for the stationary energy system.

Biomass potential

The future potential availability for biomass for energy purposes is subject to various conditions such as land use, food demand and agricultural productivity, and estimations of future potentials are linked to uncertainty. The reviewed global modeling studies show significant differences in regard to biomass potentials. For example, Akashi and Hanaoka (2012) and Turton (2006), at the end of their modeled time horizons, assume biomass potentials of 364 EJ and 320 EJ, respectively, while, for instance, Grahn et al. (2009) and Kitoues et al. (2010) assume levels around 200 EJ. While the former mentioned studies present a widespread use of transport biofuels in their results, the latter mentioned studies show significantly smaller shares of transport biofuels. Several of the studies also highlight biomass availability as a central constraint for transport the utilization of transport biofuels. Gül et al. (2009) conclude that the key limiting factor for a further deployment of biofuels is the availability of biomass and that biomass is more cost-effectively utilized in electricity and heat production in a carbon constrained world. Sensitivity analyses of different studies in which the biomass potential is increased generally also increase the deployment of transport biofuels in stringent climate scenarios (e.g., Azar et al., 2003; Grahn et al., 2009b) although there are exceptions (Anandarajah et al., 2013).

Technology representation in transport sector

In regard to technology representation in the transport sector, the availability of low carbon options in addition to biofuels is of significance for the competitiveness of transport biofuels. This concerns the technologies that are represented in the models, but also what assumptions on costs and performance characteristics that have been made, which are of similar importance. Simply put, an assumed high potential for low cost hydrogen FCVs or electric vehicles would reduce the competitiveness of biofuels, and vice versa. Since the models generally apply a long time horizon and often assume decreasing costs for new technologies over time, there is also a time aspect to this.

In many of the reviewed studies, electricity and non-biomass-based hydrogen obtain dominating positions in the transport sector at the end of the studied time horizons, see e.g. Gül et al. (2009), Van Ruijven and van Vuuren (2009), Anandarajah et al. (2013), and Grahn et al. (2009b). However, Gielen et al. (2003) obtain a significant contribution of transport biofuels in the results and no hydrogen and electricity. As previously highlighted by Grahn et al. (2007), the BEAP model lacks representation of low-carbon alternatives in the transport sector other than biofuels, while several low-carbon options were represented in the stationary energy system. Thus, as carbon targets become strict, the transport sector of the BEAP model has no other option than turning to biofuels.

Turton (2006) and Akashi and Hanaoka (2012) are among the studies that obtain the highest biofuel utilization. As showed in Figure 1, this is a result of utilization of both “conventional” biofuels and a considerable share of biomass-based hydrogen production in combination with BECCS. Several studies exclude the latter alternative (hydrogen production with BECCS) in their models.

Whether this option is included or not is of course of relevance for the competitiveness of biomass-based hydrogen production compared to non-biomass based options.

Technology representation in stationary energy sector

Not only is the nature of the representation of technology options in the transport sector of significance for the resulting transport biofuel utilization, but so are choices made in regard to technology representation of the stationary energy system.

The availability of future low-cost, non-biomass based low carbon electricity generation can be a significant contributing factor to a high transport biofuel use, since this lowers the demand for biomass in the stationary energy system. In the reviewed studies, this can be noted in scenarios allowing a high use of nuclear power generation and/or electricity generation based on CCS. These are two low-carbon options for electricity generation, with technically high potential, which for future conditions often are assumed to have relatively low costs compared to other options, such as solar power. However, their deployment is to large degree dependent on political and public acceptance issues. Partly due to this, assumptions regarding these technologies differ widely. Turton (2006) presents a scenario in which a large increase in nuclear power generation is allowed and the electricity sector is predominantly based on nuclear. This is one reason for the very large utilization of transport biofuels which is the case in this scenario. Further examples are given by Hedenus et al. (2010). In three different scenarios they allow different penetration of CCS and nuclear respectively. With low penetration levels for these technologies, solar dominates the long-term electricity sector and the transport biofuel market share reaches about 14% at the end of the century. However, with CCS and nuclear dominating the sector in two alternative scenarios, the transport biofuel market share reaches to 26 (nuclear case) and 35% (CCS case).

Another aspect of technology representation in the stationary energy system of importance for the resulting transport biofuel utilization is to what degree biomass can supply industrial process heat demands. Hedenus et al. (2010) increase the level of detail in regard to process heat demand and introduces limitations for the amount of biomass allowed in the GET model. Partly due to this, a higher level of transport biofuel utilization is noticed in results by Hedenus et al. (2010) compared to results generated by other versions of the same model (Grahn et al., 2009ab; Azar et al., 2003). Similar limitations are likely to be behind the large transport biofuel market shares in results presented by Akashi and Hanaoka (2012) and Turton (2006). In these cases, industry heat demands are predominantly supplied by natural gas rather than biomass.

Climate ambitions

The impact of the assumed climate ambitions, i.e. the level of GHG reductions that should be met, on the level of transport biofuel utilization is not entirely straightforward. Generally, no-policy scenarios end up with a low use of bioenergy in general and transport biofuels in particular. The reason for this is simply that there are cheaper energy sources available, such as coal. Exceptions to this are given by Van Ruijven and van Vuuren (2009) who show significant transport biofuel usage also in such scenarios. This is most likely explained by high oil price assumptions combined with the model’s lack of representation of low-cost coal-based liquid synfuels.

With increasing climate ambitions and thus higher CO_2 emission penalties, bio-energy increase in competitiveness compared to fossil fuel options. For “medium” climate ambitions (e.g., 550 ppm), a certain amount of transport biofuels is also cost-effective in many of the reviewed studies. However, for very stringent climate targets, results are more diverse. Grahn et al. (2009b) and Gül et al. (2009) suggest that the cost-effective transport biofuel usage tends to peak at medium CO_2 reduction targets. While, as mentioned, fossil-based transport fuels are likely to dominate at less ambitious reduction targets, more stringent targets, at first increases the cost-effective transport biofuel usage but, as reduction targets increase even more, the models tend to choose other low-carbon options for the transport sector (hydrogen and/or electricity) while allocating biomass resources to heat and power production in the stationary energy system. There is also a time aspect to this as, in order to meet CO_2 stabilization targets at the end of the century, emission reductions get more stringent over time. This suggests that transport biofuels could be seen as a bridging technology to other low carbon options such as hydrogen and/or electricity (Gül et al., 2007). Whether or not model results show a peak in biofuel use at medium emission reduction levels depend, in line with what has been described above, on the technology representation of the models (technology availability, potentials, relative costs). For instance, if no low-carbon transport options other than biofuels available, more stringent CO_2 reductions will give further incentives to increase use of transport biofuels (see, e.g., Gielen et al., 2003). The same situation can occur if cheap non-biomass low-carbon electricity generation is abundant (see, e.g., Turton et al., 2006).

Time aspect

As already indicated in the above sections, the time-related aspects can influence transport biofuel utilization in model results. Studies that apply a shorter time horizon often obtain higher biofuel utilization than studies applying a longer time horizon (see Figure 1 and Figure 2). Part of the explanation of such effect could include assumptions regarding development of new alternative technology over time (cost reductions and improvements in technical performance) and regarding requirements for early CO_2 reductions.

Generally, medium-term studies show larger CO_2 reductions in the medium term than long-term studies do since long-term studies often have the possibility to postpone emission reductions to the far future. In the long term (e.g., at the end of the century), alternatives to biofuels (e.g., hydrogen FCVs and electric vehicles) may have gotten less costly and biomass resources can often be used more cost-effectively elsewhere. Further, due to the process of discounting, emission reduction in the far future are cheaper than emission reductions in the near future (the higher the assumed discount rate, the better to wait with emission reductions). Medium-term studies cannot, to the same degree, postpone emission reductions. On the other hand, comparing model end-years, required emission reductions are generally not as high for the medium-term studies as for the long-term studies, making the competition for available biomass somewhat lower. In Table 4, schematic overview of model of these model dynamics, which to some extent explains biofuel utilization differences between long-term and medium-term global modeling studies, is given.

Grahn et al. (2009b) provide examples of how regional emission caps, implying early emission reductions in industrialized regions, give higher biofuel utilization than a global cap.

Table 4. Schematic overview of principle model workings exemplifying potential differences in long-term and medium-term global modeling studies

	Model years 2020-2050	Model year 2100
Long-term studies		
CO_2 reduction required	Low	High
Low carbon transport options available	Biofuels Costly electricity and hydrogen options	Biofuels Cheap electricity and hydrogen options
Model choice in results	Oil products	Cheap electricity and hydrogen options
Medium-term studies		
CO_2 reduction required	Medium	-
Low carbon transport options available	Biofuels Costly electricity and hydrogen options	-
Model choice results	Biofuels (& Oil products)	-

3 REGIONAL AND NATIONAL STUDIES

Energy-economic system modeling studies with regional or national geographic focus show similarities but also differences to global modeling studies. While also in regional and national studies the overall objective is the analysis of possible transport and energy system futures under certain environmental targets, in regional or national approaches, this is often complemented by policy-oriented investigations. Model approaches are in many ways similar but some additional model considerations compared to global modeling are necessary. In this section, the approaches and results of recent model studies, applying regional and national perspectives, are reviewed. Focus is on Europe, a region with comparably ambitious targets for GHG emission reduction and transport biofuel deployment, but an outlook on studies analyzing USA as well as Canada is also made. Section 3.1 introduces identified studies and model approaches applied, and Section 3.2 presents the transport and biofuel-related results of each study.

3.1 STUDIES AND MODEL APPROACHES

3.1.1 Selected studies

Model studies analyzing different aspects of the European energy system are numerous in the literature and so is the case for national energy systems. However, the number of studies that apply a comprehensive energy and transport systems approach for investigating the co-evolution of these systems and contribute with visions regarding the future utilization of transport biofuels is smaller. Still, several relevant studies have been identified and selected from recent years' scientific journal literature. The studies are presented in Table 5 together with a description of the model used in each respective study. Similar to the reviewed global modeling studies in previous chapter, most of the regional and national modeling studies that are of relevance from a transport biofuel perspective are based on partial equilibrium, optimization modeling, although there are also examples of general equilibrium and hybrid approaches.

The TIMES modeling framework is used at the European level in several different model applications and studies. The Pan-European TIMES (PET) model was developed within two European Commission funded projects (NEEDS and RES2020[1]) and then further developed and applied by, e.g., Blesl et al. (2010, 2012). The PET model is a multi-regional model containing all countries of the EU-27 as well as Switzerland, Norway and Iceland. The PET model covers, at the country level, all sectors connected to energy supply and demand (the supply of resources, the public and industrial generation of electricity and heat, and the end-use sectors industry, commercial, households and transport). Blesl et al (2010) analyze the role of different technologies in the EU-27 with regard to efficiency improvements, fuel switching and energy saving measures under stringent CO_2 emission targets to 2050.

---

[1] Further information: http://www.cres.gr/res2020

Table 5. Selected European and national modeling studies and their related model features.

Reference	Model – Geographical scope	Model characteristics	End-year
Blesl et al. (2010)	TIMES PanEU – EU27 + Norway, Switzerland and Iceland	Optimization, Partial Equilibrium, Perfect Foresight, Bottom Up	2050
Berndes and Hansson (2007)	PEEP – EU27 excluding Malta, Cyprus and Bulgaria	Optimization, Partial Equilibrium, Perfect Foresight, Bottom Up	2030
Gitiaux et al. (2012)	MIT EPPA– Europe (in focus, but world economy modeled)	Simulation, General Equilibrium, Recursive-Dynamic (myopic), Top down (but with bottom-up data), Elasticities	2030
Capros et al. (2012)	PRIMES – EU27	Simulation (Hybrid), Partial Equilibrium, Perfect/Limited Foresight, Bottom Up	2050
Jablonski et al. (2010)	MARKAL – UK	Optimization, Partial Equilibrium, Perfect Foresight, Bottom Up, Endogenous Technology Learning	2050
van Vliet et al. (2011)	MARKAL – Netherlands	Optimization, Partial Equilibrium, Perfect Foresight, Bottom Up	2050
Schulz et al. (2007)	MARKAL – Switzerland	Optimization, Partial Equilibrium, Perfect Foresight, Bottom Up	2050
Börjesson and Ahlgren (2012a; 2012b)	MARKAL – Sweden	Optimization, Partial Equilibrium, Perfect Foresight, Bottom Up	2050; 2030
Blesl et al. (2007)	TIMES – Germany	Optimization, Partial Equilibrium, Perfect Foresight, Bottom Up	2050
Martinsen et al. (2010)	IKARUS – Germany	Optimization, Partial Equilibrium, Myopic, Bottom Up	2030
Yeh et al. (2008)	MARKAL – USA	Optimization, Partial Equilibrium, Perfect Foresight, Bottom Up, Elastic Demand	2050
Karplus et al. (2010)	MIT EPPA – USA and Japan (in focus, but world economy modeled)	Simulation, General Equilibrium, Recursive-Dynamic (myopic), Top down (but with some bottom-up tech. data), Elasticities	2100
McCollum et al. (2012)	TIMES – California	Optimization, Partial Equilibrium, Perfect Foresight, Bottom Up	2050
Steenhoof and McInnis (2008)	CanESS – Canada	Simulation, Bottom Up, “Socio-economic model”	2050

A bottom-up optimization modeling approach is also used by Berndes and Hansson (2007); here with the focus of studying the prospects for using domestic biomass resources in Europe. In particular, it is investigated whether different policy objectives underlying the support of bioenergy agree on which options that should be utilized. Such policy objectives include cost-effective climate change mitigation, employment creation and reduced dependency on imported fuels. The linear programming-based, regionalized energy- and transport-system system model PEEP (Perspectives on European Energy Pathways) is utilized. Compared to other reviewed studies, the time horizon is short and reaches to 2030.

The MIT Emissions Prediction and Policy Analysis (EPPA) model applies a general equilibrium approach. This implies that the entire economy, and not only the energy system, is considered in the analysis. The MIT EPPA model has been applied in various studies, but generally not in contexts of relevance for the present review. However, Gitiaux et al. (2012) examine the effect of biofuels mandates and climate policy on the European vehicle fleet, in particular in regard to diesel and gasoline vehicles’ market shares. While the analysis is based on a dynamic CGE model of the world economy, the focus is on Europe. The EPPA model typically includes second generation cellulosic biofuels technology, while first generation biofuels only are implicitly represented. However, Gitiaux et al. (2012) argue that current biofuel technologies are likely to contribute to meeting near-term mandates, and may be critical in shaping the transition to second generation biofuels. Therefore, more explicit representation of these technologies is added to the model in this study.

The PRIMES energy system model has been used to provide various energy scenario forecasts for the EU. Capros et al. (2012) present scenarios for a decarbonization of the European energy and transport system. The PRIMES model is a partial equilibrium model that simulates the response of energy consumers and the energy supply systems to different economic developments and exogenous constraints and drivers. In the model, a market equilibrium solution for each member state of the EU is simulated separately. In contrast to purely optimizing energy systems models, PRIMES to a higher degree incorporates behavioral aspects, formulating decisions of agents according to microeconomic theory. It also represents the available energy demand and supply technologies and pollution abatement technologies. The system reflects considerations about market competition, economics, industry structure, energy/environmental policies and regulations.

The MARKAL and TIMES modeling frameworks have been applied to a large number of national energy systems worldwide and not least in Europe. While not all studies are of relevance from a transport biofuel perspective or have been published in the peer-reviewed scientific literature, a number of studies meeting these criteria have been identified and selected for further analysis. Using MARKAL, van Vliet et al. (2011) explore the co-evolution of the power and transport sectors under strict CO_2 emission reduction policies in the Netherlands. Different scenario variants are used to investigate the development up to 2040.

Schulz et al. (2007) assess the economic conditions under which the production of synthetic natural gas (bio-SNG) from wood in a methanation plant becomes competitive using the SWISS-MARKAL model. SWISS-MARKAL projects future technology investments and provides an integrated analysis of primary, secondary, final and end-use energy in Switzerland with a time horizon to 2050.

For the case of Sweden, Börjesson and Ahlgren (2012a, 2012b) develop and utilize a MARKAL-based model including a comprehensive description of the energy and transport system. The model includes a number of options for biofuel production and vehicle technologies in the road transport sector. Börjesson and Ahlgren (2012a) investigate potential system effects of different transport fuel taxation strategies (such as with and without tax exemption on biofuels) and apply a time horizon to 2050. In a subsequent study, Börjesson and Ahlgren (2012b) investigate costs and system effects of reducing oil use in the passenger car sector for different potential future biofuel pathways to 2030.

Several studies based on analyses with the MARKAL-UK model have been published in recent years (e.g., Clarke et al., 2009; Strachan et al. 2009; Anandarajah and Strachan, 2010; Jablonski et al., 2010; Usher and Strachan, 2012). The MARKAL-UK model includes a comprehensive description of the UK energy system including the transport sector and provides exploration of least-cost system configurations across the modeled time horizon, which ranges from 2000 to 2050. Clarke et al. (2009) and Jablonski et al. (2010), in relation to other MARKAL-UK studies, more explicitly focus on bioenergy futures. Clarke et al. (2009) explore the potential contribution of bioenergy technologies to meet 60-80% carbon reduction targets in the UK and outline the potential for accelerated technological development of bioenergy chains. Jablonski et al., (2010) point out that this modeling exercise focus only on a few bioenergy chains, and further develop the MARKAL UK model with more detailed representation of bio-energy chains and end-uses to better understand the potential role of bioenergy.

Several national studies based on models following the structure of the earlier mentioned Pan European TIMES model have been published in recent years; examples include Labriet et al. (2010), Krook Riekkola et al. (2011) and Pietrapertosa et al. (2010) for the cases of Spain, Sweden and Italy, respectively. Blesl et al (2007) examine the German energy system using a TIMES model. The focus in the study is on impacts of efficiency improvement measures at the level of individual sectors level as well as in a combined implementation, in terms of energy savings, technological development, emissions and costs. None of the above mentioned TIMES national model studies specifically focus on the development of the transport sector, although they do include transport sector representation with several transport biofuel options and different alternative vehicle technologies.

Another example of comprehensive bottom-up modeling analysis for the case of Germany is provided by Martinsen et al. (2010). In this case, the prospects for integration of biofuels in the German transport system are analyzed by utilization of the IKARUS model. The IKARUS model is a time-step dynamical linear optimization model mapping the energy system of Germany. The model’s time horizon extends to 2030 and is divided into five-year intervals. In contrast to perfect-foresight energy systems models, each time interval is optimized by itself taking into account past events but not future changes. According to the authors this enables a more realistic character of prognosis and projection (Martinsen et al., 2010).

Moving the focus from Europe to North America, it can be noted that there are several modeling studies applying a comprehensive view of the US economy and energy system; however, often the development of the transport sector is modeled without including biofuel options or making conclusions in this regard. Example of such studies are carried out by Schäfer and Jacoby (2006), who utilize a combination of the models EPPA and MARKAL, and Morrow et al. (2010), who apply the NEMS model. Including biofuels in the scope of the analysis, Yeh et al. (2008) use a US national MARKAL model to analyze the potential role for the transportation sector under CO_2 constraints in the US, in the short- to medium-term perspective (up to 2050). Further, Karplus et al. (2010) investigate different aspects of PHEV market entry, e.g., in the presence and absence of an advanced cellulosic biofuels technology and a strong economy-wide carbon constraint. For the analysis, the CGE model EPPA is used and in addition to USA also Japan is studied.

Even though the main focus of the present review is not on regions within countries, a relevant study covering the state of California has been further looked into. The state of California has taken a leading role in regulating GHG emissions in North America, requiring that its emissions be reduced down to the 1990 level by 2020. The state also has a long-term, aspirational goal of an 80 percent reduction below the 1990 level by 2050. McCollum et al. (2012) explore technologies and policies for decarbonizing the California energy system over the long term. The paper introduces a California version of the TIMES model, CA-TIMES, which forms a bottom-up model for the analysis of the evolution of the transportation, fuel supply, and electric generation sectors.

Steenhoof and McInnis (2008) use a full systems model of the Canadian economy, the Canadian Energy System Simulator (CanESS), to model the future trajectory of road-based passenger transportation in Canada. The CanESS model represents Canada's total energy supply-demand system. It is calibrated to historical data and contains logic and mathematical formulae that track energy supply and demand. CanESS simulates the level of human activities and the evolving physical stock of human artifacts, with associated flows of energy and emissions. The study seeks to contrast emission and fuel-related impacts of different climate change policies targeting low carbon LDV technologies: electric vehicles, hydrogen fuel cell vehicles, and vehicles fuelled by ethanol.

3.1.2 Example of input and scenario assumptions

Table 6 presents model inputs and climate policy scenario assumptions regarding included policies, biomass supply and technology representation in road transport for the analyzed studies applying regional or national approaches.

In contrast to the global studies that often utilize CO_2 concentration stabilization levels as targets within their modeled scenarios, the regional and national studies generally apply a CO_2 reduction level in percentage compared to a base year (which is a reasonable approach considering that the action of one world region alone cannot determine the CO_2 concentration level in the atmosphere). An exogenous CO_2 penalty cost is also a common approach in the climate policy scenarios (in these cases, the resulting emission reduction level has for comparison purposes been indicated within brackets in the table). The studies are often policy focused and, in addition to climate policies, they regularly include other policy measures such as taxes and subsidies. Often the aim of the studies includes an investigation of effects related to the introduction or change of a certain policy, such as the introduction of biofuel mandates within the EU (Gitiaux et al., 2012). Generally, regional and national studies compared to global studies often show a much more diversified picture in terms of research questions, focus of study, scenarios investigated and consequently in the types of results provided.

Both in terms of national and regional modeling, assumptions regarding trade with surrounding regions outside the geographical system boundary are required (in global modeling, this can to a higher degree be handled endogenously). For instance, as presented in Table 6, different assumptions are made with regard to biomass supply; some studies investigate consequences if the region was to rely on domestic biomass resources while other allow a large degree of bio imports in their scenarios.

As for technology representation in the road transport sector, regional and national modeling studies generally apply a less aggregated approach than global studies. For instance, biofuels and biofuel production are often specified as specific alternatives rather than as one generic biofuel option. In most cases, there is also a fairly detailed representation of different vehicle technologies. However, some of the reviewed studies do not include the vehicle sector but specify transport fuel demands (rather than transport service demands).

Table 6. Policies applied, handling of biomass supply and fuel and technology representation in road transport for selected national and regional studies. Blanks indicate info were unclear or could not be obtained.

Reference	Climate policy or target	Other policies	Biomass supply	Technology representation road transport		
				Biofuels	Other low carbon options	Vehicle technologies
Blesl et al. (2010)	71% CO_2 reduction by 2050	Nuclear phase out in corresponding countries. Reduced net imports in alternative scenarios.	Primarily domestic	FT-Diesel , Methanol, Bodiesel, Biogas, EtOH	H2 Electr.	ICEV, HEV, EV, PHEV, FCV
Berndes and Hansson (2007)	40% CO_2 reduction by 2030	Biofuel mandates in alternative case	Domestic	EtOH, Biodiesel, “Biomass gasification fuel”, H2	H2	no (fuel demand is input to model)
Gitiaux et al. (2012)	Main current policies	Import tariffs, fuel taxes, biofuel mandates		EtOH, Biodiesel, BtL		
Capros et al. (2012) [a)]	85% CO_2 reduction by 2050	Representation of main current energy polices		EtOH, Biodiesel, FT-diesel, biogas, SNG , H2	H2 Electr.	ICEV, HEV, EV, PHEV, FCV
Jablonski et al. (2010)	80% CO_2 reduction by 2050	In some scenarios, energy security policies are included.	Domestic & Imports	EtOH, Biodiesel, FT-liquids		ICEV, HEV
van Vliet et al. (2011)	87% CO_2 reduction by 2050	No	Domestic & Imports	EtOH, Biodiesel, DME, FT-liq., MeOH, H2	H2 Electr.	ICEV, HEV, EV, PHEV, FCV
Schulz et al. (2007)	(about 16% CO_2 red.)	Different levels of Bio-SNG subsidies	Domestic wood	FT-liquids, Bio-SNG, H2	H2	ICEV
Börjesson and Ahlgren (2012a)	Cost incr. from 20 to 80 EUR/tCO_2 in 2010-2050 (6-48% CO_2 red.)	Different configurations for energy taxes on transport fuels	Domestic	EtOH, Biodiesel, Biogas,SNG, BtL, H2	H2 Electr.	ICEV, HEV, EV, PHEV, FCV
Börjesson and Ahlgren (2012b)	30-50% CO_2 reduction by 2030	Different levels of exogenously forced oil reduction	Domestic	EtOH, Biodiesel, Biogas, SNG, MeOH, DME, FT-liq., H2	Electr.	ICEV, HEV, EV, PHEV
Blesl et al. (2007)		Sectorial energy efficiency standards		“Biofuel”	Electr.	ICEV, EV
Martinsen et al. (2010)	CO_2 cost range 100-300 EUR/tCO_2 applied (-39 to -45% to 2030)	Alternative cases test CO_2 penalties in transport sector only	Primarily domestic	EtOH, Biodiesel, BtL, FT-liq., MeOH, SNG, H2		
Yeh et al. (2008)	50% CO_2 reduction by 2030	No		EtOH	H2 Electr.	ICEV, HEV, EV, PHEV, FCV
Karplus et al. (2010)	70% CO_2 reduction by 2100	Fuel taxes		BtL	Electr.	ICEV, PHEV
McCollum et al. (2012)	80% CO_2 reduction by 2050	Representation of main adopted and presently planned energy polices	Domestic & Imports	EtOH, Biodiesel, Synthetic diesel, Synthetic gasoline, H2	H2 Electr.	ICEV, HEV, EV, PHEV, FCV
Steenhoof and McInnis (2008)		Technology strategies for LDV transport		EtOH	Electr. H2	ICE, EV, PHEV, FCV

a) Supporting info from E3Mlab (2013)

3.2 MODEL RESULTS

3.2.1 Biofuel utilization

Main transport and biofuel related results for the reviewed regional and national studies are presented in Table 7 as well as comments on sensitivity analyses, developments in the stationary energy sector and other factors that could be of relevance for the biofuel results. For most of the studies, the resulting transport biofuel market shares are also visualized in Figure 3. Some of the studies do not have an analysis approach in which the biofuel market share is a result of the modeling. For instance, in some cases, the biofuel share is an exogenous assumption and the model results are instead the emission reduction achieved by this biofuel share or the costs or required investments the assumed biofuel share gives rise to (e.g., Börjesson and Ahlgren, 2012b; Steenhoof and McInnis, 2008). In other cases, transport biofuels market shares are not clearly presented; for instance, Karplus et al. (2010) only include biofuel as a test of the robustness of PHEVs and the resulting biofuel share is not reported. Note that some of the presented levels have been read from graphs and small errors compared to the original results might therefore exist.

In terms of biofuel utilization levels, the transport biofuel market share of the studies ranges from low to high shares. For the studies that analyze Europe as a whole, Blesl et al. (2010) present the highest share reaching almost 50% for a stringent CO_2 emission reduction scenario. Also Capros et al. (2012) present similar results; for a scenario with delayed electrification the transport biofuel market share reaches 44% while it with base assumptions level reaches 28% (the same CO_2 reduction applies in both cases). At the other end of the scale, Berndes and Hansson (2007) conclude that biomass is almost exclusively used in stationary applications if not sector specific policies is applied (the precise transport biofuel share is not given).

Also the national studies show diversified results in terms of resulting transport biofuel market shares and transport biofuel penetration levels range from small to large. Diversified results for national studies are not so surprising considering that the geographical areas differ between studies, and by that, the conditions regarding, e.g., biomass resource availability, transport fuel demands and energy prices. An example of a result in the high range, with a complete transport sector oil phase out to 2030 enabled through use of FT diesel and ethanol, is presented by van Vliet et al. (2011) for the case of the Netherlands. In this case, CO_2 emissions are reduced by 80% to 2030 and a crude oil price of 90 EUR/barrel is assumed. In the low range, a very small biofuel use is noted in a model result presented by Börjesson and Ahlgren (2012a); in this case, the resulting CO_2 emission reduction from the assumed CO_2 penalty is only 6% to 2050 and the assumed crude oil price is 60 USD/barrel. This study shows that either tax exemptions or higher crude oil prices are required to make biofuels cost-competitive (Börjesson and Ahlgren, 2012a). While biofuel shares in the studies' main scenarios differ widely, several of the studies indicate that transport biofuels can be competitive with conventional fuels at crude oil prices of about 90-120 USD/barrel (Schulz et al., 2007; van Vliet et al., 2011; Börjesson and Ahlgren, 2012ab; Martinsen et al., 2010).

In terms of biofuel choices, not all studies are specific regarding which type of biofuel is the best option. However, in several cases the dominating option is described as a liquid second-generation biofuel (Capros et al., 2012; Börjesson and Ahlgren, 2012a, Martinsen et al. 2010), which implies a fuel with a low-cost feedstock (wood waste, etc.) and low costs associated with distribution and vehicle technology. Other studies are more specific; Blesl et al. (2010), Jablonski et al. (2010), van Vliet et al. (2011) and McCollum et al. (2012) mention FT-liquids as a the preferred alternative, while Schultz et al. (2007) and Börjesson and Ahlgren (2012b) highlight SNG and methanol respectively. Yeh et al. (2008) and Steenhoof and McInnis specify the biofuel used in their results as ethanol; however, in these cases there are no other biofuel options available which means little could be said about its competitiveness compared to other biofuel alternatives.

Table 7. Transport biofuel related results of national and regional climate policy scenarios.

Reference	Transport and biofuel results for climate policy scenario	Comments and sensitivity
Blesl et al. (2010) *Area: Europe*	Total final energy use in transport is about 17 EJ in 2050, or about 15% higher than in 2000. Biofuels account for 8 EJ (47%), electricity for 1.5 EJ (9%) and oil products for 16 EJ (40). The small remaining parts are hydrogen (based on coal and CCS) and natural gas. FT-Diesel accounts for the major part of the biofuels. *Biofuel share 2050: 47% (transport)*	High CO_2 reduction. In 2050, natural gas combined with CCS accounts for more than half of the electricity production. Nuclear accounts for about 21%. Remaining part is dominated by renewables, primarily hydro and wind. Alternative scenario, with nuclear dominating electricity supply does not affect transport sector choices.
Berndes and Hansson (2007) *Area: Europe*	Without sector specific policies, biomass is almost exclusively used in stationary applications (primarily for heat). Increasing transport biofuel use with policy obligations shows a positive effect on employment creation. *Biofuel share 2030: not clear (but low)*	Medium/High CO_2 reduction. Biomass is for most of the period 2010–2030 used to the maximum of its potential. Biomass potential in 2030 is 12.2 EJ. The study focuses on prospects for using domestic biomass resources in Europe; bioenergy imports are not allowed in the study.
Gitiaux et al (2012) *Area: Europe*	Current trend of an increasing share of diesel vehicles in the vehicle fleet is robust to the EU biofuels mandates since the existing fuel tax and tariffs structure favors diesel vehicles. However, a harmonization of excise duties on diesel and gasoline or a reduction on tariffs for biofuel imports can change this trend and, in such way, affect the system efficiency costs and environmental effectiveness of the renewable fuel strategies. *Biofuel share 2020: 10% - Exogenous*	The study examines the effects on the vehicle fleet configuration of the EU biofuel mandates, which stipulate 10% of renewable fuels should be used in the union by 2020.
Capros et al. (2012) *Area: Europe*	In 2050, the total final energy demand in the transport sector is about 11 EJ or about 30% lower than 2005. Of this, biofuels accounts for about 3 EJ (28%), electricity for about 3 EJ (31%) and oil products for the remaining part. *Biofuel share 2050: 28% (transport)*	High CO_2 reduction. Oil price is about 65 EUR/barrel. In 2050, nuclear accounts for 26% of the electricity production (about the same share as today), fossil fuels with CCS 22%, biomass 8% and other renewables 43% (wind is the largest contributor). In a scenario with delayed transport electrification, transport biofuel use reaches 5.2 EJ (44%) in 2050.
Jablonski et al. (2010) *Area: UK*	In the short- to medium-term perspective, biofuels are only used as a result of renewable transport fuel obligations. In the longer term, transport biofuels can be a cost-effective low-carbon option at CO_2 price levels around 250 GBP/tCO_2. For a scenario with energy security objectives (i.e. less imports), about 600 PJ transport biofuel is used in 2050. For a scenario without energy security objectives, about 100 PJ transport biofuel is used. *Biofuel share 2050: 4-26% (transport)** ** Biofuel share is here calculated with assumption that UK transport fuel use in 2050 is the same as in 2010*	High CO_2 reduction. Significant amounts of imported bioenergy are allowed (in 2050, 700-800 PJ, i.e. about half of total primary bioenergy use, is imported). In addition to imported biofuels, domestic biofuel production based on the combined production of FT bio-diesel and bio-kerosene appears to be attractive.

van Vliet et al. (2011) *Area: Netherlands*	Conventional petrol and diesel are phased out by 2030 and primarily replaced by ethanol and FT diesel. In the 2020-2030 timeframe, ethanol is based on cellulosic biomass. The FT liquids are produced from a mix of coal and biomass, with utilization of CCS to the extent possible. Hybrid vehicles are used if insufficient low-carbon fuels are available. *Biofuel share 2040: 100%* (road transport)* ** Including coal-based FT-diesel with CCS*	High CO_2 reduction. Oil price is 90 EUR/bbl. The study finds that the lowest overall cost of CO_2 reduction are achieved by making reductions in transportation first (and then in electricity sector) due to high oil price. Significant amounts of biomass import are allowed. Halved biomass supply results in a 15% share for petroleum products and an increased share of fuel efficient vehicle technologies such as hybrids.
Schulz et al. (2007) *Area: Switzerland*	Oil price needs to reach about 110 USD/barrel for bio-SNG to start penetrate the market. With an oil price of 130 US$/bbl, the amount of bio-SNG in the Swiss transport sector in 2050 reaches about 35 PJ, corresponding to about 9% of final energy use in the sector. *Biofuel share 2050: 9% (transport)*	Low CO_2 reduction. Variations of oil prices and fuel subsidies are tested. Subsidies decrease the need for high oil price for a market introduction.
Börjesson and Ahlgren (2012a) *Area: Sweden*	Without transport biofuel tax exemptions, the study shows negligible market shares for biofuels. Tax exemptions increase the biofuel market share significantly. If jointly taking policy objectives of reducing CO_2 emissions and oil dependence into account, a combined strategy utilizing both biofuels and fuel-efficient vehicle technologies (plug-in hybrids, etc.) shows an advantageous system cost performance. *Biofuel share 2050: 1% (road transport) (without tax exemptions)*	Low CO_2 reduction. Oil price in base case is 60 USD/barrel. No biomass imports allowed (but comparably high domestic resources). Sensitivity analyses with oil price around 90 USD/barrel (resulting in medium CO_2 reduction levels, -30%) show a biofuel utilization level of 28% in 2050.
Börjesson and Ahlgren (2012b) *Area: Sweden*	A methanol based pathway gives incremental system costs in the range of −0.9 to 3 billion EUR for a complete phase-out of passenger car oil use to 2030 (range is due to different oil price and CO2 reduction levels). Other biomass gasification-based fuel pathways add about 3 billion EUR to the incremental system costs, and cellulosic ethanol- and electricity-based pathways add about 4 to 5 billion EUR. At lower oil reduction levels, the cost differences between the pathways are smaller and an electricity-based pathway is more cost-competitive. *Biofuel share 2030: 0-100% (Passenger car transport) - Exogenous*	Medium/High CO_2 reduction. Oil price is 60 and 115 USD/bbl. Different fuel pathways are simulated for the passenger car sector; different combinations of oil reduction levels and system-wide CO_2 reductions are tested. Negative incremental costs are noted for several pathways at higher oil prices (compared to a situation without oil reduction). Results indicate that a partly electrified passenger car sector is cost-effective, but full electrification is costly.
Martinsen et al. (2010) *Area: Germany*	Transport biofuel production varies with assumed CO_2 penalty level. For 2030, 100-150 EUR/tCO_2 gives an amount of 200 PJ consisting of 1st generation ethanol and biodiesel. At 300 EUR/tCO_2 advanced second generation biofuels (synthetic gasoline and diesel) are introduced. This results in a transport biofuel use of 400 PJ (15%). *Biofuel share 2030: 7-15% (transport)*	Medium/High CO_2 reduction. Oil price about 120 USD/barrel. No CO_2 penalty gives about 300 PJ of biofuel production (the higher levels than for with a penalty of 100-150 EUR/tCO_2 are due to less biomass competition from the stationary sector). Imports of refined biofuels (ethanol, etc.) are allowed to some degree.

Blesl et al. (2007) *Area: Germany*	The transport sector achieves efficiency targets through shifting from petrol to diesel in private transport, use of electric vehicles, and shifting to methanol or biofuel-based light and heavy trucks. *Biofuel share 2050: not clear*	The transport sector shows expensive CO_2 reductions compared to other sectors.
Yeh et al. (2008) *Area: USA*	With economy-wide CO_2 reduction of 50% to 2050, the total final energy use for passenger vehicles decreases by 23% to about 12 EJ. In 2050, ethanol, primarily cellulosic, accounts for about 61% (or 7 EJ) of the final energy use in the sector. Hybrids and plug-in hybrids dominate. Electricity accounts for 17%. Gasoline plays an important role throughout the studied period and accounts for the remaining 22% in 2050. *Biofuel share 2050: 61% (LDV transport)*	Medium/High CO_2 reduction. Ethanol is the only biofuel option represented in the study. Results suggest that most of the emission reduction will come from the electricity sector, in particular by employing CCS. Corresponding ethanol levels for CO_2 -40% is 3.5 PJ (25% of total). Total fuel use is higher due to less plug-in hybrids.
Karplus et al. (2010) *Area: USA/JAPAN*	PHEVs have the potential to reduce CO_2 emissions as well as oil demand and reaches high market shares in model results. However, with climate policy applied, the presence of a CO_2 -neutral biofuel alternative reduces significantly the penetration of PHEVs since the availability of biofuels makes it possible to continue to drive conventional vehicles and still meet CO_2 constraints. *Biofuel share: not clear*	High CO_2 reduction. Study investigates different aspects of PHEV market entry. Biofuels are only studied from the perspective of its potential effects on the competitiveness of PHEVs
McCollum et al. (2012) *Area: California*	Total final energy demand in transport is about 5% higher in 2050 than in 2005. Petroleum makes up 64% of total transportation fuel use in 2050; biofuels, hydrogen and electricity account for 26%, 8% and 2% of consumption respectively. The contribution of ethanol declines during the time horizon and instead, biomass for the production of bio-derived gasoline, diesel, jet fuel, and residual fuel oil increases in importance. In particular, biomass-based FT plants with CCS are competitive. *Biofuel share 2050: 26% (transport)*	High CO_2 reduction. Renewables (wind, solar, hydro) and nuclear dominate electricity generation. Also CCS makes as noteworthy contribution. Bioenergy imports to the state are allowed.
Steenhoof and McInnis (2008) *Area: Canada*	The study contrasts GHG emission and fuel-related impacts of (1) electric vehicles, (2) hydrogen fuel cell vehicles, and (3) vehicles fuelled by ethanol. Scenarios based on hydrogen and electric cars result in similar emission reductions. Preferred hydrogen production is based on biomass. Emission reductions for ethanol are somewhat lower due to fossil fuel requirements, in particular, regarding grain-based ethanol production. By 2050 ethanol is primarily based on cellulose, showing larger emission reductions but also requiring possibly unsustainable amounts of crop residue as feedstock. *Biofuel share 2050: not clear*	Low CO_2 reduction. In three separate model scenarios, each respective alternative vehicle technology/fuel is simulated to reach 100% of the new vehicle market by 2050.

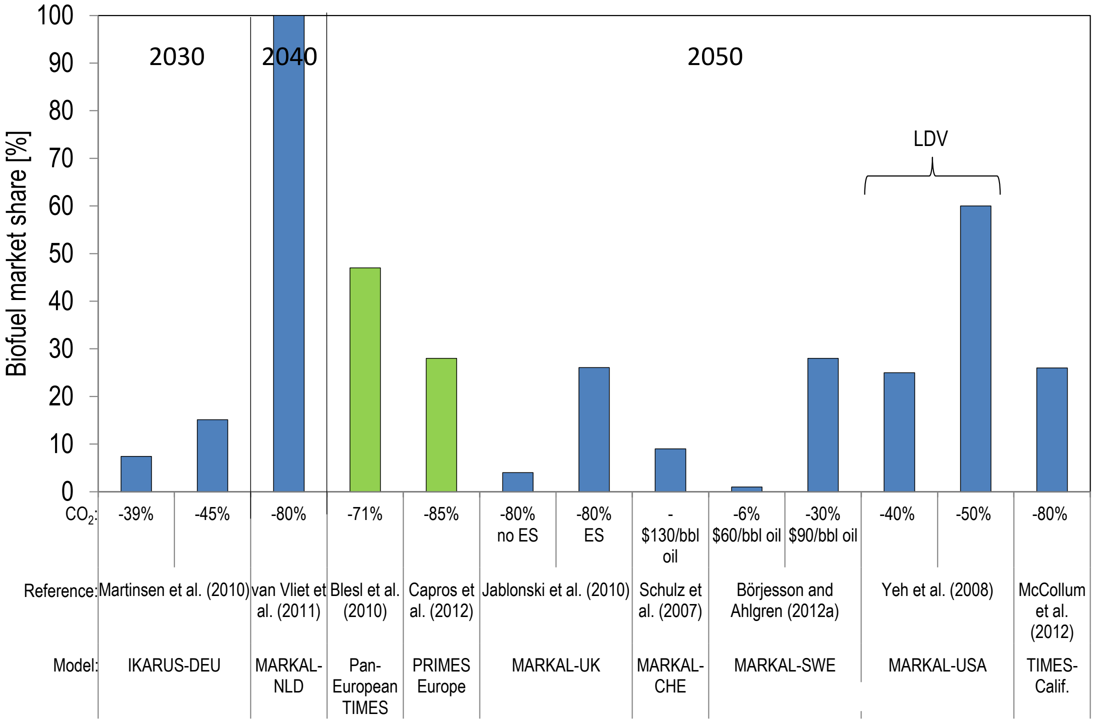

Figure 3. Biofuel market shares for model end-years (indicated) for regional and national studies. Results for studies on European level are green. For Jablonski et al. (2010), "ES" refer to that energy security targets are applied. For Yeh et al. (2008), results refers to the light duty vehicle (LDV) sector. For van Vliet et al. (2011), results, in addition to biofuels, include FT-diesel from coal-based production with CCS.

3.2.2 Factors influencing biofuel utilization

As for global modeling studies, the reasons for differences in transport biofuel utilization for regional and national modeling studies depend on several factors. To high degree, the factors are similar to the ones highlighted for global models, i.e. assumed biomass potential, climate ambition, technology representation in transport and in stationary sector and the time horizon studied. However, due to differences in aim and set-up of regional and national studies compared to global studies, there are also differences in the way the factors are handled and how they influence the model results. Further, other influencing factors, which were not so noticeable in the case of global studies, have been identified in the case of regional and national studies; these include oil price assumptions and handling of energy policies in addition to climate constraints, such as energy taxes.

Technology representation, time horizon and climate ambition

Compared to global studies, regional and national studies generally apply a shorter time horizon. Often, a 2050 perspective is applied. Thus, the aspects earlier described (Section 2.2.2) in relation to time aspects for global models come into play. Firstly, low carbon alternatives to biofuels such as hydrogen-based systems (FCVs, etc.) and electricity based systems (EVs, etc.) are generally assumed to have a higher cost in the short/medium term than in the long term. Consequently, none of the national and regional studies presents hydrogen as a dominating transport fuel alternative (which several of the global studies do). Secondly, the flexibility of meeting emission targets is lower, i.e. emission reduction cannot be postponed. However, several of the regional and national studies also have comparably low CO_2 reduction requirements or CO_2 penalties, making it possible to continue with an oil-based transport sector throughout the modeled time horizon and make emission reductions primarily in other sectors (but whether this is the best option is also dependent on other factors such as oil price).

Even though the conditions differ, the principal workings of the influence of technology representation and climate ambitions are similar for regional/national models and global models. For instance, regarding technology representation in the transport sector, Capros et al. (2012) highlight that a delayed introduction of electric vehicles significantly increases the share of transport biofuels. Blesl et al. (2010) present a stationary energy system based on CCS and nuclear and receives a significant use of transport biofuels. In a “medium” climate target range, several of the studies note an increase in biofuel use with increasing reduction level or CO_2 penalty (e.g., Yeh et al. 2008).

In regard to climate ambitions and biofuel choice, Börjesson and Ahlgren (2012b) note that first generation crop-based biofuels, such as wheat-based ethanol, can be competitive to second generation biofuel options if targets for CO_2 (and oil reduction) are low (less ambitious), i.e. when land use and biomass resource competition is not critical (Börjesson and Ahlgren, 2012b). This effect is also shown by Martinsen et al. (2010).

Oil price

Regional/national model studies, generally to a higher degree depend on exogenous assumptions than global models, for instance in regard to future oil prices. That is, while the future oil price could, potentially, be a result from a global run, it is generally an exogenous input to regional/ national studies. With exogenous oil prices, there are no feed-back loops influencing the price level if demand drops. Studies that because of high oil prices show a large drop in oil use (for instance being replaced by biofuels), are therefore primarily valid under either one of the two following conditions: (1) the modeled region in which this development occurs is too small to have significant influence on the world market oil price, or; (2) the high oil price is a consequence of limitations in supply.

Assumptions regarding the future oil price are of large importance for the cost-competitiveness of alternative transport sector energy carriers. Not surprisingly, higher oil prices are generally linked to a higher use of transport biofuels. In contrast to many other studies (not least earlier presented global studies), van Vliet et al. (2011) find that the lowest overall cost of CO_2 reduction are achieved by making reductions in transportation first (and then in the electricity sector). The authors explain this by the comparably high oil price, which in the study is assumed to 90 EUR/barrel. Several studies indicate that transport biofuels can be competitive with conventional fuels with crude oil prices of about 90-120 USD/barrel (Schulz et al., 2007; van Vliet et al., 2011; Börjesson and Ahlgren, 2012ab; Martinsen et al., 2010).

The oil price assumptions become less important with more stringent CO_2 constraints. For instance, if no fossil fuels at all are allowed to be utilized (due to stringent emission constraints, etc.) exogenously assumed fossil fuel prices are irrelevant. In practice, this means that oil price/cost assumptions are of higher importance in the short- to medium-term time horizon and/or with low to medium ambitions in terms of emission reduction. With increasingly stringent emission constraints, an endogenous CO_2 penalty will eventually be so high that exogenous assumptions regarding oil prices will not have significance for the model results.

Biomass potential

As previously mentioned, the assumed level of available biomass resources for energy purposes can be an important influencing factor for the resulting transport biofuel share in model results. While global model studies generally incorporate estimations on the global biomass supply in the models, regional/national studies need to consider domestic availability but also require strategies on how to look upon potential imports of biomass and biofuels. Biomass trade is an issue also in regionalized global models, but in this case it does not affect the total potential supply of biomass (only the regional allocation). Different approaches in regard to this are noticed in the reviewed regional and national studies. Several studies disregard to possibility of biomass imports or constrain import levels at low levels and instead focus the investigation the possible contribution of the domestic biomass potential (Börjesson and Ahlgren, 2012ab; Gül et al., 2007; Berndes and Hansson, 2007). Other studies apply different approaches; for example, van Vliet et al. (2011) make the assumption that the Netherlands is allocated a certain amount of the world biomass potential: the average of two allocation principles is used: (1) equal biomass supply per capita, and (2) current share of national energy use in global energy use. This opens the possibility for a much larger bioenergy utilization, as well as transport biofuel utilization, than what would be possible for the Netherlands if only relying on domestic resources. Also Jablonski et al. (2010) assume for the case of UK large bioenergy imports, which significantly influences the results.

Non-climate related energy policy measures

In contrast to global studies, many of the studies with regional and national perspectives, in addition to the climate issue, also include other policy targets that could influence resulting transport biofuel utilization. For instance, increased energy security or less dependence on imported energy carriers are non-climate related objectives that are incentives for oil use reduction. Many studies include sector-specific policies for the transport sector, such as energy taxes transport fuels or biofuel subsidies (e.g., Börjesson Ahlgren, 2012a; Schultz et al., 2007) or exogenously forced introduction of alternative fuels (e.g., Börjesson Ahlgren, 2012b, Steenhoof and McInnis, 2008; Gitiaux et al., 2012). Such scenario set-ups obviously have important influence on the resulting biofuel shares, and the results require a somewhat different interpretation.

Berndes and Hansson (2007) find that the different policy objectives do not agree on the order of priority among bioenergy options. Maximizing climate benefits from a cost perspective is in conflict with maximizing employment creation. The former advises the use of lignocellulosic biomass in the stationary sector, while the latter advises biofuels for transport based on traditional agricultural crops. Further, the authors conclude, that from a security-of-supply perspective, the benefits of the different bioenergy options depend on how oil and gas import dependencies are looked upon and prioritized relative to each other (Berndes and Hansson; 2007). Börjesson and Ahlgren (2012a) highlight that if jointly taking policy objectives of reducing CO_2 emissions and oil dependence into account, a combined strategy utilizing both biofuels and fuel-efficient vehicle technologies (such as hybrids and plug-in hybrids) shows an advantageous cost-performance from a systems perspective.

4 DISCUSSION

In the present work, model-based studies, in which the transport sector is represented as an integrated part of the energy system and transport biofuels constitute an important part of the analysis, have been reviewed. The geographical scope has ranged from global to national studies, also including studies focusing on Europe as a region. The review provides insights into the level and characteristics of the transport biofuel utilization in these studies and to factors influencing their model results.

There are numerous energy-economic models available for the analysis of national, regional and global energy systems. Consequently, the number of performed studies based on such models is even larger. In this work, a selection of studies for analyzes and comparison has been made based on a set of criteria. These include: focus of study, comprehensiveness of model, geographical scope and relevance from a transport biofuel perspective. Further, the intention was to cover different models as well as different research groups and analysts. In the selection, only peer-reviewed scientific journal articles published in recent years have been considered. The review does not claim to be exhaustive, but the amount of analyzed studies should still constitute a well-founded base for general insights of the area in focus.

A difficulty in a work of this kind is that, even though the reviewed studies from a broader perspective apply similar type of approach and scope, the specific objectives of the reviewed studies are at times very diverse. This complicates the process of comparing and contrasting similar types of parameters. Further, while long-term modeling is important to raise awareness of long-term effects and potential conflicts with current strategies, this kind of studies are also subject to large uncertainties with regard to input data. Since the result of a model run simply is the logical consequence of the model inputs, it is vital that assumptions made are made clear to the addressees of the studies. However, this is not always the case. Even though sought after data at times have been missing, the sum of the information provided from the different studies enabled a comparative analysis and a number of insights.

In terms of results and insights, the review demonstrates that energy-economic modeling studies portray a diverse picture in regard to the future transport biofuel utilization. Regardless of geographical scope of the studies (global, regional or national), the studies show transport biofuel market shares that range from low to high penetration levels. However, the main part of the studies shows biofuel share below 40% at the end of the modeled time-horizon, with several studies showing results well below this level. Even though transport biofuels do not tend to dominate the transport sector in the long-run, compared to today’s transport biofuel utilization level, many model studies show a significant increase.

Not all studies are concerned or explicit about which type of biofuel is the most advantageous choice. However, among those studies that include a number of different specified biofuel options in the modeling, some trends emerge. Generally, liquid wood-based second-generation biofuels emerge in many of the model results. More specifically, FT liquids are one biofuel option that his highlighted in several of the reviewed studies. The possibility of using existing infrastructure and vehicles is, in these cases, probably of high significance, but also the combined production of jet-fuels (for the aviation sector) and synthetic diesel/gasoline (for the road transport sector) of the FT process is pointed out as valuable. In addition, other biofuels, such as biomass-to-alcohol options and bio-based SNG show to be advantageous options in different studies, although less frequently than FT liquids.

A number of factors influencing the resulting transport biofuel utilization in the modeling results have been identified. These include biomass potential, climate ambition/policies, technology representation in the transport sector as well as in the stationary energy sector, oil price, and energy policies in addition to GHG related constraints or penalties. Since the models cover long time horizons and the conditions often change over time there is also a time aspect to many of the mentioned factors (e.g., technology costs, CO_2 reduction requirements and energy prices).

In what way the above mentioned factors influence the results are not straightforward. Further, the relative importance of each respective factor varies depending on conditions. The *climate ambition* (the level of GHG reduction constraints or emission cost penalties) is relevant for how much of the available biomass is used, the higher climate ambition, the higher the proportion of the total biomass potential is used. At high climate ambitions, the full (or close to full) biomass potential is used in many of the studies. The *technology representation*, i.e. what technologies that are available in the model, to what relative costs and to what potential, determine the allocation of biomass. The relative cost of alternative technologies is complex and varies with scarcity rents and CO_2 penalties, which, in turn, are functions of the climate ambition. This relates to transport biofuels in relation to other technologies in the transport sector as well as in the stationary energy system, but also between different transport biofuel options. For example, a high (allowed) potential and a low cost for non-biomass based low-carbon electricity generation, such as CCS or nuclear power, imply a low demand for biomass in the stationary system and, in many cases, this means more available biomass for transport biofuel production. A similar effect is seen if the assumed possibilities for biomass-based process heat in industry are low. On the contrary, a high (allowed) potential and low costs for hydrogen or electricity-based transportation will decrease the competitiveness of transport biofuels. A high total *biomass potential* can imply that the potential of the most cost-effective biomass usage can be filled and still leave biomass resources to other, less cost-effective, alternatives. In some cases, transport biofuel are not among the most cost-effective choices for biomass use, but with a high biomass potential, a certain amount of transport biofuel can still be possible. However, if the potential for the most cost-effective biomass application is very large, a higher biomass potential gives no effect on alternative possible use. A higher *oil price* increases the cost-competitiveness of transport biofuels and other alternatives compared to conventional oil-based transport fuels as well as to other potential use of the biomass resources. *Energy policies* such as energy taxes, tax exemptions, subsidies and other types of policies alter the relative costs of fuel and technology alternatives and can depending on design significantly affect the transport biofuel utilization in modeling results.

The transport biofuel utilization in model results depends on several factors and many studies show large differences. Differences depend in many cases on quantitative assumptions regarding more or less uncertain input data. While this highlights difficulties with quantitative long-term modeling of energy-economic systems, it also demonstrates a strong relevance of the same: without making quantitative statements regarding numerous parameters (such as biomass potentials, cost of alternative technologies, system-wide CO_2 reduction aimed for), not much can be said about the future effective contribution of transport biofuels from an overall system perspective.

5 CONCLUSIONS

Comprehensive systems modeling applying a co-evolution approach to the development of the energy and transport system is an important and relevant analysis approach since shared resource constraints increasingly will influence both systems. The number of studies applying such an approach has grown in recent years.

In this review, we find that the future market penetration of transport biofuels range from low to high levels in the reviewed model results. Most of the studies show low to intermediate biofuels market shares (below 40%) at the end of the studied time horizons for climate policy scenarios not including sector specific polices. Biofuels are to a higher degree seen in medium-term model results. In the long term, many of the models instead favor hydrogen and electricity as competition for limited amounts of biomass increases with more stringent emission targets. Factors influencing biofuel utilization in the model results include: biomass potential, climate ambition/policies, technology representation in the transport sector and in the stationary energy sector, oil price, and energy policies in addition to GHG related constraints or penalties.

Although transport biofuels do not tend to dominate the transport sector at the end of the modeled time horizons, compared to today’s level many model studies show a significant increase in transport biofuel use. Liquid biofuels with comparably low cost-feedstock base (wood waste, etc.) and low incremental costs in distribution and vehicles are the preferred biofuel choice in many of the model results. Specifically, fuels based on biomass gasification and the FT process is frequently mentioned, but also other options. Besides transport biofuels, the development and deployment of energy efficient vehicle technologies, such as plug-in hybrids and FCVs (in the longer term), is an essential part in many of the future transport scenarios.

REFERENCES

Akashi, O, Hanaoka, T, 2012. Technological feasibility and costs of achieving a 50 % reduction of global GHG emissions by 2050: mid- and long-term perspectives. Sustainability Science 7, 139–156.

Anandarajah, G., Strachan, N., 2010. Interactions and implications of renewable and climate change policy on UK energy scenarios. Energy Policy 38, 6724–6735.

Anandarajah, G., McDowall, W., Ekins, P., 2013. Decarbonising road transport with hydrogen and electricity: Long term global technology learning scenarios. International Journal of Hydrogen Energy 38, 3419–3432.

Azar, C., Lindgren, K., Andersson, B.A., 2003. Global energy scenarios meeting stringent CO_2 constraints— cost-effective fuel choices in the transportation sector. Energy Policy 31, 961–976.

Berndes, G., Hansson, J., 2007. Bioenergy expansion in the EU: Cost-effective climate change mitigation, employment creation and reduced dependency on imported fuels. Energy Policy 35, 5965–5979.

Blesl, M., Das, A., Fahl, U., Remme, U., 2007. Role of energy efficiency standards in reducing CO_2 emissions in Germany: An assessment with TIMES. Energy Policy 35, 772–785.

Blesl, M., Kober, T., Bruchof, D., Kuder, R., 2010. Effects of climate and energy policy related measures and targets on the future structure of the European energy system in 2020 and beyond. Energy Policy 38, 6278–6292.

Börjesson, M., Ahlgren, E.O., 2012a. Assessment of transport fuel taxation strategies through integration of road transport in an energy system model—the case of Sweden. International Journal of Energy Research 36, 648–669.

Börjesson, M., Ahlgren, E.O., 2012b. Modelling transport fuel pathways: Achieving cost-effective oil use reduction in passenger cars in Sweden. Technological Forecasting & Social Change 79, 801–818.

Clarke, D., Jablonski, S., Moran, B., Anandarajah, G., Taylor, G., 2009. How can accelerated development of bioenergy contribute to the future UK energy mix? Insights from a MARKAL modeling exercise. Biotechnology for Biofuels 2:13.

Canes, M.E., 2002. Economic Modeling of Climate Change Policy. International Council for Capital Formation, Brussels.

Capros, P., Tasios, N., De Vita, A., Mantzos, L., Paroussos, L., 2012. Transformations of the energy system in the context of the decarbonisation of the EU economy in the time horizon to 2050. Energy Strategy Reviews 1, 85-96.

E3Mlab, 2013. The PRIMES model. Website information, available at: <http://www.e3mlab.ntua.gr/e3mlab/index.php?option=com_content&view=category&id=35&Itemid=80&lang=en>

EC (European Commission), 2009. Directive 2009/28/EC of 23 April 2009 on the promotion of the use of energy from renewable sources. Journal of the European Union, 16-62.

Erb, K-H., Haberl, H., Krausmann, F., Lauk, C., Plutzar, C., Steinberger, JK., et al., 2009. Eating the planet: feeding and fuelling the world sustainably, fairly and humanely - a scoping study. Institute of Social Ecology and PIK Potsdam, Vienna.

Fulton , L., Cazzola, P., Cuenot, F., 2009. IEA Mobility Model MoMo and its use in the ETP 2008. Energy Policy 37, 3758–3768.

Føyn, T.H.Y., Karlsson, K.B., Balyk, O., Grohnheit, P.E., 2011. A global renewable energy system: A modelling exercise in ETSAP/TIAM. Applied Energy 88, 526-534.

Gielen, DJ., Fujino, J., Hashimoto, S., Moriguchi, Y., 2002. Biomass strategies for climate policies? Climate Policy 2, 319–333.

Gielen, D., Fujino, J., Hashimoto, S., Moriguchi, Y., 2003. Modeling of global biomass policies. Biomass and Bioenergy 25, 177 – 195.

Gitiaux, X., Rausch, S., Paltsev, S., Reilly, JM., 2012. Biofuels, Climate Policy, and the European Vehicle Fleet. Journal of Transport Economics and Policy 46, 1–23.

Grahn, M., Azar, C., Lindgren, K., Berndes, G., Gielen, D., 2007. Biomass for heat or as transportation fuel? A comparison between two model-based studies. Biomass and Bioenergy 31, 747–758.

Grahn, M., Azar, C., Williander, M.I., Anderson, J.E., Mueller, S.A., Wallington, T.J., 2009a. Fuel and Vehicle Technology Choices for Passenger Vehicles in Achieving Stringent CO_2 Targets: Connections between Transportation and Other Energy Sectors. Environmental Science and Technology 43, 3365–3371.

Grahn, M., Azar, C., Lindgren, K., 2009b. The role of biofuels for transportation in CO_2 emission reduction scenarios with global versus regional carbon caps. Biomass and Bioenergy 33, 360–371.

Gül, T., 2008. An energy-economic analysis of alternative fuels for transport. Dissertation, ETH, Zürich.

Gül, T., Kypreos, S., Turton, H., Barreto, L., 2009. An energy-economic scenario analysis of alternative fuels for personal transport using the Global Multi-regional MARKAL model GMM. Energy 34, 1423–1437.

Hedenus, F., Karlsson, S., Azar, C., Sprei, F., 2010. Cost-effective energy carriers for transport – The role of the energy supply system in a carbon-constrained world. International Journal of Hydrogen Energy 35, 4638 – 4651.

IEA International Energy Agency, 2008 Energy Technology Perspectives 2008 IEA, Paris. <wwwieaorg>

IPCC, 2001. Climate change 2001: mitigation: contribution of Working Group 3 to the third assessment report of the Intergovernmental Panel on climate change. Cambridge University Press, Cambridge.

Jablonski, S., Strachan, N., Brand, C., Bauen, A., 2010. The role of bioenergy in the UK's energy future formulation and modelling of long-term UK bioenergys scenarios. Energy Policy 38, 5799–5816.

Jaccard, M., Lolou, R., Kanudia, A., Nyboer, J., Baile, A., Labriet, M., 2003. Methodological contrasts in costing greenhouse gas abatement policies: Optimisation and simulation modelling of micro-economic effects in Canada. European Journal of Operational Research 145, 148-164.

Karplus, V.J., Paltsev, S., Reilly, J.M., 2010. Prospects for plug-in hybrid electric vehicles in the United States and Japan: A general equilibrium analysis. Transportation Research Part A 44, 620–641.

Kitous, A., Criqui, P., Bellevrat, E., Chateau, B., 2010. Transformation Patterns of the Worldwide Energy System - Scenarios for the Century with the POLES Model. The Energy Journal 31, 49-82.

Krook Riekkola, A., Ahlgren, E.O., Söderholm, P., 2011. Ancillary benefits of climate policy in a small open economy: The case of Sweden. Energy Policy 39, 4985–4998.

Kyle, P., Kim, S.H., 2011. Long-term implications of alternative light-duty vehicle technologies for global greenhouse gas emissions and primary energy demands. Energy Policy 39, 3012-3024.

Labriet, M., Cabal, H., Lechón, Y., Giannakidis, G., Kanudia, A., 2010. The implementation of the EU renewable directive in Spain. Strategies and challenges. Energy Policy 38, 2272–2281.

Labriet, M., Kanudia, A., Loulou, R., 2012. Climate mitigation under an uncertain technology future: A TIAM-World analysis. Energy Economics 34, 366-377.

Lanza, A., Bosello, F., 2004. Modeling energy supply and demand: a comparison of approaches. Encyclopedia of Energy 4, 55-64.

Martinsen, D., Funk, C., Linssen, J., 2010. Biomass for transportation fuels – A cost-effective option for the German energy supply? Energy Policy 38, 128–140.

McCollum, D., Yang, C., Yeh, S., Ogden, J., 2012. Deep greenhouse gas reduction scenarios for California – Strategic implications from the CA-TIMES energy-economic systems model. Energy Strategy Reviews 1, 19-32.

Morrow, W.R., Sims Gallagher, K., Collantes, G., Lee, H., 2010. Analysis of policies to reduce oil consumption and greenhouse-gas emissions from the US transportation sector. Energy Policy 38, 1305–1320.

Nakata, T., 2004. Energy-economic models and the environment. Progress in Energy and Combustion Science 30, 417-475.

OECD/IEA, 2012. World Energy Outlook 2012, OECD/IEA, Paris.

Pietrapertosa, F., Cosmi, C., Di Leo, S., Loperte, S., Macchiato, M., Salvia, M., Cuomo, V., 2010. Assessment of externalities related to global and local air pollutants with the NEEDS-TIMES Italy model. Renewable and Sustainable Energy Reviews 14, 404–412.

Remme, U., Blesl, M., 2011. A global perspective to achieve a low-carbon society (LCS): scenario analysis with the ETSAP-TIAM model. Climate Policy 8, 60-75.

Rivers, N., Jaccard, M., 2006. Useful models for simulating policies to induce technological change. Energy Policy 34, 2038–2047.

Rout, U.K., Voss, A., Singh, A., Fahl, U., Blesl, M., Gallachóir, B.P.Ó., 2011. Energy and emissions forecast of China over a long-time horizon. Energy 36, 1-11.

Schulz, T.F., Barreto, L., Kypreos, S., Stuck, S., 2007. Assessing wood-based synthetic natural gas technologies using the SWISS-MARKAL model. Energy 32, 1948–1959.

Schäfer, A., Jacoby, H.D., 2006. Vehicle technology under CO_2 constraint: a general equilibrium analysis. Energy Policy 34, 975–985.

Steenhof, P.A., McInnis, B.C., 2008. A comparison of alternative technologies to de-carbonize Canada's passenger transportation sector. Technological Forecasting and Social Change 75, 1260–1278.

Sterman, J.D., 1991. A Skeptic’s Guide to Computer Models. In: Barney, G O et al. (eds.), Managing a Nation: The Microcomputer Software Catalog Westview Press, Boulder.

SOU, 2013. Utredningen om fossilfri fordonstrafik. <http://www.sou.gov.se/sb/d/17384>

Strachan, N., Balta-Ozkan, N., Joffe, D., McGeevor, K., Hughes, N., 2009. Soft-linking energy systems and GIS models to investigate spatial hydrogen infrastructure development in a low-carbon UK energy system. International Journal of Hydrogen Energy 34, 642-657.

Swedish Government, 2009. An integrated climate and energy policy – Information sheet about the governmental bills 2008/09:162 and 163, Ministry of Environment, Ministry of Enterprise, Energy and Communications, Stockholm.

Takeshita, T., 2009. A strategy for introducing modern bioenergy into developing Asia to avoid dangerous climate change. Applied Energy 86, S222–S232.

Takeshita, T., 2012. Assessing the co-benefits of CO_2 mitigation on air pollutants emissions from road vehicles. Applied Energy 97, 225–237.

Takeshita, T., Yamaji, K., 2008. Important roles of Fischer–Tropsch synfuels in the global energy future. Energy Policy 36, 2773– 2784.

Turton, H, 2006. Sustainable global automobile transport in the 21st century: An integrated scenario analysis. Technological Forecasting & Social Change 73, 607–629.

Turton, H., Barreto, L., 2007. Automobile technology, hydrogen and climate change: a long term modelling analysis. International Journal of Alternative Propulsion 1, 397-426.

Usher, W., Strachan, N., 2012. Critical mid-term uncertainties in long-term decarbonisation pathways. Energy Policy 41, 433–444.

van Ruijven, B., van Vuuren, D.P., 2009. Oil and natural gas prices and greenhouse gas emission mitigation. Energy Policy 37, 4797–4808.

van Vliet, O., van den Broek, M., Turkenburg, W., Faaij, A., 2011. Combining hybrid cars and synthetic fuels with electricity generation and carbon capture and storage. Energy Policy 39, 248–268.

Wene, C.-O., 1996. Energy-economy analysis: Linking the macroeconomic and systems engineering approaches. Energy 21, 809-824.

Worldwatch Institute, 2011. Website information. < http://www.worldwatch.org/>

Yeh, S., Farell, A., Plevin, R., Sanstad, A., Weyant, J., 2008. Optimizing US Mitigation Strategies for the Light-Duty Transportation Sector: What We Learn from a Bottom-Up Model. Environmental Science and Technolgy 42, 8202-8210.

APPENDIX: MODEL TYPES AND CONCEPTS

There are many different modeling approaches developed to analyze energy-economic systems. In this Appendix, a background on some main model types and model concepts frequently used in energy and environmental system analysis is given.

A.1 MODEL TYPES

There are numerous different models which are used for different types of energy-economic modeling and analysis. There are also many ways of categorizing these models. Here, focus is on a commonly used classification principle based on the concepts of bottom-up and top-down models, see Section A.1.1 and A.1.2 respectively. The division between these model types is not clear-cut and models often have features from both categories; this is highlighted in Section A.1.3.

It should be pointed out that, due to the focus of the present study on the role of transport biofuels in energy-economic scenarios, a certain amount of "bottom-up" technology data is required in the model in order for the model study to fall within the scope of this literature review. This means that strict macroeconomic top-down models, with very limited explicitness in terms of technology and fuel representation, are not covered in the literature review. Nevertheless, the model type will be described here for background purposes and to put other models (of more relevance for the present review) into context.

A.1.1 Bottom-up models

The distinction between bottom-up and top-down models relate to which perspective the system is studied from, and the terms are in this respect sometimes considered to exchangeable with "disaggregate" and "aggregate" models (Nakata, 2004). Bottom-up analyses start out "from the bottom" in the sense that the energy systems are, in the models, built up from representations of their basic physical elements, i.e. the energy technologies and energy flows of the system. Due to their focus on technologies, bottom-up models are often described as engineering or techno-economic models.

The model representation of the energy system is often structured as a network of energy technologies and energy commodities, and can include a description of the energy systems all the way from fuel extraction via different types of energy conversion technologies and distribution chains to end-use demands on energy services such as transportation and heating. Depending on the focus of the analysis, different parts of this chain can be described at different levels of detail. While some models focus on the supply side, others focus on end-use technologies while yet others aim to capture the whole chain from mining to end-use energy services with an equally high level of detail. The represented technologies, which can be currently available as well as possible future options, are described by a number of technology-specific characteristics such as conversion efficiency, environmental performance (e.g., emissions per output), capital cost, operation and maintenance costs and lifetime of conversion facilities. In addition, factors such as current technology-specific installed capacities (and age structure of these) as well as potential market and resource constraints are generally important parts of the system characterization.

Bottom-up models can basically be grouped into energy accounting models and optimization models (Lanza and Bosello, 2004), examples include LEAP and MARKAL respectively. The basic difference between these two model types relates to how combinations of technologies are chosen to meet the exogenously set energy demands. For energy accounting models, which often are spreadsheet models, most changes of the system are externally made by the model analyst, i.e. different technology combinations and systems solutions are tested more or less “manually” in a simulating manner. In optimization models, a mathematical algorithm optimizes the system and thereby endogenously chooses the optimal combination of energy technologies under given boundaries, including new investments.

Bottom-up models are often partial equilibrium models, meaning that only the energy sector is represented and that the markets, in terms of the physical demand and supply of energy products and services, within the sector are in equilibrium. Potential feedback effects from the activities in the energy sector on the rest of the economy, and vice versa, as well as effects of market disequilibrium are usually ignored. Demand projections of energy and energy services (heating, lighting, transport, etc.) are to a large extent exogenous and utilized to calculate the required levels of primary energy use, production of intermediate energy carriers, and generation of end-use energy services. End-use demand is often disaggregated into societal sectors such as residential, manufacturing, service and transport. With this said, it should also be mentioned that many bottom-up models represent elastic demand of energy services (generally own-price elasticity), meaning that a cost increase (or decrease) in the provision of a service endogenously lead to a decreased (or increased) demand for that service. This is one way of representing some of the economic feedback loops which often to larger degree are associated with top-down models.

Predominantly, the model optimization is made through cost-minimization and is often based on linear programming, although mixed-integer programming (MIP) and non-linear programming also are utilized. In the case of elastic demand, a maximization of consumers’ and producer’ surpluses are (instead of cost-minimization) generally carried out. Linear programming implies that the objective function to be optimized and the equations constraining the problem are approximated as linear functions. The objective function is generally an expression of the discounted sum of all costs arising in the system during the studied time horizon, while the problem constraints, for instance, can be capacity constraints for energy technologies, emission constraints and resource constraints. In the case of cost-minimization, a model run delivers under the given conditions (e.g., regarding energy prices, emission constraints and other policy measures) the least-cost combination of energy conversion technologies, energy distribution chains and fuel supply systems that meet the given energy demands.

Bottom-up models are normally only concerned with direct, techno-economic capital and operating costs of energy technologies (the financial costs). Due to the partial equilibrium approach, neither indirect costs on the macroeconomic level nor costs associated with market adjustment are generally taken into account (Canes, 2002).

A.1.2 Top-down models

Top-down models seek to give a comprehensive view of the entire economy including the interactions and feedbacks between the energy system and rest of the economy (Lanza and Bosello, 2004). They deal with effects of changing prices on economic activity such as reallocation of resources that influence capital formation and economic growth. The energy-economic relations utilized to model current and future market behavior are based on historical data, which are parameterized by calibration of data from a certain point in time (a base year) or by econometrical estimation from time-series data (Lanza and Bosello, 2004). Top-down models are, however, generally not concerned with choice of specific energy technologies.

Macroeconomic top-down models for medium- and long-term economic projections can be divided in two main types: computational general equilibrium models (CGE) and time-series econometric models (IPCC, 2001). The main characteristic of CGE models is that they have an explicit specification of the behavior of all relevant economic agents in the economy. In the forming of equilibrium in all markets, they often use assumptions on optimizing rationality (such as cost-minimizing behavior by producers, household demands based on optimizing behavior), free market pricing, many firms and suppliers of factors, and perfect competition (IPCC, 2001). In time-series econometric models, the estimation of the parameters used to a higher degree relies on statistical time-series data and past correlations than theoretically founded relations. Thus, results from this kind of model are not only explained by its assumptions but are also to high degree an effect by the quality and coverage data used, which can be extensive (IPCC, 2001). However, econometric models have increasingly added long-run theory and formal econometric methods; several models now include a mixture of features (IPCC, 2001).

In contrast to bottom-up models, top-down models generally apply a high aggregation level regarding energy technologies. The technical energy system (energy technologies and related energy flows) is to a great extent treated as a black box described by transfer functions with elasticities which indicate the propensity to alter the mix of fuels used by the system (Wene, 1996). Energy is, jointly with other production factors (labor, capital, etc.), included in a production function. The interchange between production factors are handled with elasticities of substitution (Jaccard et al., 2003). Changes in prices lead to modified relations between the use of energy and other production factors but the underlying technologies accountable for these changes are not specified. Top-down models can capture indirect macro-economic effects and, in some cases (disequilibrium models), costs associated with market adjustment (Canes, 2002). However, since top-down models primarily are based on historic data influenced by the corresponding technology regime, their ability to capture future market behavior under the introductions of new technologies has been questioned.

A.1.3 Cross-over features

Bottom-up models and top-down models have, as described, differences in focus and structure. They have both their respective strengths and weaknesses. Rivers and Jaccard (2006) suggest three aspects from which the strengths of energy-economy models can be compared in terms of their usefulness for policy makers: technology explicitness, ability to represent market equilibrium, and behavioral realism. According to Rivers and Jaccard (2006), conventional (optimization) bottom-up models score high on technology explicitness, intermediate regarding the equilibrium aspect and low on behavioral realism. Contrary, CGE models score high on the equilibrium aspect, intermediate on behavioral realism, and low on technology explicitness. Lastly, time-series econometric models are claimed to score high on behavioral realism, intermediate on equilibrium, and low on technology explicitness.

The respective advantages of different model types have driven a trend of model development towards an incorporation of bottom-up features in top-down models and vice versa. The possible combinations and variations are many. For instance, CGE models can include “bottom-up” data in the form detailed technology descriptions (e.g., MIT EPPA) and, as mentioned, optimization energy system models frequently include features such as elastic demand. Further, macroeconomic general equilibrium equations can be added to optimization energy systems models (e.g., MARKAL-MACRO). To increase the behavioral realism in technology-oriented (bottom-up) models and to a higher degree simulate decision making based on microeconomic theory (and not only rely on financial cost optimization), some models include intangible/perceived costs and/or relative price dependent distribution functions (e.g., PRIMES, CIMS).

Models that to high degree include features and characteristics associated with different model types are often denoted hybrid models. Another common approach is also linking of models, which basically means that different models are run in conjunction. In this regard, the terms hard- and soft-linking are often used, indicating to what degree the different models are integrated with each other (by integration of model structures and equations, or in a “manual” iterative modeling procedure).

A.2 MODEL CONCEPTS

This section provides short explanations for some important model concepts used in this report (as well as used in the model literature in general).

A.2.1 Static – Dynamic

A model can be either static or dynamic. A static model is time-invariant, it represent a certain point in time, such as a year. Static models cannot change the structure of the model system endogenously and there is no feed-back loops incorporated in the model. In contrast, a dynamic model take time-dependent changes into account, the structure of the model system can change endogenously (e.g., through endogenous investments in new technology capacity) and feed-back loops are often important features of the model.

A.2.2 Perfect foresight – Recursive/Myopic

Many models, in particular bottom-up optimization models, apply so-called perfect foresight. This means that all features of the model, such as future costs of technologies, future emission constraints, availability of fuels, are known at all time steps of the modeled time horizon. The opposite is recursive models, or models applying a limited/myopic foresight, indicating that technology and fuel selection occur for one model year at a time, influenced by previous model years (e.g., in regard to already installed capacities) but “unaware” of future developments of for instance energy prices and technology costs.

A.2.3 Endogenous Technology Learning – Exogenous Technology Learning

A concept of relevance for the dynamics of technological change in energy-economy models is that of technological learning, i.e. how the cost (and/or performance, but usually cost only) of a technology changes and develop in the model. Technology learning can be exogenous or endogenous. In the exogenous case, the change of technology costs are decided as input to the model solely as a function of time (i.e., the model analyst might, e.g., assume that a fuel cell vehicle will decrease 50% in cost in 20 years’ time, i.e. regardless to how the energy system develops under this time). In the endogenous case, the technology costs change as function of how much the technology is invested in, i.e. investments must occur for a technology to become cheaper. This requires a technology-learning rate to be defined exogenously, indicating the relation between additional investments and cost reductions.