

RESEARCH REVIEW

Transport biofuels in global energy–economy modelling – a review of comprehensive energy systems assessment approaches

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The high oil dependence and the growth of energy use in the transport sector have increased the interest in alternative nonfossil fuels as a measure to mitigate climate change and improve energy security. More ambitious energy and environmental targets and larger use of nonfossil energy in the transport sector increase energy–transport interactions and system effects over sector boundaries. 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 and assessments of energy–transport interactions now grow in importance. In recent years, the scientific literature has presented an increasing number of global energy–economy future studies based on systems modelling treating the transport sector as an integral part of the overall 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 studies on transport biofuels in global energy–economy modelling and investigates what future role comprehensive global energy–economy modelling studies portray for transport biofuels in terms of their potential and competitiveness. The results vary widely between the studies, but the resulting transport biofuel market shares are mainly below 40% during the entire time periods analysed. Some of the reviewed studies show higher transport biofuel market shares in the medium (15–30 years) than in the long term (above 30 years), and, in the long-term models, at the end of the modelling horizon, transport biofuels are often substituted by electric and hydrogen cars.

Keywords: comprehensive energy systems assessment approaches, energy–transport interactions, futures, global energy–economy modelling, transport biofuel market shares, transport biofuels, transport sector

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Introduction

The high oil dependence and the growth of energy use in the transport sector have increased interest in alternative transport fuels as a measure to mitigate climate change and improve energy security. Local air pollution is also a driver for 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, for example coal or natural gas.

Biofuels (in this study ‘biofuel’ is used to denote bio-based transport fuels) currently only contribute to a small share of the energy supply to the transport sector;

while the total global final fuel use in the sector is about 100 EJ (OECD/IEA, 2012), the use of biofuels is only about 2.5 EJ. However, several governments and intergovernmental organizations have policy targets aiming at a future increase in biofuel use; for example, 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, 2015).

While the stationary energy sector (e.g., electricity and heat generation) and the transport sector previously to a large extent 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 due to several reasons; competition for biomass resources, which can be used both for biofuel production and/or heat/power production (ultimately due to land scarcity); system interactions due to plants

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coproducing several outputs, such as biofuels, heat and electricity; and electric cars and hydrogen production based on electrolysis affecting the electricity generation system by increasing demand and, possibly, by evening out the load curve and allowing more intermittent generation. Environmental and climate concerns also stress interaction over sector boundaries as both the stationary energy sector and the transport sector give rise to greenhouse gas (GHG) emissions and fill up the common (politically and/or environmentally set) emission quota. As economical resources are limited, a system-wide allocation strategy is imperative.

Methodological approaches in which the parts of the energy and transport system are investigated separately have been, and still are, common in environmental and energy systems planning and future studies. However, as the importance of dynamic interactions over sector boundaries increases, an expanded systems view in which the coevolution of an integrated energy and transport system is analysed increases in importance. In recent years, a growing number of energy–economy future studies based on systems modelling treating the transport sector as an integrated part of the energy system and/or economy have emerged in the scientific literature.

Global energy–economy systems modelling can be an important tool in future studies on how to achieve a more environmentally friendly transport and energy system. With regards to biofuels, the modelling can give significant insights on feasible future market penetration levels.

Thus, important insights regarding the potential future role of 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.

There are several modelling studies applying a system-wide perspective on the future role of biofuels, but synthesis studies in this field are rare. Girod *et al.* (2013) present a modelling analysis on the climate impact of transportation but the presentation of biofuel results is rather limited. In their study, which is not a review but rather a modelling comparison, five global models are run with common global income and population assumptions.

To clarify similarities and differences in approaches and results of modelling studies providing insights on biofuel futures, the present work seeks to review and synthesize studies carried out within this field. Thus, the aim of the study was to determine what future role do comprehensive global energy–economy modelling studies portray for biofuels in terms of their future potential and competitiveness. The specific questions guiding the study are:

- What future utilization levels for biofuels do the studies depict as likely/cost-effective?
- What factors influence differences in results?
- What overall insights can be reached based on the aggregate results of the studies?

This review is based on a systematic selection of studies. The selection criteria are rather restrictive in order to increase chances of drawing valid conclusions based on the selected material. The selection criteria limit the review to scientifically published (in peer-reviewed journals) modelling studies with a global energy system coverage. Only more recent publications (publication after year 2000 and until year 2015) are included. The included studies should also have a comprehensive systems approach treating the transport sector as an integral part of the overall energy system and/or economy. In addition, included studies should be applying a medium-term (15–30 years) to long-term (above 30 years) time horizon. They should further preferably focus on the transport sector or, otherwise, be of relevance from a biofuel perspective (implying that they present biofuel-specific results). These selection criteria have resulted in seventeen studies to be covered by this review (including one, IEA (2008), which not entirely fulfil the selection criteria but which is added since one of the selected studies, Fulton *et al.* (2009), is building upon it and it adds essential material), a sufficiently large number of studies to enable the formation of justifiable general insights.

The studies

The bulk of recently published modelling studies utilizing a global approach and analysing questions related to future use of biofuels are based on bottom-up, optimization energy system modelling. In the models used in these studies, fossil energy resources are generally represented 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 availabilities are generally linked to a model year, that is a maximum potential use of biomass per year is assumed. The models are to different degrees regionalized; while some models see the world as one global region with, for example 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 CO₂ emissions and regional targets for 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. The studies are briefly presented below:

Takeshita & Yamaji (2008) examine the potential role of FT synfuels in competition with other fuel options, and Takeshita (2012) assesses cobenefits of CO₂ reduction and reduction air pollutants from road vehicles. Both are using the REDGEM70 model.

Turton (2006) describes a sustainable automobile transport scenario using the model ECLIPSE. 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.

Azar *et al.* (2003), Grahn *et al.* (2009a,b) and Hedenus *et al.* (2010) use the GET model to study the cost-effectiveness of optimal fuel choices in the transport sector under various assumptions of future developments of carbon policy, carbon capture and storage, and electricity generation technologies.

Gielen *et al.* (2002, 2003) study the optimal use of biomass for GHG emissions reductions using the BEAP model.

Gül *et al.* (2009) utilize a global MARKAL model, denoted the Global Multi-regional MARKAL model (GMM), to analyse long-term prospects of alternative fuels in personal transport, focusing on biofuels and hydrogen. In this study, the bottom-up energy system model is linked to the climate change model MAGICC (in a similar manner as Turton, 2006).

Fulton *et al.* (2009) present transport-related results and modelling 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.

Anandarajah *et al.* (2013) give special focus to the road transport sector (using a version of the TIAM model referred to as TIAM-UCL) and investigate the role of hydrogen and electricity for transport sector decarbonization.

Akashi & Hanaoka (2012) examine the technological feasibility of large cuts in GHG emissions using the AIM/Enduse [Global] model.

Van Ruijven and van Vuuren (2009) explore the energy system impacts of different future hydrocarbon prices, using the global energy model TIMER.

Kitous *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.

Kyle & 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 using the GCAM model and by simulating five different technology scenarios.

Table 1 summarizes the seventeen selected global modelling studies and some of their respective model features. In section 2.1, the models utilized in the selected studies are presented in more detail, and section 2.2 presents the scenarios applied.

Models utilized

The REDGEM70 model (Takeshita & Yamaji, 2008; Takeshita, 2012) is a bottom-up, global energy systems linear optimization model regionally disaggregated into 70 regions. The model has a long-term time horizon from 2000 to 2100. It considers a number of energy conversion technologies as well as carbon capture and storage (CCS) in power generation, oil refinery and production of synthetic fuels. The model includes several technologies for production of alternative transport fuels, for example hydrogen (H₂), methanol (MeOH), dimethyl ether (DME), Fischer Tropsch (FT)-diesel; bioethanol (EtOH) and biodiesel. The comparably high regional disaggregation level enables capturing of trade flows between world regions and associated distribution and infrastructural costs.

The integrated assessment model ECLIPSE incorporates the energy systems model ERIS with macroeconomic and passenger transport demand models and is further linked to the climate model MAGICC (Turton, 2006). The ERIS model is a bottom-up optimization model for studies of the global energy system. It has been developed to include non-CO₂ 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 depends on the level of its deployment.

GET is a bottom-up energy system model based on linear optimization of system cost for the study of long-term development of the global energy system under carbon constraints (Azar *et al.*, 2003; Grahn *et al.*, 2009a,b; Hedenus *et al.*, 2010). It is driven by exogenously given energy demands in four different stationary end-use sectors as well as transportation demands divided into different transport modes. Many published studies using GET focus on cost-effective fuel choices in the transport sector and system-wide effects associated with this. In later applications, the model has been regionalized and the model's heat sector representation has been improved.

The BEAP model (Gielen *et al.*, 2002, 2003) is a further example of a bottom-up optimization (of system cost) global energy systems model. It is based on mixed integer programming, in which the development of the

Table 1 Selected global modelling studies and their related model features. Optimization refers to system cost optimization

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 <i>et al.</i> (2003); Grahn <i>et al.</i> (2009a,b); Hedenus <i>et al.</i> (2010)	GET – 1; 6/10; 1 region(s)*	Optimization, Partial Equilibrium, Perfect Foresight, Bottom-Up	2100
Gielen <i>et al.</i> (2002, 2003)	BEAP – 12 regions	Optimization, Partial Equilibrium, Perfect Foresight, Bottom-Up, Elastic demand	2040
Gül <i>et al.</i> (2009)	GMM (MARKAL) – 6 regions	Optimization, Partial Equilibrium, Perfect Foresight, Bottom-Up, Endogenous Technology Learning	2100
Fulton <i>et al.</i> (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 <i>et al.</i> (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
Kitous <i>et al.</i> (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

*The four different studies apply GET model versions with various regionalizations: 1, 6, 10 and 1 regions, respectively.

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, labour costs and technology availability. Trade of resources, energy carriers, food products and materials between the regions are possible but result 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 (of system cost) type and generally based on linear programming. The Global Multi-regional MARKAL model (GMM) is a global 6-world region MARKAL model (Gül *et al.*, 2009). GMM has a detailed representation of alternative fuel chains. In terms of biofuels, it includes biodiesel, FT-diesel, ethanol, methanol, DME and synthetic natural gas (SNG) derived from biomass. Several hydrogen production routes are represented, including routes based on biomass gasification.

MoMo is a spreadsheet model aimed at estimating and projecting travel indicators, energy consumption, pollutant emissions and GHGs generated for worldwide mobility (Fulton *et al.*, 2009). 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 representing the global energy system (Anandarajah *et al.*, 2013). TIMES (an acronym for The Integrated MARKAL-EFOM System) is an update of the MARKAL modelling framework. The basics of the two modelling frameworks are the same; that is, also TIMES models can be described as bottom-up energy systems models based on system cost optimization. Compared to MARKAL, TIMES includes several enhanced features, for example a more flexible seasonal and diurnal time division.

The AIM/Enduse model framework (Akashi & Hanaoka, 2012), in a similar manner as MARKAL and TIMES, has been utilized combined with different databases and in different studies to analyse national energy systems as well as the global energy system. The global

version of AIM/Enduse model, AIM/Enduse [Global], 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 energy prices and technology costs.

While the above-described models rely largely on optimization in the choice of future fuel and technologies, three of the selected studies apply models of a more simulatory approach and also seek to incorporate other aspects in the technology choices made. These models are presented below.

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 (van Ruijven & van Vuuren, 2009). Here, costs combined with preferences are used in sectoral multinomial logit models in the selection of technologies. The multinomial logit model allocates most of the investments for the technologies with the lowest costs, but if there are other only slightly more costly technologies, a small share of the investment is made into these also (this is in contrast to strict linear programming optimization in which the lowest cost option takes it all if no other constraints apply).

The POLES model can also be described as utilizing a simulating approach. It is a recursive simulation model of the global energy system and has been used in various studies at both national and international levels (Kitous *et al.*, 2010). Integrating a detailed regional, sectorial and technological specification, the POLES model allows assessments of GHG mitigation policies. Explicit technological description is used for secondary fuel 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 behavioural 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 (Kyle & Kim, 2011). The model calculates an equilibrium for energy goods and services, agricultural goods, land and GHG emissions.

Scenarios applied

Many of the global modelling studies apply climate policies with exogenously determined targets for future

atmospheric CO₂ concentration levels. The use of biofuels in the transport sector is contrasted to fossil transport fuels and often also to other potential low-carbon transport options, which generally are based on either hydrogen or electricity. Table 2 summarizes the model input data related to transport sector technology representation and scenario assumptions.

While many of the studies present a number of model scenarios with different input data and assumptions, here we focus on scenarios with stringent climate policies. Most of the studies apply a stabilization target for atmospheric CO₂ concentration, but some studies instead apply an exogenous CO₂ penalty cost. In the latter case, the resulting emissions or CO₂ stabilization level is an output of the model (for comparison purposes, this output has been included in Table 2 within parentheses). The scenarios include climate ambitions from medium (such as 550 ppm CO₂ concentration) to high levels (such as 400 ppm). The assumed biomass potential, that is the maximum amount of biomass that can be used for energy purposes per year in the models, also 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 for how the outcome should be interpreted. Many of the studies treat biofuels in an aggregate way and thus only include a single generic bio-based fuel option: denoted biomass to liquid (BtL), synthetic fuel, methanol or simply 'biofuel'. Other studies include a range of biofuel options. The representation of non-biofuel low-carbon transport fuels as well as vehicle technologies varies between the studies.

Model results

Biofuel utilization

In the presentation of results, summarized in Table 3 and visualized in Figs 1 and 2, four of the 17 studies are excluded: Grahn *et al.* (2009a), Gielen *et al.* (2002), Anandarajah *et al.* (2013) and Kyle & Kim (2011). Gielen *et al.* (2002) was excluded since the model utilized is the same and scenarios similar to Gielen *et al.* (2003), and the biofuels presentation is considerably more extensive in the latter. In Anandarajah *et al.* (2013), it is not possible to identify the biofuel share. Grahn *et al.* (2009a) as well as Kyle & Kim (2011) present clear biofuel results but only for the light-duty vehicle segment and, thus, their results are not directly comparable with the rest. Further, Fulton *et al.* (2009) builds upon IEA (2008) and, thus, only the results from Fulton *et al.* (2009) are presented in Figs 1 and 2.

The resulting biofuel utilization and market shares vary in a wide range. For most model-scenario

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

Reference	Climate policy or target	Max biomass per year	Technology representation road transport		
			Biofuels	Other low-carbon options	Vehicle technologies
Takeshita & Yamaji (2008)	550 ppm	300 EJ (2050); 250 EJ (2100)*	Biodiesel, EtOH, biogas, FT- liq., DME, MeOH, H ₂	H ₂	ICEV, HEV, FCV
Takeshita (2012)	400 ppm	300 EJ (2050); 250 EJ (2100)*	Biodiesel, EtOH, biogas, FT- liq., DME, MeOH, H ₂	H ₂ , Electricity	ICEV, HEV, EV, PHEV, FCV
Turton (2006)	550 ppm	235 EJ (2050); 320 EJ (2100)	H ₂ , alcohol, FT- liq.	H ₂	ICEV, HEV, FCV
Azar <i>et al.</i> (2003)	400 ppm	200 EJ	MeOH, H ₂	H ₂	ICEV, FCV
Grahn <i>et al.</i> (2009a)	450 ppm	205 EJ	BtL, H ₂	H ₂ , Electricity	ICEV, HEV, EV, PHEV, FCV
Grahn <i>et al.</i> (2009b)	450 ppm	205 EJ	BtL, H ₂	H ₂	ICEV, FCV
Hedenus <i>et al.</i> (2010)	400 ppm	200 EJ	Synthetic fuel, H ₂	H ₂ , Electricity	ICEV, HEV, EV, PHEV, FCV
Gielen <i>et al.</i> (2003)	80 \$/tCO ₂ cost (75% GHG red. compared to the 1995 level)	Depends on land prices and on costs for intensification of agriculture calculated by the model [†]	MeOH, FT-gasoline, EtOH	No	ICEV
Gül <i>et al.</i> (2009)	450 ppm	195 EJ	Biodiesel, FT-diesel, EtOH, MeOH, DME, bio-SNG, H ₂	H ₂ , Electricity	ICEV, HEV, EV, PHEV, FCV
Fulton <i>et al.</i> (2009)	450 ppm	Not clear (results = 150 EJ)	Biodiesel, EtOH, BtL (BtL, biodiesel, LC ethanol)	H ₂ Electricity	ICEV, HEV, EV, PHEV, FCV
IEA (2008)					
Anandarajah <i>et al.</i> (2013)	Global mean temp. not rise more than 2 °C	Probably about 100–150 EJ [†]	Biodiesel, EtOH, H ₂	H ₂ Electricity	ICEV, HEV, EV, PHEV, FCV
Akashi & Hanaoka (2012)	Cost incr. from 0 to 600 \$/tCO ₂ in 2000–2050 (50% GHG red. compared to the 1990 level)	364 EJ	'Biofuel'	H ₂ , Electricity	ICEV, HEV, EV, PHEV, FCV
van Ruijven & van Vuuren (2009)	100 \$/tCO ₂ cost (10–45% CO ₂ red. compared to the 1990 level)		'Biofuel'	H ₂	ICEV
Kitous <i>et al.</i> (2010)	400 ppm	200 EJ	'Biofuel', H ₂	H ₂ Electricity	ICEV, HEV, EV, PHEV, FCV
Kyle & Kim (2011)	Cost incr. from 10 to 400 \$/tCO ₂ in 2020–2095 (450 ppm)		BtL, biomass-based gas	H ₂ , Electricity	ICEV, HEV, EV, PHEV, FCV

ICEV, internal combustion engine; HEV, hybrid electric vehicle; FCV, fuel cell vehicle; EV, Electric vehicle (battery-powered); PHEV, plug-in hybrid electric vehicle.

*Supporting info from Takeshita (2009).

†Supporting info from Erb *et al.* (2009).

combinations, the biofuel share stays below 40% and some of the studies show very low levels (0–10%). Studies showing biofuel market shares above 40% rely not

only on 'regular' biofuels but also on hydrogen based on bio-energy with carbon capture and storage (BECCS). Even though market shares for biofuels in

Table 3 Biofuel-related results of global climate policy scenarios*

Reference	Transport and biofuel results for climate policy scenario	Comments and sensitivity
Takeshita & 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. <i>Biofuel share 2050: 10% (transport)</i> <i>Biofuel share 2100: 23% (transport)</i>	High biopotential; 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 are petroleum products (68 EJ), electricity (39 EJ) and a small amount of H ₂ (1 EJ). <i>Biofuel share 2050: 2% (road transport)</i> <i>Biofuel share 2100: 11% (road transport)</i>	High biopotential; 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. <i>Biofuel share 2050: 6% (transport)</i> <i>Biofuel share 2100: 67% (transport)</i>	High biopotential; 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.
Azar <i>et al.</i> (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 biofuels enters the scenario. <i>Biofuel share 2050: 0% (transport)</i> <i>Biofuel share 2100: 0% (transport)</i>	Low biopotential; high CO ₂ reduction. Higher H ₂ -related costs, larger biomass potential or restrictions for bio-industrial heat give 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 <i>et al.</i> (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). <i>Biofuel market share 2050: 9% (transport) - RC</i> <i>Biofuel market share 2100: 4% (transport) - RC</i>	Low biopotential; 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 <i>et al.</i> (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. <i>Biofuel share 2050: 10% (transport)</i> <i>Biofuel share 2100: 14% (transport)</i>	Low biopotential; 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 with other GET model versions (Azar <i>et al.</i> , 2003) and Grahn <i>et al.</i> (2009b), the use of biomass for high temperature industrial heat is restricted.

(continued)

Table 3 (continued)

Reference	Transport and biofuel results for climate policy scenario	Comments and sensitivity
Gielen <i>et al.</i> (2003)†	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) are used in the transport sector. <i>Biofuel share 2020: 35% (road transport)</i> <i>(Biofuel share 2050: 70% (road transport))</i>	High biopotential; high CO ₂ reduction. Majority of the biomass used is allocated for the production of transport 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).
Gül <i>et al.</i> (2009)‡	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. Favoured 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. <i>Biofuel share 2050: 25% (of vehicle km in personal road transport)</i> <i>Biofuel share 2100: 7% (of vehicle km in personal road transport)</i>	Low biopotential; 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 (non-bio) renewables 400 EJ.
Fulton <i>et al.</i> (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. <i>Biofuel share 2050: 26% (transport)</i>	Low biopotential; 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.
Anandarajah <i>et al.</i> (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. <i>Biofuel share: not clear (but low)</i>	Low biopotential; 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).
Akashi & 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). <i>Biofuel share 2050: 45% (transport)</i>	High biopotential; 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. <i>Biofuel share 2050: 23–27% (transport)</i>	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.

(continued)

Table 3 (continued)

Reference	Transport and biofuel results for climate policy scenario	Comments and sensitivity
Kitous <i>et al.</i> (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. <i>Biofuel share: not clear (but low)</i>	Low biopotential; 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.
Kyle & 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. <i>Biofuel share 2050: <10% (LDV transport)</i> <i>Biofuel share 2095: <10% (LDV transport)</i>	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.

Biofuel shares are shown in italics.

*High, medium and low biomass potentials refer to >300, 250–300 and <250 EJ annually, respectively. High, medium and low CO₂ reduction refer to CO₂ atmospheric concentration stabilization levels of 450 ppm or less, 500–550 ppm and above 550 ppm, respectively.

†Supporting info from Grahn *et al.* (2007).

‡Supporting info from Gül *et al.* (2009).

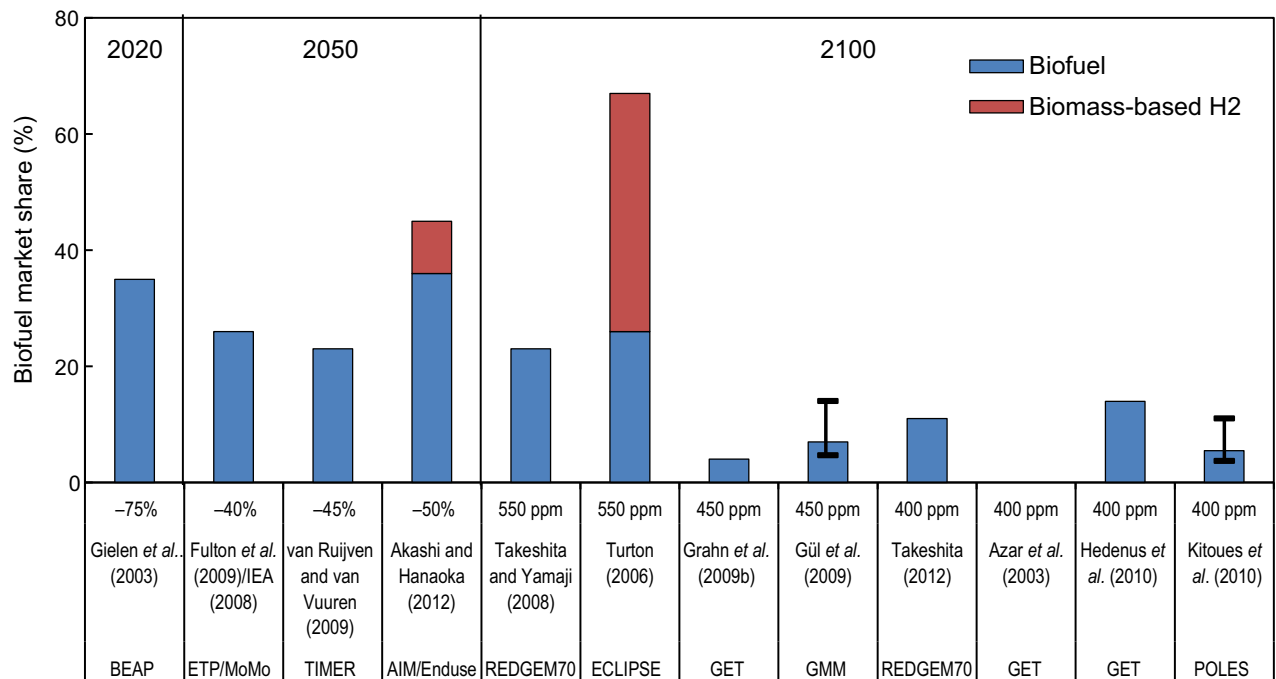


Fig. 1 Biofuel market shares at the model end-year for the thirteen comparable reviewed global studies. The presented shares for Gül *et al.* (2009) and Kitous *et al.* (2010) have been calculated assuming a total final transport energy use of 200 EJ, and the uncertainty bars correspond to 100–300 EJ of total final energy (due to lack of directly comparable data in the articles).

most of the scenarios stay at low–medium levels (0–40%), many of the scenarios show a significant increase in biofuel use in absolute terms compared with 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 biofuel use compared with

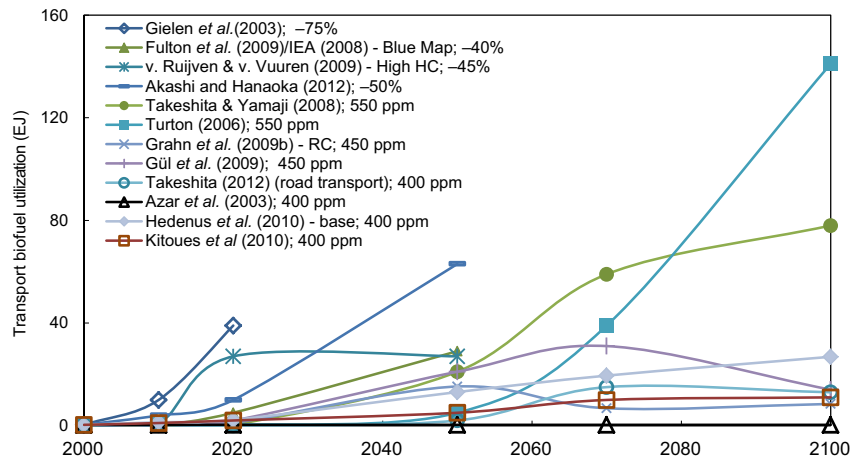


Fig. 2 Development of biofuel utilization over the modelled time horizons for each of the thirteen studies. After the reference, the end-year CO₂ atmospheric concentration constraint is provided.

today's level but show, at the same time, that biofuels tend to not 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 & Yamaji (2008) and Takeshita (2012) highlight FT liquids (synthetic diesel, gasoline and kerosene) as an advantageous alternative, partly due to its potential to fuel the aviation sector. Akashi & Hanaoka (2012) and Turton (2006) point out bio-hydrogen combined with BECCS and Turton (2006) also favour bio-alcohol over FT liquids. Fulton *et al.* (2009) mention ethanol as well as FT liquids.

Factors influencing the biofuel utilization

From comparing the scenario results of the different studies, factors of importance for the global biofuel utilization can be identified. These include the assumed biomass potential, the assumed climate ambition and the model technology representation for the transport sector as well as for the stationary energy system.

The future potential availability of biomass for energy purposes depends on competition for land and water including land use and biodiversity issues, food demand as well as agricultural productivity, which all are linked to large uncertainties. The reviewed global modelling studies show significant differences in regard to assumed biomass potentials. For example, Akashi & Hanaoka (2012) and Turton (2006), at the end of their modelled time horizons, assume biomass potentials of 364 EJ and 320 EJ, respectively, while Grahn *et al.* (2009b) and Kitoues *et al.* (2010) assume levels around 200 EJ. This could be one reason explaining that the former present a widespread use of biofuels in their

results, while the latter show significantly lower shares of biofuels.

Several of the studies also highlight biomass availability as a central constraint for the utilization of 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 testing robustness show that an increased biomass supply potential generally also increases the deployment of biofuels under stringent climate scenarios (e.g., Azar *et al.*, 2003; Grahn *et al.*, 2009a,b) although there are exceptions (Anandarahaj *et al.*, 2013).

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 biofuels and, in particular, optimism with regard to the development of hydrogen FCVs and/or electric vehicles does reduce the competitiveness of biofuels. As the models generally apply a long time horizon and often assume decreasing costs for new technologies over time, this is particularly true towards the end of the studied time horizons.

Turton (2006) and Akashi & Hanaoka (2012) are among the studies obtaining the highest biofuel utilization (together with Takeshita & Yamaji (2008)). As shown in Fig. 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 relevance for the competitiveness of biomass-based hydrogen production compared with non-biomass-based options.

Not only is the representation of technology options in the transport sector of significance for the resulting biofuel utilization, but also the technology representation of the stationary energy system. The availability of future low-cost, non-biomass-based low-carbon electricity generation can be significantly contributing to a high biofuel use, as this lowers the demand for biomass in the stationary energy system. In particular, this can be seen in scenarios allowing a high use of nuclear power generation and/or electricity generation based on CCS (the two low-carbon electricity generation options with a high potential and lowest cost in the reviewed studies). Assumptions regarding these technologies and their future deployment differ widely partly due to political and public acceptance issues.

Another aspect of technology representation in the stationary energy system of importance for the resulting biofuel utilization is to what degree biomass can supply industrial process heat demands. When Hedenus *et al.* (2010) increase the level of detail in regard to representation of process heat demand and introduce limitations for the amount of biomass allowed in the GET model, this results in higher biofuel utilization than in other GET modelling studies. Similar limitations may be of significance also in other models.

The impact of the assumed climate objectives on the biofuel utilization is not entirely straightforward. Generally, no-policy scenarios show a low use of bioenergy in general and biofuels in particular due to the availability of cheaper energy sources, such as coal.

With increasing climate ambitions and thus higher CO₂ emission penalties, bioenergy increases in competitiveness compared with fossil fuel options. For 'medium' climate ambitions (e.g., 550 ppm), a certain amount of 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 biofuel usage tends to peak at medium CO₂ reduction targets. While fossil-based transport fuels are likely to dominate at less ambitious reduction targets, more stringent targets increase the cost-effective biofuel usage, but with CO₂ reduction targets in line with a 450-ppm atmospheric CO₂ concentration stabilization or 2-degree maximum temperature increase, the models tend to choose other low-carbon options for the transport sector (hydrogen and/or electricity) and biomass resources are instead allocated to heat and power production in the stationary energy system. There is also a time aspect to this as, in order to meet CO₂ stabilization targets at the end of the century, emission reductions get more stringent over time. This suggests that biofuels could be seen as a bridging technology to other low-

carbon options such as hydrogen and/or electricity (Gül *et al.*, 2009).

As already indicated in the above sections, time-related aspects can influence the biofuel utilization. Studies applying a shorter time horizon often obtain higher biofuel utilization than studies applying a longer time horizon (see Figs 1 and 2). This is mainly due to assumptions of development (cost reductions and improvements in technical performance) of new alternative technologies over time.

Finally, we are presenting outcomes of the comparison and analysis of the reviewed modelling studies stressing the quantitative conclusions and with a particular emphasis on the importance of the above-discussed critical factors and assumptions. These outcomes may be summarized in the following six points:

- Only studies assuming high biomass potentials (an annual maximum potential of at least 300 EJ) result in biofuel market shares of 35% or more.
- Five of the six studies assuming low biomass potentials (250 EJ or less) result in low (below 10%) biofuel market shares.
- Only studies resulting in a considerable bio-based H₂ deployment also result in high (at least 40%) biofuel market shares.
- All long-term (end-year around 2100) studies assuming large GHG reduction (atmospheric CO₂ concentration stabilization of 450 ppm CO₂ or less) result in low (below 10%) biofuel market shares.
- Three of the eight long-term (end-year around 2100) studies show that the amount of biofuel utilization passes through a maximum and then decreases towards the end of the modelling period.
- Of the eight long-term (end-year around 2100) modelling studies, the two studies with the lowest climate policy ambition (atmospheric CO₂ concentration stabilization of 550 ppm CO₂) show the highest and most strongly increasing biofuel utilization.

Discussion

The presented review provides insights into levels and characteristics of biofuel futures and on factors influencing biofuel deployment. It demonstrates that energy-economy modelling studies portray a diverse picture in regard to future biofuel utilization with shares in most cases ranging from low levels to medium levels (up to about 40%) at the end of the modelled time horizon.

Not all studies are explicit about the type of chosen biofuel but some trends emerge. Generally, liquid wood-based second-generation biofuels and, more specifically, FT liquids are options highlighted in

several of the studies. The possibility of using existing infrastructure and vehicles is, in these cases, probably of high significance, but also the combined production based on the FT process of jet fuels (for the aviation sector) and synthetic diesel/gasoline (for the road transport sector) is pointed out as valuable.

A number of factors influencing the resulting biofuel utilization in the modelling results have been identified. These are mainly climate ambition/policies, the technology representation in the transport sector as well as in the stationary energy sector and the assumed biomass potential. As 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, CO₂ reduction requirements and energy prices).

The *climate ambition/policy* (the level of GHG reduction constraints or emission cost penalties) is relevant for how much of the available biomass is used. With higher climate ambition, the proportion of the total biomass potential that is used increases.

The *technology representation*, that is what technologies that are available in the model, to what relative costs and to what potential, determines the allocation of biomass. The relative cost of alternative technologies is complex and varies with scarcity rents and CO₂ penalties, which, in turn, are functions of the climate ambition. This relates to biofuels in relation to other technologies in the transport sector as well as in the stationary energy system, but also between different biofuel options. For example, favourable assumptions regarding 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 biofuel production. On the contrary, a high (allowed) potential and low costs for hydrogen or electricity-based transportation will decrease the competitiveness of biofuels. A high total *biomass supply 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.

The resulting biofuel utilization depends on several factors and there are considerable differences between the studies. Differences are in many cases due to quantitative assumptions regarding more or less uncertain input data. While this highlights challenges with quantitative long-term future modelling of energy-economic systems, it also demonstrates a strong relevance of the same: without making quantitative statements regarding parameters such as biomass potentials, system-wide CO₂ reduction objectives and cost of alternative technologies, not much can be said about the effective

future contribution of biofuels from an overall systems perspective.

In this review of future studies based on global energy systems modelling, we find that the future market penetration of biofuels range from low (0–10%) to high levels (above 40%) 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 policies. The total biofuel market share exceeds 40% only in studies resulting in large-scale deployment of bio-based hydrogen.

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 biofuels tend to not dominate the transport sector at the end of the modelled time horizons, compared with today's level, many model studies show a significant increase in biofuel use. Besides biofuels, the development and deployment of energy-efficient vehicle technologies, such as hybrids and fuel cell vehicles (in the longer term), are essential in many of the future transport scenarios.

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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, 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 BA (2003) Global energy scenarios meeting stringent CO₂ constraints— cost-effective fuel choices in the transportation sector. *Energy Policy*, **31**, 961–976.
- 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.
- EC (European Commission) (2015) Directive (EU) 2015/1513 of the European Parliament and of the Council of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources.
- Erb K-H, Haberl H, Krausmann F *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.
- 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.
- Girod B, van Vuuren DP, Grahn M, Kitous A, Kim SH, Kyle P (2013) Climate impact of transportation A model comparison. *Climatic Change*, **118**, 595–608.
- 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, Willander MI, Anderson JE, Mueller SA, Wallington TJ (2009a) Fuel and vehicle technology choices for passenger vehicles in achieving stringent CO₂ 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 CO₂ emission reduction scenarios with global versus regional carbon caps. *Biomass and Bioenergy*, **33**, 360–371.
- 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. Available at: <http://www.iea.org> (accessed 15 May 2016).
- 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.
- Kyle P, Kim SH (2011) Long-term implications of alternative light-duty vehicle technologies for global greenhouse gas emissions and primary energy demands. *Energy Policy*, **39**, 3012–3024.
- OECD/IEA (2012) *World Energy Outlook 2012*, OECD/IEA, Paris.
- van Ruijven B, van Vuuren DP (2009) Oil and natural gas prices and greenhouse gas emission mitigation. *Energy Policy*, **37**, 4797–4808.
- 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 CO₂ 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 and Social Change*, **73**, 607–629.