Systems perspectives on alternative future transportation fuels

A literature review of systems studies and scenarios, challenges and possibilities for bioenergy, production of biofuels and use of alternative transportation fuels

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2015-03-31

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THE SWEDISH KNOWLEDGE CENTRE FOR RENEWABLE TRANSPORTATION FUELS

Report within project "A pre-study to prepare for interdisciplinary research on future alternative transportation fuels", financed by The Swedish Energy Agency.

Summary

This report is part of a synthesis project trying to identify knowledge gaps and research needs in the area of renewable transportation fuels with focus on the overall system from well to wheel. The focus of this report is to present the state of the art for systems aspects during fuel production (well-to-tank), highlighting the questions that still need further investigation in order to allow for a better holistic approach when planning for the future alternatives among renewable transportation fuel solutions.

Research topics within the biofuel value chain from a systems perspective are presented and discussed, and a number of international studies addressing the whole chain from well to wheel are outlined and compared.

Based on that analysis the authors attempt to identify research needs within the different areas of biofuel systems analysis for four different categories of biofuels:

- **currently available biofuel options**
  such as ethanol, FAME, HVO, biogas etc.
- **conventional (large-scale) biofuel options under development**
  such as FT-Diesel, methanol, DME, SNG etc.
- **non-conventional biofuel options under development**
  such as butanol, furans, etc.
- **future biofuel options that are not yet discussed at large scale or even not yet identified**
  such as algae-based fuels or electrofuels (e.g., power-to-gas).

An attempt to qualitatively represent the research needs (indicated by the number of question marks) as well as research already performed (darker shading of green indicating a higher level of research efforts to date) is made using the following matrix:

? research need	Feedstock potential	Conversion process to biofuel	Sustainability: Economic	Sustainability: Environmental	Sustainability: Societal	Distribution infra-structure
Currently available biofuel options	??	?	?	??	???	?
Conventional biofuel options under development	??	??	??	??	???	??
Non-conventional biofuel options under development	??	??	??	??	???	???
Future biofuel options	??	???	???	???	???	???

Considering for example the feedstock potential for current biofuels, a lot of research has been conducted to date. However, there still resides considerable uncertainty in the estimates and research efforts are needed to address and reduce this uncertainty. Even for emerging biofuels the feedstock situation is quite well investigated while for future biofuels – e.g. based on algae – the feedstock potential is less well defined. For all biofuel categories however, a certain level of research is still needed to improve estimates of the biomass potential.

More specifically, the authors identified research needs in the following key areas:

- multi-objective optimization accounting for parameter uncertainties to identify robust pathways for the future.
- studies accounting for regional differences and opportunities/risks for both feedstock growth and harvest as well as production processes (e.g. integration to existing industry infrastructure).
- interactions between biofuel production processes and the stationary energy sector, again including regional differences; in particular electrofuels are of interest in this regard.
- continuous update of systems studies with most recent developments in production process development.
- better understanding of land use change effects and feedback loops to facilitate decision making for avoiding pathways with negative effects with respect to greenhouse gas emissions and environmental performance from a systems perspective.
- social factors – even though not being quantifiable at the same level as economic and environmental ones – need to be included for both fossil and renewable fuels as an additional measure for decision making; work is even needed for developing methods better taking into account social factors.

Finally, the systems analysis of biofuel production processes could be extended to a higher level tackling question on how to realize the theoretical potentials of biofuels without interfering with other interests. In particular interference with food production needs to be studied in more detail to avoid negative lock-in situations. There is room for increasing bioenergy and biofuel production and at the same time reducing impact on agricultural markets and food production by prioritizing a diversification of production technologies as well as types of biofuels and identifying different future options. This in turn requires regional optimization of land use and adapted sustainability policies that are supported by intergovernmental rules and policies. Possible measures for avoiding competition with the food sector could be the intensification of food production, using fallow land for biofuel production, or reducing losses in food chain. All these options are interlinked and their effects need to be studied with a holistic approach.

Sammanfattning

Denna rapport är en del av en förstudie som syftar på att identifiera kunskapsluckor och forskningsbehov inom området förnyelsebara drivmedel med fokus på hela systemet från källa till hjul. Fokus i denna rapport ligger på att presentera och diskutera forskningsläget inom bränsleproduktion från källa till tank (well-to-tank), samt att identifiera de områden med fortsatt forskningsbehov. Syfte med hela förstudien är att förmedla en bättre helhetssyn vid planering av forskning för framtida förnyelsebara drivmedel.

I denna rapport presenteras och analyseras de olika aspekter inom systemforskning för biodrivmedelsproduktion, och ett antal internationella studier som behandlar hela kedjan från källa till hjul sammanställs och analyseras mot varandra.

Utifrån denna analys försöker författarna av denna rapport identifiera forskningsbehov inom de olika områdena för systemforskning för biodrivmedelsproduktion, grovt indelade i följande fyra bränslekategorier:

- **dagens storskaliga biodrivmedel**
  såsom etanol, FAME, HVO, biogas osv.
- **konventionella (storskaliga) biodrivmedel under utveckling**
  såsom FT-Diesel, metanol, DME, SNG osv.
- **icke-konventionella biodrivmedel under utveckling**
  såsom butanol, furaner, osv.
- **framtida biodrivmedel som inte diskuteras (för storskalig produktion) eller som inte ens identifierats**
  såsom t.ex. algbaserade drivmedel eller elektrobränslen (tex power-to-gas).

Ett försök att – på ett kvalitativt sätt – visualisera forskningsbehoven (antal frågetecken) samt redan genomförda forskningsinsatser (mörkare nyans av grön indikerar att större forskningsinsatser redan har gjorts i dagsläget) görs med följande matris:

? forsknings-behov	Råvaru-potential	Omvand-lings-processer	Hållbarhet: Ekonomi	Hållbarhet: Miljö	Hållbarhet: Samhälle	Infra-struktur för distribution
Dagens biodrivmedel	??	?	?	??	???	?
Konventionella drivmedel under utveckling	??	??	??	??	???	??
Icke-konventionella drivmedel under utveckling	??	??	??	??	???	???
Potentiella framtida biodrivmedel	??	???	???	???	???	???

Råvarupotentialen för dagens biodrivmedel, till exempel, har undersökts med ett flertal studier i dagsläget, varav den mörkgröna fyllningen. Det kvarstår dock en betydande osäkerhet och författarna anser att det fortfarande finns behov av forskning för att minska den. Detta gäller på samma sätt för de nya drivmedlen samt de som ligger ännu längre fram i tiden.

Mer specifikt, så har författarna identifierat kunskapsluckor och forskningsbehov inom följande nyckelområden:

- Flermålsoptimering som tar hänsyn till osäkerheterna i de olika modellparametrar med huvudsyftet att identifiera robusta utvecklingsvägar inför en osäker framtid.
- Studier som fångar upp de regionala skillnader knutna till möjligheter / risker angående såväl odling och skörd av råvaran såsom produktionsprocesser (t.ex. integrering till befintlig industriell infrastruktur).
- Samspel mellan produktionsprocesser för biodrivmedel och den stationära energisektorn, (återigen inklusive aspekter av regionala skillnader); särskilt elektrobränslen är av intresse i detta avseende.
- Kontinuerlig uppdatering av systemstudier med den senaste utvecklingen inom produktion processutveckling
- Bättre förståelse av effekterna från förändrad markanvändning och återkopplingar för att skapa bättre underlag för beslutsfattare och för att undvika inriktning mot lösningar som bara ger marginella eller rentav negativa effekter med avseende på miljöprestandan ur ett systemperspektiv.
- Sociala aspekter - även om de inte är kvantifierbar på samma nivå som ekonomiska och miljömässiga – så borde de vägas in i större utsträckning i processen för beslutsfattande och policyutvecklingen (gäller både för förnyelsebara och fossila drivmedel); det behövs även fortsatt utveckling av metoder för att ta hänsyn till sociala aspekter.

Slutligen, så borde systemanalys av processer för biodrivmedlen även lyftas till en högre nivå där man adresserar frågan om hur man kan förverkliga den teoretiska potentialen för biobränslen utan konflikt med andra intressen. I synnerhet konkurrens med livsmedelsproduktion behöver studeras mer i detalj för att undvika negativa lock-in situationer. Det finns utrymme för att öka bioenergi- och biodrivmedelsproduktion utan negativ påverkan på jordbrukssektorn genom att prioritera en diversifiering av produktionsteknik och av typer av biodrivmedlen som produceras. Detta kräver i sin tur en regional optimering av markanvändning och en anpassad hållbarhetspolitik som stöds av internationella regler och styrmedel. Möjliga åtgärder för att undvika konkurrens med livsmedelssektorn kan t.ex. vara intensifieringen av livsmedelsproduktionen, minskning av matsvinnet, eller användning av outnyttjad mark samt mark som används för foderproduktion. Alla dessa åtgärder påverkar dock varandra och deras effekter behöver studeras med helhetssyn.

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Background

This report is part of a synthesis project trying to identify knowledge gaps and research needs in the area of renewable transportation fuels with focus on the overall fuel system from well to wheel. Focus in this report is to present the state of the art for systems aspects during fuel production (well-to-tank), highlighting the questions that still need further investigation in order to allow for a better holistic approach when planning for future alternatives among renewable transportation fuel options. This refers in particular to so-called tailor-made fuels that can explicitly be synthesized for specific engine applications and that have to be analyzed taking into account their potential production pathways in order to avoid sub-optimality from an overall systems perspective.

Major input to the report originates from studies conducted within the framework of the Swedish Knowledge Centre for Renewable Transportation Fuels f3. These studies in turn cover a broad range of international research knowledge. Additionally, a literature search on academic systems studies for biofuel value chains has been conducted and finally a number of recent reports on biofuel well-to-wheel analysis are presented and discussed.

The biofuel value chain in a systems perspective

Systems analysis of biofuel production basically covers the whole chain from biomass resource extraction via processing and distribution to end-use. The latter aspect is not covered in the scope of this report but only the so-called well-to-tank aspects, as illustrated in Figure 1, are presented and discussed.

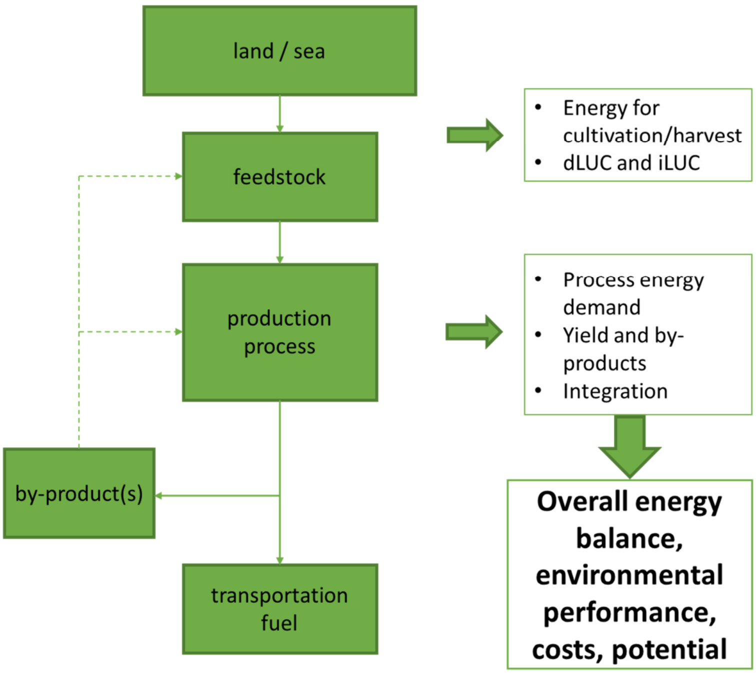


Figure 1: Major steps accounted for in biofuel production systems analysis (adapted from Börjesson et al. (2013)). Acronyms used are dLUC = direct land use change and iLUC= indirect land use change.

Biofuel feedstock can basically be grouped into four major types (Börjesson *et al*. 2013):

- *sugar-based feedstock*, e.g. sugar cane or sugar beet
- *starch-based feedstock*, e.g. corn, wheat and other cereals
- *oil-based feedstock*, e.g. rape seed, palm oil, tall oil from pulping industry, animal fats from e.g. slaughtering
- *lignocellulosic feedstock*, e.g. wood, forest residues, straw, or bagasse.

Algae are another potential feedstock for biofuels with large potential from a long term perspective. With different algae species being built up of different material, a classification according to the above criteria is difficult. However, algae may e.g., be rich of organic carbon which is a good base for anaerobic digestion into biogas or rich of lipids which make them similar to oil-based feedstock. Figure 2 illustrates another way of classification that has been adopted by the European Biofuels Technology Platform (EBTP), also covering waste streams.

Dedicated Crops	**Wastes and Residues**
Sugar Crops Starch Crops Oil Crops Lignocellulosic Crops Algae and Aquatic Biomass	Oil-based Residues Lignocellulosic Residues Organic Residues and others Waste gases

Figure 2: Biofuel feedstock alternatives (taken form EBTP webpage (EBTP 2014)).

The major components in a feedstock basically determine the type of processing that is most adequate for biofuel production. Three major process platforms for biofuel processing exist:

- *thermochemical conversion*, basically biomass gasification, in particular suitable for lignocellulosic material,
- *biochemical conversion* processes (e.g. fermentation, anaerobic digestion) mainly applied to sugar- and starch-based feedstock and
- *hydrogenation/esterification* processes for conversion of oil-based materials, such as vegetable oils or animal fats, to fuels (mainly FAME and HVO).

While being far from a complete mapping of all imaginable processing pathways, Figure 3 illustrates the complexity and variety of major process chains currently discussed. In addition to the represented biofuel products there are a number of other options under development (e.g. biofurans such as dimethyl furan (DMF)). Furthermore, a number of fuel additives are currently produced at industrial scale based on fossil feedstock, but could be replaced by renewables. Examples are ethyl tert-butyl ether (ETBE) and methyl tert-butyl ether (MTBE), both being produced in an additional synthesis step from ethanol or methanol, respectively. A number of biofuels are considered as standalone fuel whereas other alternatives are used as blends or additives to gasoline or diesel (e.g. ETBE and MTBE). An emerging research area is investigating tailor-made fuels that specifically are designed to comply with certain criteria for optimum combustion performance in a specific engine concept. These types of fuels might either have a considerably different production pathway from the above mentioned biofuels.

However, among the many alternatives for tailor-made fuels, most can be built using and extending the common pathways presented above.

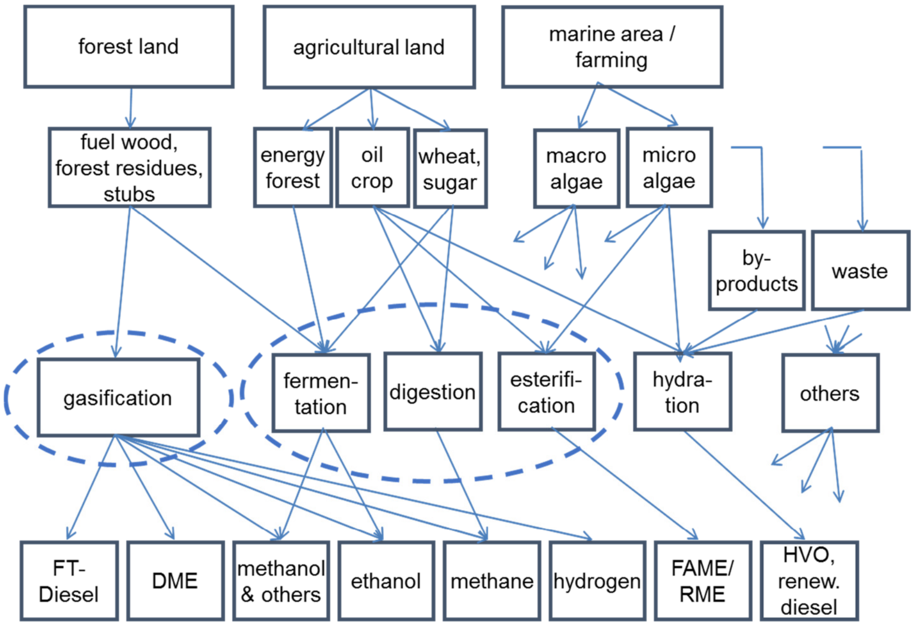


Figure 3: Major production pathways for currently discussed biofuel alternatives (adapted from Börjesson et al. (2013)).

Research on biofuel systems covers sustainability aspects in the supply chain from biomass cultivation, harvesting and transport via conversion processes to distribution and end use. A recent review on the assessment and optimization of biofuel supply chains from forest biomass with respect to these three aspects identifies a "need for further development of decision support tools that consider economic, environmental and social criteria to aid the design and planning of forest biomass supply chains" (Cambero & Sowlati 2014). The study also points out that a field of research recently gaining large attention is the combination of life cycle assessment (LCA) with multi-objective optimization techniques. This allows covering several aspects and handling (potentially) competing objectives such as for example economic and environmental performance. Both LCA and social aspects however are stated to be more difficult to quantify and therefore rather serve as supportive tool for decision makers than for precise ranking among different process alternatives. Optimization approaches for the biofuel value-chain are also reviewed by Yue *et al.* (2014), pinpointing the key challenges and opportunities as well as "identifying fertile avenues for future research" (Yue *et al*. 2014).

In the following paragraphs the major aspects for the biofuel production value chain from biomass to fuel are presented and the state of knowledge in research presented. Both general aspects in systems analysis as well as specific issues related to the sustainability approach are addressed.

Important general aspects in biofuel systems analysis

Sustainability criteria

Sustainability is a concept with numerous aspects and existing studies basically address the three major dimensions:

- (Techno-)Economic

- Environmental and
- Social

In order to evaluate biofuels different parameters that cover all or some of the above mentioned dimensions have to be set. Börjesson *et al* (2013) list e.g. four major parameters:
- Energy efficiency
- Greenhouse gas performance
- Land use efficiency
- Economic performance

Obviously, on a general level, these indicators can be defined in numerous ways with considerable differences for example between studies having a life cycle assessment (LCA) perspective and studies focusing on industrial systems analysis, according to Börjesson *et al.* (2013). The definition of the systems boundaries can, in addition, have a large impact on the actual value of the different criteria. Thus, a very important aspect for enabling a transparent comparison between different studies is the proper definition of systems boundaries and how cogenerated by-products are valued.

Systems definition

For biofuels, studies generally adopt a well-to-tank perspective accounting for the process chain from biomass growth and harvest to final biofuel product. In LCA studies focus is often on the feedstock provision aspects with associated emissions and energy demand (see e.g. Figure 1), whereas industrial systems analysis-inspired studies mainly focus on the biofuel conversion process performance. Depending on the kind of feedstock and the conversion process in question, however, both can be of importance for the overall systems performance. Even within LCA methodology there are different systems perspectives and definitions used. For example, there is an important difference between the ISO standard for life cycle assessment (ISO 14044) and the Renewable Energy Directive (RED) with respect to how to account for by-products. As illustrated in

Figure 4, the ISO standard recommends system expansion assuming a by-product to replace a given product with, for example, the GHG and energy benefits being allocated to the main product investigated. In contrast, according to RED, the GHG footprint and energy balance performance are distributed among the different products generated, based on their respective energy content.

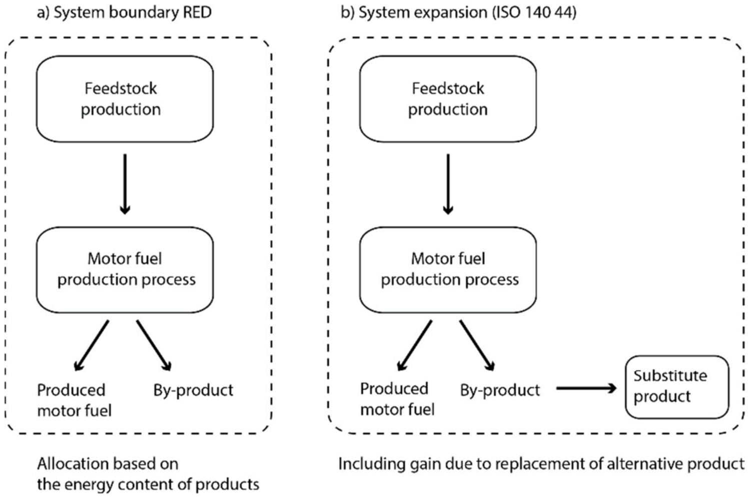


Figure 4: Different allocation principles for RED and ISO standard.

For the example of energy efficiency, Figure 5 illustrates three alternative ways of accounting for co-generated products and services, from an industrial systems analysis perspective. Alternative *a)* only considers the biofuel yield from feedstock, whereas in *b)* also the electricity balance is accounted for. Usually, biofuel production processes are electricity consumers but integrating for example a steam power cycle for making use of available process heat may turn the process to a net electricity generator. Finally, alternative *c)* accounts for generated by-products and heat as well.

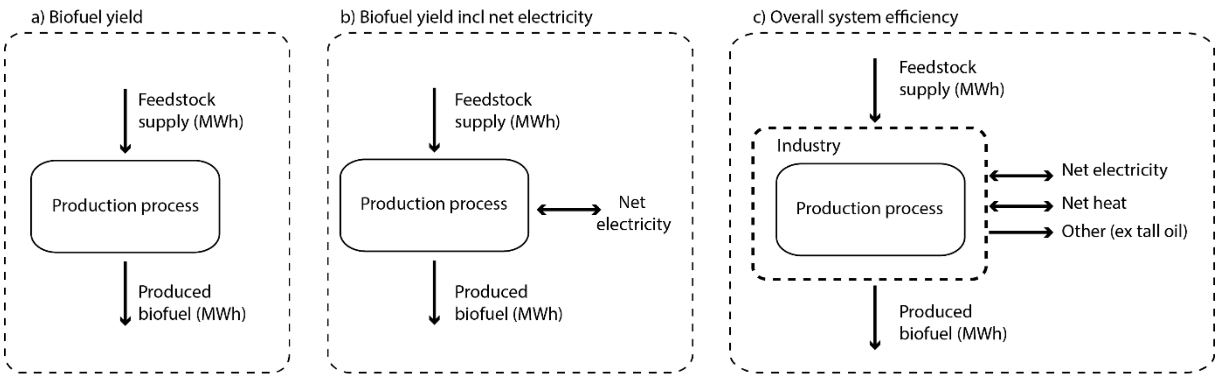


Figure 5: Energy efficiency definition alternatives in systems analysis.

When accounting for by-products in energy systems analysis the reference services assumed for the background energy systems can influence the performance to quite some extent. In general, it is very difficult to compare results from different studies as there is no single preferred way to define the systems boundaries and set the value of by-products and services. A clear definition of the assumptions made is crucial for making sure the results can be recalculated to some other basis.

For energy systems modelling, in particular the interaction of the transport sector with the stationary energy sector is of growing importance. In a review on energy-economy modelling of the biofuel value chain, Börjesson, Grahn *et al.* (2013) state that increased effects across systems boundaries make it necessary to consider the two systems interlinked to a large degree. Examples on such aspects are for example resource competition (increased demand for biomass from both transport and stationary sector), cogeneration of heat and power (as illustrated in Figure 5), electric cars, or advanced biofuel process concepts used as energy storage for excess electricity from renewables (e.g. a power-to-gas concept (Mohseni 2012; Specht *et al*. 2010)).

Feedback loops

When modelling and analyzing large systems, a compromise that has to be made is limiting the model complexity without losing too much in accuracy. One aspect that is difficult to analyze and rarely accounted for in models is feedback loops (as illustrated in Figure 6) for the human-induced climate change. Feedback loops can appear both in economic and environmental systems and either dampen or amplify an initial effect. According to Börjesson *et al.* (2013) there are hardly any studies including these aspects in relation to biomass for biofuels. This is both due to the fact that feedback loops are complex to implement into models, and that feedback loops are not yet completely understood.

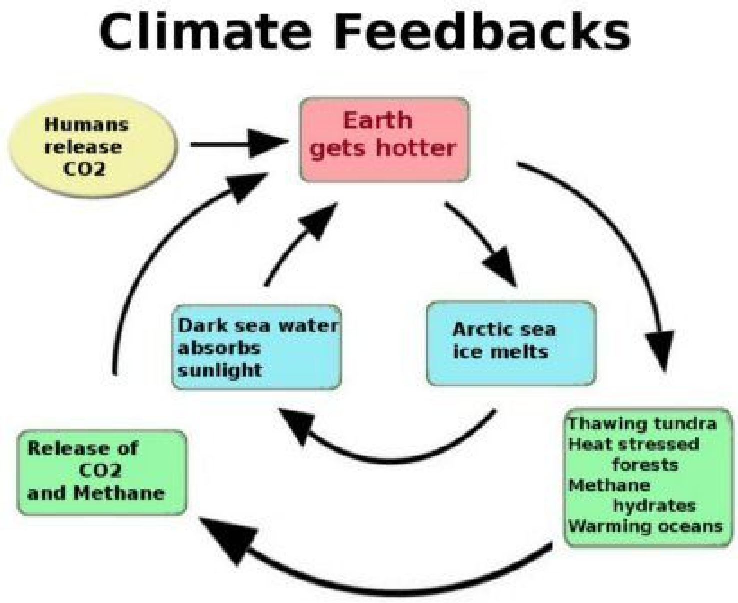


Figure 6: Climate change feedback loop illustration (www.climatevictory.org/feedbacks.html).

General modeling vs specific locations

Systems studies often use general assumptions on the energy systems for analyzing effects such as cogenerated by-products or services. For a given process however, energy, economic and environmental performance of a given process pathway may considerably improve when integrated into a matching infrastructure. Benefits might be the mutual exchange of both material and energy streams reducing costs and carbon footprint. A recent study (Wetterlund *et al*. 2013) applying the BeWhere model (Leduc 2009; IIASA 2014) to Sweden investigates the opportunities and costs for biofuel production, mapping all opportunities for co-location of plants to existing industry infrastructure. Large reductions in e.g. investment costs are demonstrated for suitable matches between biofuel process and host industry (Wetterlund *et al*. 2013).

Deterministic models vs. stochastic models – how to keep track of uncertainties

In a review on optimizing the biomass energy value chain, Shabani *et al.* (2013) conclude that deterministic models[1] are an important tool for identifying optimum value chains. They should not only include economic but also environmental and social impact factors in a multi-objective framework. Even though the latter impacts are not quantitative as economic parameters they provide important information for decision makers. However, according to Shabani *et al.* (2013) stochastic models and sensitivity analysis are even more important tools as biovalue chains intrinsically incorporate parameters that cannot be exactly determined and may change with time. These parameters include wood quality & supply, market situation, prices, and yields, among others. Including the uncertainties associated to the different parameters in stochastic models is deemed to add considerable value to the analysis. Even investigating correlation between uncertain parameters is concluded to be a topic of interest by Shabani *et al*. (2013).

Time horizon and time perspective

Another important general aspect is the time horizon of a given study, i.e., whether the study investigates current or future systems. Implications on assumptions within biofuel value chains are for example the availability of biomass, the energy use of the transport sector, or the availability of advanced biomass to biofuel conversion processes at large scale.

Regarding time another perspective is whether the environmental benefits are analyzed in the short or long term. Climate effects from using forest biomass for biofuels can differ substantially depending on the timeframe, with a risk of increased GHG emissions when adopting a short term perspective (due to e.g. deforestation that is not compensated for on short term). Berndes *et al*. (2013) emphasize that both short and long term aspects have to be taken into account to obtain a fair picture of the climate change mitigation potential of bioenergy solutions.

The techno-economic dimension in systems analysis

Both technical and economic aspects are often considered more quantifiable than environmental aspects. This however does not necessarily imply a reduced uncertainty in these two dimensions of performance analysis. For mature processes both technology performance and cost may be well known. New process concepts such as gasification based options for biofuel production, however, still entail a certain degree of uncertainty with respect to both energy and economic performance. For a certain biofuel a number of technically feasible production pathways exist with either technically mature or newly developed process steps. Tar cleaning in biomass gasification, for example, is mature as low temperature technique using scrubbers putting a penalty on the energy performance (as the gas needs to be cooled and reheated and tars are removed from the gas). Reforming tars at high temperature is technically only at the verge of commercialization but has a potential of improving process performance (reducing losses from gas cooling and keeping tar chemical energy in the gas). In systems studies, the level of detail for the different production pathways is often simplified due to the complexity of the problem at systems level and only an overall performance indicator is used for a given biofuel.

[1] Deterministic models describe systems assuming no randomness exists. This type of model will always produce the same output for given initial and boundary conditions.

With respect to economic evaluation two factors of uncertainty exist: investment cost on the one hand and future energy market prices on the other hand. Investment estimations of new process concepts are often factor based estimated using literature data, implying a level of uncertainty of about +/- 30% at its best (Smith 2005). Energy service prices levels (feedstock, electricity, district heat, biofuel, etc.) need to be estimated when future scenarios with a time frame of 2030–2050 are investigated. Again, this introduces uncertainty that e.g. can be handled with sensitivity analysis. Another difficult aspect to handle is the comparison of economic data on established processes to cost estimations for new process concepts. A common way of avoiding these problems is to compare plant costs for a so-called *n*-th plant, meaning that based on a learning curve investment costs for a future *n*-th plant will be lower than for a first-of-its-kind or demonstration plant.

Prices for different energy services may also change with plant location. This is particular valid for the case of district heating (DH), that has a very local market and changes depending on the current situation in the DH systems under consideration.

Finally, costs for distribution infrastructure have to be accounted for with difficulties in estimating the cost for completely new infrastructure for example for distribution of DME. Even for biogas or natural gas the cost for new infrastructure is hard to define as other users (than the transportation sector) might benefit from the infrastructure as well, leading to questions on cost allocation between different products/services.

The environmental dimension in systems analysis

One of the most discussed parameters, within the environmental dimension, is how much biomass that can be grown without competing with food production, affect sensitive ecosystems or in other ways have a negative environmental impact.

Global bioenergy potential

There are multiple studies that have assessed the global bioenergy potential from different perspectives often presenting very different estimations. To better understand the wide variations, also multiple review studies have been made, with comparisons to find and structure underlying differences in methods and assumptions. In this chapter we have listed results from review studies as well as examples of “stand-alone” studies modelling future bioenergy potential, see Table 1.

Table 1. List of selected studies modelling future global bioenergy supply as well as review studies with the aim of understanding why "stand-alone" studies differ and reflect over reasonable potential.

Source	**Time perspec-tive**	**Bioenergy potential (EJ/yr)**	**Aim of the study**
Examples of review studies, with the aim of understanding why "stand-alone" studies differ and reflect over global bioenergy potential			
Bauen *et al* (2009)	2050	< 250	Review resource, technical, economic, environmental, social and policy aspects of bioenergy. Comment: Authors found in literature that the technical potential for biomass production in 2050 lies within a range of 50–1500 EJ/year and conclude a sustainable supply potential estimate up to 250 EJ/yr.
Berndes *et al* (2003)	2050	100–400	Discusses the contribution of biomass in the future global energy supply based on a review of 17 studies.
Chum *et al* (2011)	2050	100–300	An IPCC special report on bioenergy where supply potential is reviewed in Chapter 2.2. Comment: In IPCC Fourth Assessment report global technical potential was estimated to 20–400 EJ with a best guess on 250 EJ. This report concludes that based on available scientific literature, deployment levels of biomass for energy could reach a range of 100–300 EJ/yr around 2050.
Creutzig *et al* (2014)	2050	10–245	Based on literature review, bring together perspectives of various communities involved in the research and regulation of bioenergy deployment and provide an update on estimates of technical resource potential.
Dornburg *et al* (2008, 2010)	2050	200–500	Assessment of global biomass potential estimates, focusing on factors affecting these potentials, such as food supplies, soil quality, water availability, biodiversity, protected areas and agroeconomics. Comment: Authors discuss that current understanding of the potential future technical biomass supply could range from about 100 EJ (using only residues) up to an ultimate technical potential of 1500 EJ/yr but conclude a range of 200–500 EJ/yr when taking above mentioned aspects into account.
Haberl *et al* (2010)	2050	160–270	Based on a review of recent literature, identify a range of future technical bio-energy potentials that take sustainability criteria such as nature conservation and food production into account.
Some examples of "stand-alone studies" modelling studies			
Beringer *et al* (2011)	2050	130–270	Estimate bioenergy potentials from dedicated biomass plantations taking sustainability requirements (to safeguard food production, biodiversity and terrestrial carbon storage) into consideration.
Campbell *et al* (2008)	Not specified	32–41	Estimate global potential for bioenergy on abandoned agriculture lands.
Doornbosch and Steenblik (2007)	Not specified	245	Shed light on bioenergy issues e.g. that biofuels will increase energy-price volatility, food prices and life-cycle emissions of greenhouse gases. Comment: Supply potential calculated assuming average productivity of 190 GJ/ha/year for maximum of 0.44 Gha.
Field *et al* (2008)	Current	25	Assess potential total production of biomass without negative climate or food security impacts. Comment: Authors conclude a biomass supply potential of approximately 5% of global energy demand.
Hoogwijk *et al* (2005)	2050 2100	130–410 240–850	Analyse the geographical and technical potential of energy crops for 2050–2100 for four IPCC SRES land-use scenarios.
Hoogwijk (2004)	2050	130–440	For four different scenarios and two biomass production cost levels (lower than \$2/GJ and lower than \$4/GJ),
Johansson *et al* (1993)	2100	205	Biomass supply potential from eleven world regions added together to a global figure.
Ladanai and Vinterbäck (2009)	2050	1135–1548	Scenarios predicting the future potential of biomass. Comment: Authors claim that > 1000 EJ is possible with sufficient political support.
Schueler *et al* (2013)	Not specified	< 100	Examines the effect of the RED sustainability criteria on the availability of biomass resources. Comment: This assessment does not include agricultural and forestry residues and aquatic biomass. Roughly 10% (98.5 EJ) of the total theoretical potential of 977 EJ occurs in areas free of sustainability concerns.
Smeets *et al* (2007)	2050	215–1272	Include a bottom-up assessment and review of global bioenergy potentials to 2050. Comment: The bioenergy potential on surplus agricultural land (i.e. land not needed for the production of food and feed) equaled 215–1272 EJ/yr, depending on the level of advancement of agricultural technology.
van Vuuren *et al* (2009)	2050	150	Explore how estimates of potentials for bioenergy may be influenced by factors as land degradation, water scarcity and biodiversity concerns. Comment: Authors discuss that alternative land-use scenarios and/or different yield assumptions lead to results ranging from 120–300EJ/yr and water scarcity and expansion of nature reserves lead to a global supply potential of 65EJ.
Schubert *et al* (2009)	2050	80–170	WBGU models global bioenergy potential. Comment: Authors discuss that sustainable supply potential is 30–120 EJ/yr from bioenergy crops as well as 25–50 EJ/yr from waste and residues and conclude a sustainable technical potential of 80–170 EJ/yr.

Algae

Potentials for aquatic biomass are typically not included in the reviewed studies presented in Table 1. However, another potential biomass feedstock source are algae that offer a huge potential but restriction and true potential are not yet well defined. A recently revised report originally published in 2008 on the worldwide potential of algae biomass for energy applications (Florentinus *et al*. 2008) estimates about 515 EJ per year to be available on the long term with the majority coming from macro algae cultivation. The total algae potential estimated by that report is in the range of the annual world's primary energy use (about 550 EJ). Questions for algae to be resolved therefore rather reside in removing techno-economic limitations as well as ecological concerns for large scale production.

Why the large differences?

As can be seen in Table 1 there are large differences between studies on global bioenergy supply potential. According to e.g. Haberl *et al* (2010) and van Vuuren *et al*. (2009) discrepancies primarily result from different assumptions on future yields of food and energy crops, feed conversion efficiencies in the livestock system as well as the suitability and availability of land for bioenergy production. Berndes *et al* (2003) discuss that the major reason for the differences is that the two most crucial parameters, land availability and yield levels in energy crop production, are very uncertain, and subject to widely different opinions. Also the expectations about future availability of forest wood and of residues from agriculture and forestry vary substantially among the studies. Creutzig *et al* (2014) discuss that the amount of future technically available biomass for energy depends on the evolution of a multitude of social, political and economic factors, e.g., land tenure and regulation, diets, trade and technology.

In Batidzirai *et al* (2012) it is stated that according to Hoogwijk *et al*. (2003) and Haberl *et al*. (2010) the discrepancies in bioenergy potential estimates are caused by several factors. First, studies have different objectives, scope/systems boundaries and are evaluated over different time frames (see also Thrän *et al*, 2010). Second, studies focus on different biomass resource types (e.g. energy crops, residues, etc.) and different type of biomass potentials (read more below). Third, a heterogeneous assortment of methodologies and approaches are used to derive bioenergy potential estimates. More importantly, analysts use heterogeneous datasets and scenario assumptions (due to missing empirical data) for certain aspects (e.g. yields, conversion factors, parameter correlations, and sustainability criteria). Also parameters like moisture content[2] and if calorific values are assumed in higher heating value or lower heating value affect the results. The broad variety of approaches, methodologies, assumptions and datasets is due to a lack of a commonly accepted approach to determine biomass energy potentials.

Different types of biomass supply potential

One of the reasons for the differences among bioenergy potential estimates is that the type of potential differs. As described in e.g. BEE (2010) and Batidzirai *et al* (2012), the type of potential is a crucial criterion because this determines to a large extend the approach and methodology. Five types of biomass potentials, overlapping each other, are used in the

[2] Most studies mentions that except where explicitly stated differently, they report biomass flows as dry matter (= bone dry biomass = oven dry = zero moisture content), assuming that 1 kg dry matter biomass is equivalent to 0.5 kg of carbon and has a gross calorific value of 18.5 MJ/kg. The potential to produce bioenergy from algae is generally not covered.

literature and listed below. Overlaps are illustrated in Figure 7. It should, however, be noted that the definitions of potentials in literature are often not fully consistent with the definitions presented here and several studies explicitly, or implicitly, analyse several types of potentials.

1. *Theoretical potential*: the overall maximum amount of terrestrial biomass which can be considered theoretically available for bioenergy production within fundamental bio-physical limits. In the case of biomass from crops and forests, the theoretical potential represents the maximum productivity under theoretically optimal management taking into account limitations that result from temperature, solar radiation and rainfall (Sørensen 1999; Kheshgi *et al*. 2000; Cannell 2003). In the case of residues and waste, the theoretical potentials equal the total amount that is produced (Edwards *et al*. 2005). The number of studies that focus on the theoretical biomass potential is limited, because policy makers, which are an important target audience of biomass energy assessments, are generally more interested in the technical, economic and implementation potential.

2. *Technical potential*: The fraction of the theoretical potential which is available under the regarded techno-structural framework conditions and with current technological possibilities. Spatial confinements due to competition with other land uses (food, feed and fiber production) as well as ecological (e.g. nature reserves) and other non-technical constraints are also taken into account. Although this is the most commonly used type of supply potential, in literature, results may widely differ, see e.g. Bauen *et al* (2009), Chum *et al*. (2011), Dornburg *et al*., (2008, 2010), and Haberl *et al*. (2010), showing that technical potentials can be found in literature in the range of 50–1500 EJ/yr.

3. *Economic potential*: The share of the technical potential which meets criteria of economic profitability within the given framework conditions. Economical potential is presented in e.g., Richards and Stokes (2004), Hagstrom (2006) and REFUEL (2008).

4. *Implementation potential*: The fraction of the economic potential that can be implemented within a certain time frame and under concrete socio-political framework conditions, including economic, institutional and social constraints and policy incentives. Implementation potential is e.g., presented in van Vuuren *et al*. (2007). Studies that focus on the feasibility or the economic, environmental or social impacts of bioenergy policies are sometimes also included in this category.

5. *Environmentally or ecologically sustainable potential.* This fifth potential is an additional category also used in the literature as an alternative to the economic and implementation potentials. It is defined as the fraction of the theoretical potential which meets certain environmental criteria and typically also a fraction of the technical potential. Many studies analyzing the technical potential also discuss sustainable potential, see e.g. Bauen *et al* (2009), Haberl *et al*. (2010), Beringer *et al*. (2011) and Schubert *et al*. (2009).

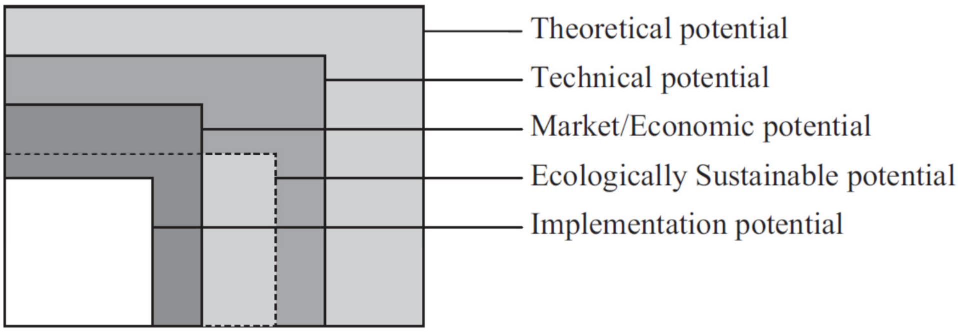


Figure 7. Overlap between five types of bioenergy potentials discussed in the literature (Batidzirai et al, 2012).

Current use, drivers for increased use of bioenergy and implications for amount of future available biofuels

According to Haberl *et al*. (2010) most researchers agree on that current use of bioenergy lies within a range of 40–60 EJ/yr, the vast majority thereof being firewood, dung or charcoal burned in simple cooking or heating stoves (see also Sims, 2007; Schubert *et al*, 2009; Bauen *et al*, 2009; Chum *et al*, 2011). According to Bauen *et al* (2009) main drivers for an increased bioenergy use are greenhouse gas savings, improved trade balances and energy security as well as opportunities for social and economic development in rural communities. Schueler (2013) reflect on that the political will to reduce global greenhouse gas emissions has largely contributed to increased global biofuel production and trade. EU policies such as the obligation for all member states to fulfill the target of minimum of 10% renewable energy in the transport sector for 2020 (European Parliament and Council, 2009) as well as policies in individual countries like the ambition of the Swedish Government for a vehicle fleet independent of fossil fuels by 2030 and a Sweden without any net greenhouse gas emissions by 2050 (indicating an entire transportation sector without fossil fuels), are policies that drives towards an increased use of renewable fuels for transport, most likely dominated by biofuels.

All types of biomass included in the bioenergy supply potential studies can be used for biofuel production. It is, however, likely that half of the bioenergy supply potential can be used for biofuel production due to the demand for bioenergy from other energy sectors. Assuming 160 EJ/year as an average with half of the potential being used for biofuel production at an average fuel conversion efficiency in the range of 50–70% results in a biofuel potential in 2050 of about 40–56 EJ/year (11,000–15,500 TWh/year). This has to be seen in relation to the total energy use in the transport sector amounting to about 94 EJ/year in 2012 and estimated to about 121 EJ/year in 2035, according to the BP Energy Outlook (BP 2014).

Risks connected to bioenergy expansions

According to many of the reviewed studies expansion of bioenergy poses challenges. Creutzig *et al* (2014) discuss that large-scale deployment (>200 EJ), of land-intensive bioenergy feedstocks could lead to detrimental climate effects, negatively impact ecosystems, biodiversity and livelihoods. Bauen *et al* (2009) state that potential competition for land and raw material with other biomass uses must be carefully managed. The productivity of food and biomass feedstocks needs to be increased by improved agricultural practices. Logistics and infrastructure issues must be addressed, and there is need for further technological innovation leading to more efficient and cleaner conversion of a more diverse range of feedstocks.

Berndes *et al* (2003) reflect on that although it seems technically feasible to produce several 100 EJ/yr of bioenergy, it is not possible to conclude whether such a large-scale biomass supply for energy is an attractive option for climate change mitigation. There are two main reasons for this. First, many studies do not provide much insight into how the expanding bioenergy sector will interact with other land uses. Development of the food and materials sector is exogenously defined in many studies, i.e. the bioenergy sector evolves in parallel and does not affect the food and materials sector. It is therefore not possible to conclude much about the socioeconomic consequences of a global large-scale expansion of biomass use for energy. Second, the environmental consequences of a realization of the assessed bioenergy potentials are often insufficiently analyzed. It is therefore unclear to what extent the assessed potentials harmonize with other environmental goals such as biodiversity and nature conservation.

According to Haberl *et al* (2010) the high end of the presented range of 30 to over 1000 EJ/yr is implausible because of (1) overestimation of the area available for bioenergy crops due to insufficient consideration of constraints (e.g., area for food, feed or nature conservation) and (2) too high yield expectations resulting from extrapolation of plot-based studies to large, less productive areas.

Reflections made in this review study

In this literature review we find that published estimates of global technical bioenergy potentials in 2050 differ by a factor of almost 50. Calculations of the potential to grow bioenergy crops on abandoned farmland yielded a range from about 30 EJ/yr (Campbell *et al* 2008; Field *et al*, 2008), while other studies suggest technical bioenergy potentials of up to 500 EJ/yr (e.g., Dornburg *et al*, 2008, 2010), some even reporting potentials exceeding 1000 EJ/yr (Smeets *et al*, 2007; Ladanai and Vinterbäck, 2009). As Creutzig *et al* (2014), we also find that the discussion following this wide range of technical potential has not resulted in a consensus on the magnitude of the future global technical bioenergy potential, but has helped to better understand some of its many structural determinants.

In this review, taking risks connected to large scale bioenergy expansions into account, we agree with many of the authors that up to 100 EJ of bioenergy can be produced in a sustainable way and that 300–500 EJ/yr may be technically possible but that such expansion might challenge sustainability criteria. Bioenergy over 500 EJ we find extremely difficult to produce in a sustainable way.

Swedish bioenergy potential

From a Swedish perspective Ecotraffic (2013) estimates a technical biofuel potential of 85 TWh/yr expressed in TWh final biofuels (in lower heating value) by 2030–2050. Börjesson *et al*. (2013) estimate that about 50–70 TWh/year of biomass could be used for bioenergy purposes in addition to today's biomass use from forest and farmland without directly competing with other agricultural or forestry cultivation. In the long run (30 to 50 years from now) this potential is estimated to increase to 80–100 TWh/year. Accounting for conversion losses in biomass to biofuel processes this still could contribute considerably to the transport sector energy demand lying in the range of 120 TWh/year for 2011 including about 30 TWh for international transport (aviation and marine transport) and a biofuel end use of 7 TWh (Energimyndigheten 2013a). Translated to greenhouse gas emissions the transport sector in Sweden stands for annual emission of about 20 million tons of CO_{2eq} per year with a decreasing trend as illustrated in Figure 8. The road transport stands for more than 90% of the emissions and the decreasing trend is mainly associated to improved fuel economy and increase in biofuel use.

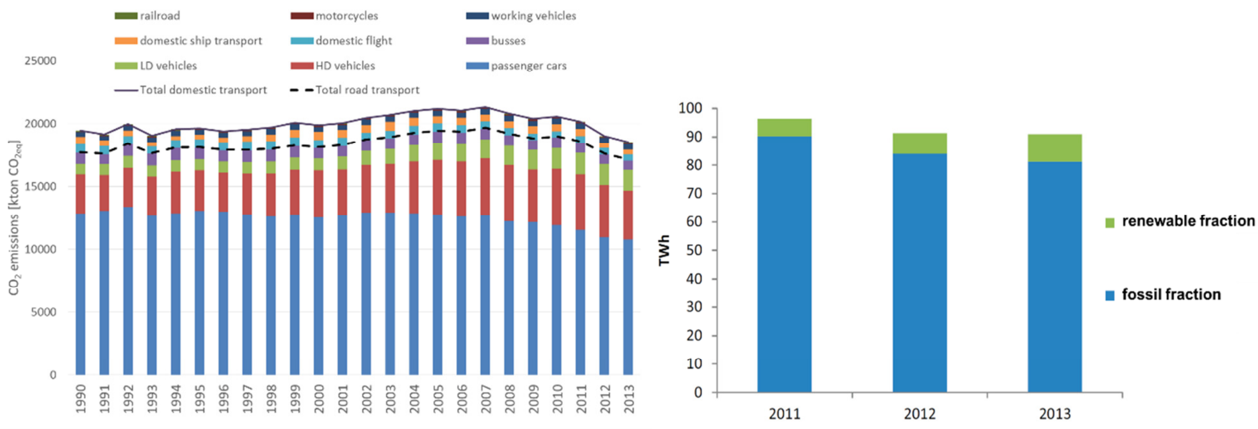


Figure 8: Left: domestic transport CO_2 emissions in Sweden (Source: www.naturvardsverket.se); right: renewable and fossil fraction of transport fuels in Sweden (Energimyndigheten, 2014).

Future predictions for the road transport (cars, busses and trucks) energy indicate a decrease despite the increase in total transports. The decrease is mainly due to improvements in energy efficiency measures and development of transport infrastructure as illustrated in Figure 9.

Börjesson *et al*. (2013) estimate a biofuel production of 25–35 TWh/year as realistic near term potential. According to Figure 9 about 20 TWh of biofuels could be used for road transport with additional 5 TWh for heavy duty working vehicles. This could even allow for export of biofuels from Sweden as illustrated in scenario 2050A in Figure 9.

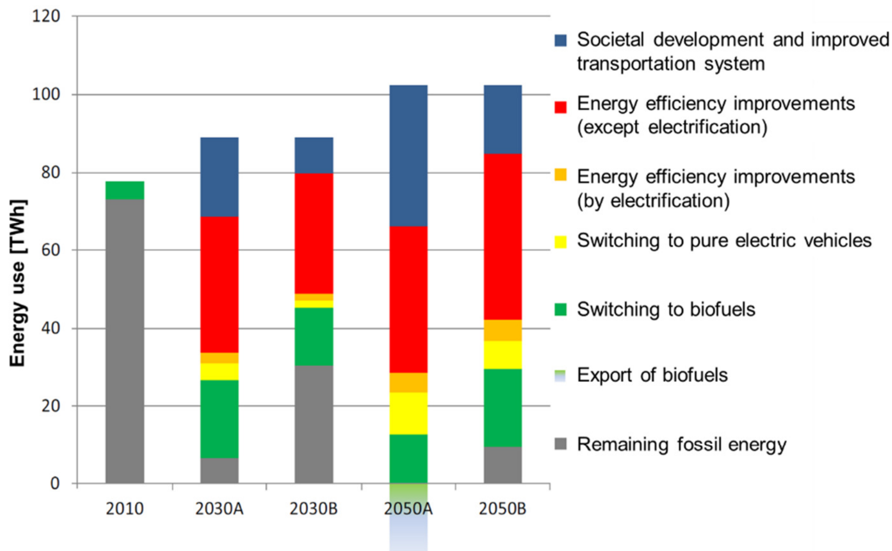


Figure 9: Fossil and total energy use in road transport (cars, busses & trucks) for two scenarios in 2030 and 2050 (taken from the report on a fossil free road transportation system in 2050 (Johansson 2013)).

Biomass origin and sustainability

The country of origin for biomass feedstock can change over time with consequences for the climate benefits of a specific biofuel. As an example, the Swedish Energy Agency presents the country of origin of biodiesel (FAME) with Australian rapeseed standing for a share of 22% of 2013's total FAME feedstock supply whereas in 2011 nothing was imported from Australia for biodiesel production (Energimyndigheten 2013b). These changes in supply chain may influence the environmental (as well as societal) performance of a production chain. With respect to these issues certification schemes for ensuring certain standards with respect to environmental, economic and societal sustainability are becoming more and more important. About one third (in energy terms) of Swedish biofuel production is certified according to a certification scheme ensuring economic and societal sustainability in addition to the sustainability criteria requested by EU's Renewable Energy Directive (RED) and Fuel Quality Directive (FQD) (Energimyndigheten 2013b). The dominant certification scheme is ISCC (International Sustainability and Carbon Certification). An assessment of the 17 certification schemes accepted by the European Commission performed by several environmental organizations (Schlamann *et al*. 2013; Goote 2013; NRDC 2014) identified the Roundtable of Sustainable Biofuels (RSB) certification scheme to be the most robust leading to better field-level implementation in the countries of origin of the biomass feedstock. Certification schemes are an important step in assuring the sustainability of biofuels, however, it should be kept in mind that as long as these are not applied to all supply there is a risk for creating two markets and thus still aggravating the potential risk with a biofuel expansion.

Water availability

Berndes (2008) intends to provide a global overview on the nexus between water availability and increasing bioenergy production. Freshwater is already scarce in some regions of the world. A growing population and changing dietary trends mean a steeply rising water demand. Under the impact of climate change the population at risk of water stress could increase substantially by the end of the century. In this context, water demand for bioenergy production might place an additional burden on water availability worldwide and induce increased competition over water resources in an increasing number of regions.

However, bioenergy demand also leads to new opportunities since a number of crops that are suitable for bioenergy production are drought tolerant, relatively water efficient and grown under multi-year rotations[3]. By adopting such crops farmers may better cope with a change in precipitation patterns. In many cases an increased bioenergy production can be positive. For example, local water harvesting and run-off collection upstream may reduce erosion and sedimentation loads in downstream rivers, while building resilience in the upstream farming communities. Conversely, the use of marginal areas with sparse vegetation for establishment of high-yielding bioenergy plantations may lead to substantial reductions in soil runoff, which can be positive or negative depending on specific context (Berndes, 2008).

Regarding water availability in the context of bioenergy potential van Vuuren *et al* (2009) and Dornburg *et al* (2010) argues that competition with other sectors for water resources as well as regional water scarcity have been largely overlooked in earlier studies assessing bioenergy potential. Also Moldon (2007) and de Fraiture *et al* (2008) argue that water scarcity is a

[3] A multi-year rotation system will reduce the demand for input energy compared to annual rotation systems.

potential factor limiting bioenergy production. In van Vuuren *et al* (2009) it is shown that 17% of global bioenergy supply potential in 2050 might need to be excluded from the baseline scenario in OECD Environmental Outlook (OECD 2008) due to severe water scarce areas (e.g. in Middle East, parts of Asia and Western USA). Dornburg *et al* (2010) find that excluding water scarce areas decreases the biomass potentials by about 15–25% for woody bioenergy crops in 2050, in a scenario with biomass potentials of about 200 EJ/yr.

Teter *et al* (2015) find, in a national scenario study for the US, that increasing land areas for growing crops for biofuel production leads to reductions in groundwater recharge by 4-11% in regions that experience agricultural extensification. However, changes in the average water intensities of biofuels from corn and soybean and total agricultural irrigation requirement are quite small, where the latter can be explained by e.g. that less irrigation is applied in regions where crops are displaced by rainfed dedicated cellulosic feedstocks (Teter *et al*, 2015).

Rockström *et al*. (2010) argue that to assess the impact of water use and management, in more details, an integrated analysis is required addressing trade-offs between water for food and other ecosystem functions and services. Impact of energy crops, on changes in hydrology, needs to be researched in order to advance our understanding of how the changes in water and land management will affect downstream users and ecosystems (Uhlenbrook, 2007).

Land use change – direct and indirect

The IPCC defined land use in general (both direct and indirect) as "the total of arrangements, activities and inputs undertaken in a certain land cover type" or in other words as "the social and economic purposes for which land is managed (e.g. grazing, timber extraction and conservation)".

Whenever land is transformed from one use to another land use change occurs with potential consequences at the overall systems level in economic, environmental and social terms. To properly account for land use change effects, in relation to biofuel production value chains, is difficult and controversially discussed. The difference between direct and indirect land use change (dLUC and iLUC) is basically that dLUC refers to effects directly linked to the land area that has a new use, whereas iLUC effects are impacts at another place and level. A simple example for dLUC would for example be deforestation for growing biomass energy crops. Indirect land use change could for example take place in case biomass energy crops (crop A) are grown on land that is used for another crop (crop B). In case the demand for crop B remains constant, land somewhere else might be used for growing that crop in order to satisfy the demand. This will lead to land use change somewhere else, but initiated by the biomass energy crop (crop A) and therefore is accounted as iLUC effect of growing that crop (crop A) in the life cycle assessment. iLUC effects can be cascaded to several levels as illustrated in Figure 10 and it is very hard to quantify them. Börjesson *et al*. (2013) present results from a number of studies trying to account for LUC with a large scatter in the resulting data. The major source for deviation is basically the type of model that has been used in the different studies as well as assumptions on future land use patterns. Many models used are not capable of differentiate between direct and indirect land use changes either, making it difficult to compare the results (Börjesson *et al*. 2013).

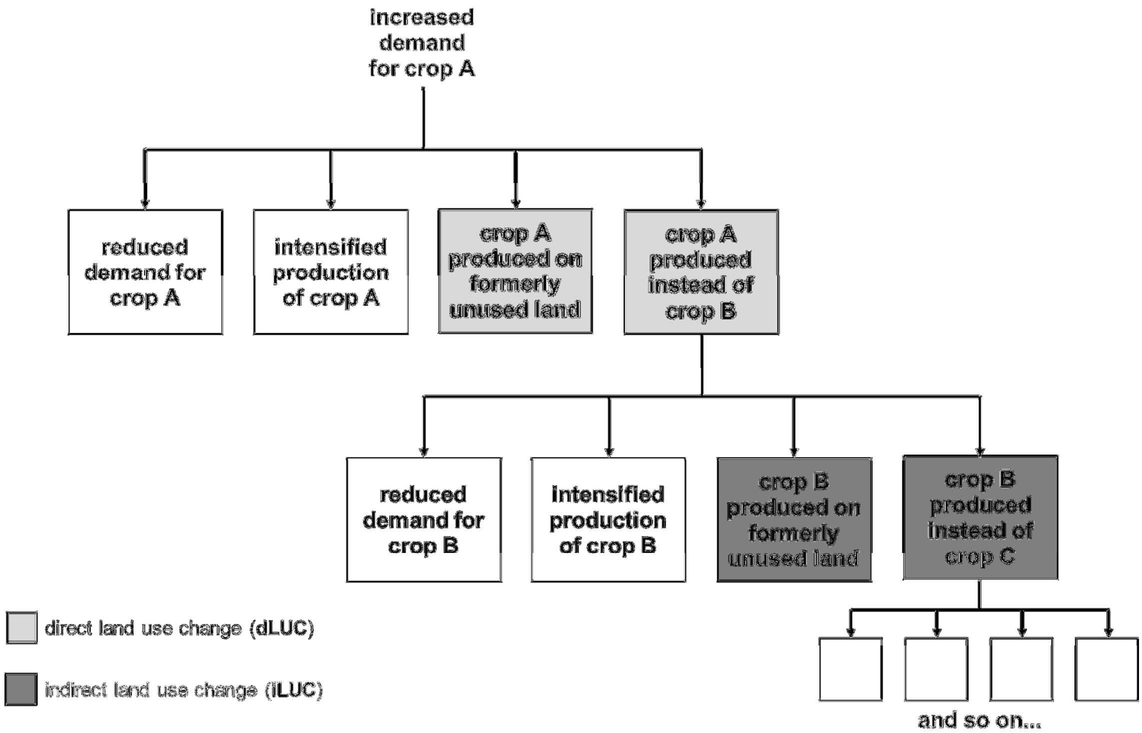


Figure 10: Illustration of direct and indirect land use change effects (taken from Börjesson et al. (2013)).

The uncertainty and impact of accounting for iLUC effects is also discussed by a study (Kocoloski *et al*. 2013) on Low Carbon Fuel Standards (LCFS) as introduced in California in 2009 (Yeh *et al*. 2013). iLUC factors increase the uncertainty of the biofuels carbon intensity considerably, with for example corn ethanol having a 90% confidence interval width of 89 gCO_{2eq}/MJ when including iLUC effects against 40 gCO_{2eq}/MJ when excluding them. Improvement in carbon intensity data can be achieved by fuel producers reporting their consumption data and improved knowledge on feedstock yield and fertilizer use during cultivation but iLUC effects still remain dominant[4]. The iLUC factor for corn ethanol in the Californian LCFS is 30 gCO_{2eq}/MJ. The European RED directive does not account for iLUC in its current form but a proposal for amendment has been worked out in 2012 that still is issue to discussion (European Commission, 2015). In the iLUC assessment underlying the commission's proposal, the indirect land use change factor for e.g. corn (maize)-based biofuel is 10 gCO_2/MJ. However, it is clearly stated that there are large uncertainties in the different iLUC factors.

Another recent report claims – based on four case studies – that EUs production targets for biofuels in 2020 can be reached and even surpassed without negative environmental impacts by introducing measures for avoiding iLUC effects (Wicke *et al*. 2015). Among the key measures proposed in the report are:

- Stimulation of increased productivity and resource efficiency in the agricultural sector
- Supporting production on currently underutilized land
- Promotion of land zoning that strives for a richness in biodiversity and conservation of ecosystems
- Intensification of forest maintenance and management

[4] 90% confidence interval of 80 gCO_{2eq}/MJ with iLUC vs 36 gCO_{2eq}/MJ without iLUC for corn ethanol, assuming a case with improved data reporting and increased knowledge (Kocoloski *et al*. 2013).

The difficulty of quantifying land use change effects is also highlighted by Höglund *et al.* (2013) who, from another perspective, identify the following major challenges related to biofuel-induced land use change effects (both direct and indirect):

- Deforestation, forest management, and climate change
- Degradation of biodiversity
- Nutrient leakage and removal
- Contribution to rising food prices and poverty
- Other socioeconomic aspects such as job creation, ways of life and recreational values.

Other consequences of biofuel expansion

Biodiversity degradation risks are often handled to some extent by certification schemes protecting natural reserve areas but more work is required to ensure sustainable biofuel production. Biodiversity can to some extent be coupled to soil carbon content with a high amount of soil carbon allowing for a higher biodiversity. This could be one option to improve the quantifiability of biodiversity (Börjesson *et al.* 2013).

Nutrient leakage and removal are for example important when considering the use of forest residues for biofuel production. Residues constitute an important link in forest fertility and care has to be taken to close nutrient loops (e.g. by recycling the nutrient rich ashes) to a large extent. It is also of interest to focus on biomass crops with low fertilizer needs and high nutrient use efficiency in order to reduce risks for nutrient leakage (Höglund *et al.* 2013).

With respect to the influence of biofuels on food prices, Persson (2014) has recently published a review on literature aiming at quantifying the effects. Increased production of corn-based ethanol – the fuel pathway investigated by majority of the 121 studies included in the review – is estimated to stand for 14–43% of the US corn prices increase in the period 2000 to 2008. The large scatter in the results is basically due to modelling assumptions on market interactions both on global and local level. Little empirical data on the demand and supply elasticity is available making it difficult to build reliable models. Persson (2014) concludes that although an increased use of biofuels was not the only reason for increased food prices during the studies period, it should be noted that there was a connection. He also points out that better data and models on market interactions as well as supply and demand responses are needed in addition to a better understanding of land use change patterns and effects.

The complexity of both the environmental system as well as the market mechanisms are general aspects in systems modelling that still need investigation. Both material loops and feedback loops that may occur due to changes to the systems are very hard to quantify and in consequence make it difficult to define indicators for decision making or policy development.

The social dimension in systems analysis

Studies investigating the social dimension of biofuel value chains are scarce and limited data is available that allows a quantifiable evaluation of the different criteria. Yue *et al.* (2014) gives a selection of possible criteria such as human rights, labor practices, decent work conditions, societal wellness and product responsibility, among others. Current efforts trying to establish quantitative indicators for these criteria and to collect them systematically in social LCA databases, still need further development. The most common indicator used by studies aiming at including the social dimension is job creation. Three different levels of job creation can be identified according to Yue *et al*. (2014):

- *Direct effects* refer to the jobs related to plant site construction and employees for operating the plant.
- *Indirect effects* refer to jobs created due to increased economic activity of the directly involved actors that in turn may engage additional suppliers, banks, accountants etc.
- *Induced effects* are generated by the increased expenditure of the people involved in the project again having a positive effect on employment on a general level.

Another recent study on social LCA uses a screening approach to identify high risk of negative social impacts for different fossil and renewable fuel life cycles (Ekener Petersen *et al*. 2013; 2014). It concludes for example that the country of origin for the raw material has a larger impact than the type of fuel produced. Another conclusion is that social LCA needs to be applied to both fossil and renewable fuels in order to give a reasonable comparison. Furthermore, even though a large uncertainty must be assigned to the social risk indicators, they can be used for indicative comparison and guidelines for designing appropriate policies.

Systems studies addressing the whole value chain

A number of studies have been investigating the whole value chain from well to wheel – including end-use in passenger cars or trucks – with focus on illustrating different perspectives on performance and ranking among fuels. Studies are performed either by industrial consortia or institutions (Volvo 2008; E4tech 2013; Albrecht *et al*. 2013; ERTRAC 2014; Edwards *et al*. 2014) or by scientific committees (KVA - Energiutskottet 2013; EASAC 2012). A selection of studies is presented in the following paragraphs. The biofuel assessment study done by the Volvo Group in Sweden (Volvo 2008) might not be completely valid anymore taking into account improvements in production processes as well as changes in data on biomass potential and environmental impact factors since 2008. The aim with presenting it within this report is to illustrate the approach adopted by this study rather than to judge between different biofuel alternatives. The Volvo study is based to a large extent on data from a European well-to-wheel analysis (Edwards *et al*. 2014) that has been continuously updated and extensively cited in literature on biofuels. Recently, a new update has been released and the major results as well as the methodological approach are also presented in the following sections. Finally, the major conclusions and the methodological concept for three additional reports are presented and discussed: E4Tech (E4tech 2013), FVV (Albrecht *et al*. 2013) and ERTRAC (ERTRAC 2014).

Volvo study: Climate issues in focus

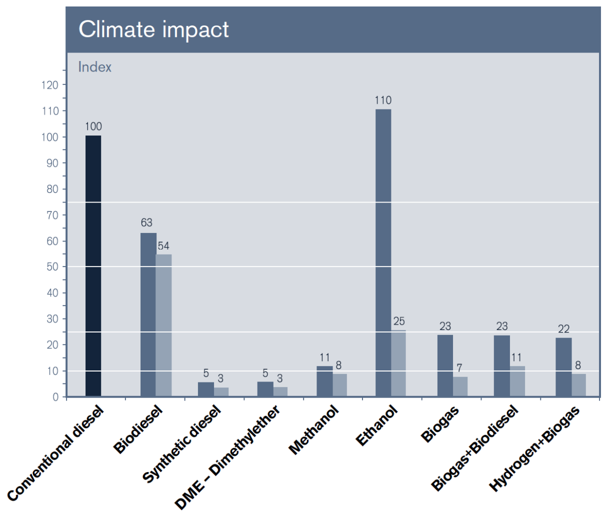
The study conducted by the Volvo group released in 2008 (Volvo 2008) focuses on biofuels that can be adapted to Diesel engines as the Volvo group's vehicle fleet range basically consists of heavy duty vehicles (trucks, busses, wheel loaders, ships). An update of the data is under way and planned for 2015[5]. The study analyses the performance of eight different biofuel (blend) options for use in Diesel engines with respect to seven different categories in a European framework. The biofuel alternatives and categories chosen are given in Table 3.

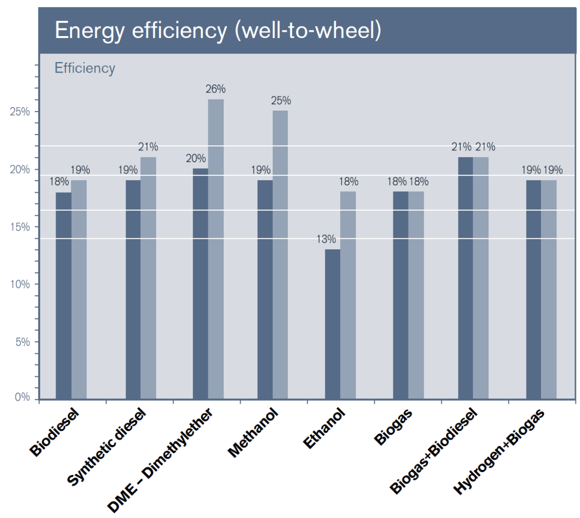
[5] Personal communication with Per Hanarp, Volvo Group Trucks Technology, 2015-01-26

Table 3: Biofuel alternatives and categories chosen in the Volvo study (Volvo 2008).

Biofuel alternatives	Categories
Biodiesel Synthetic diesel DME (dimethyl ether) Methanol Ethanol Biogas Biogas & Biodiesel Hydrogen & Biogas	Climate impact Energy efficiency Land use efficiency Fuel potential Vehicle adaption Fuel cost Fuel infrastructure

Based to a large extent on an earlier version of the JEC well-to-wheel analysis, quantitative measures are used for the different categories whenever possible. Figure 11 illustrates some examples for the measures applied. For example, climate impact of different fuels is related to the CO_2 equivalent well-to-wheel emissions for conventional diesel. Accounting for different feedstock and production alternatives for the respective fuel a best and worst case scenario is used for a number of categories. The different measures are translated to a scale from 1 to 5 for each category, with 5 indicating the best performance with respect to a given criteria. There is a considerable variation in performance between best and worst case for a number of fuels, in particular with respect to fuel cost. But also for climate impact and energy efficiency, variations between best and worst case are indicated by the results of the study. A summary of all criteria as presented in Volvo (2008) is given in Figure 12. The approach adopted in the study is very illustrative and presents a sound basis for the transport industry for strategic decision making. On the downside, it maybe oversimplifies the problematic choice between different fuels and gives little insights on how the quantitative criteria are determined (more than referring to the JEC well-to-wheel analysis).





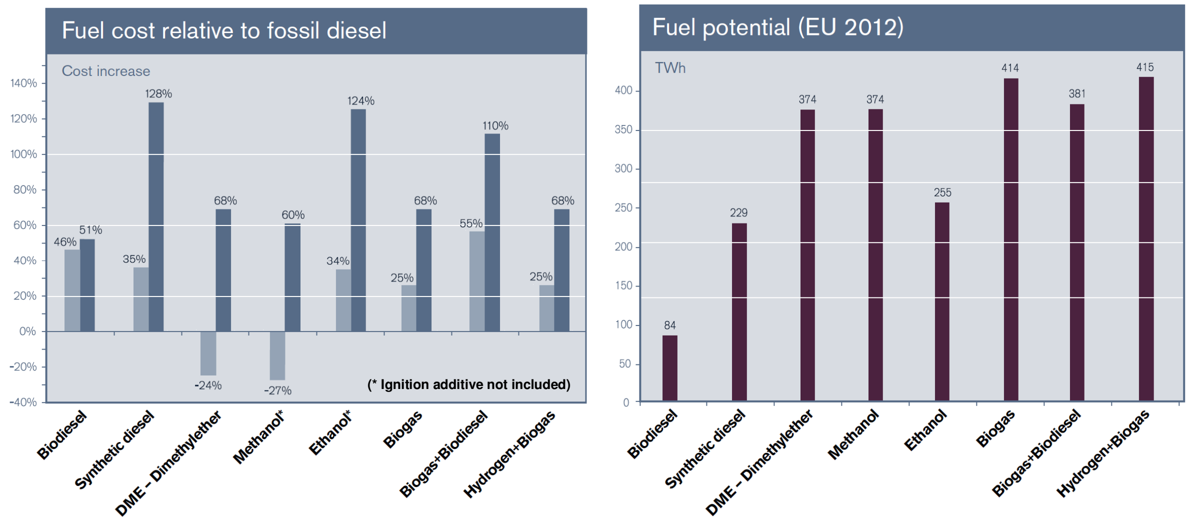


Figure 11: Classification of biofuels according to four different criteria; Climate impact, energy efficiency, fuelcost and fuel potential, where the colours indicate ■ - typical value, ■ - best case, ■ - worst case (Volvo 2008).

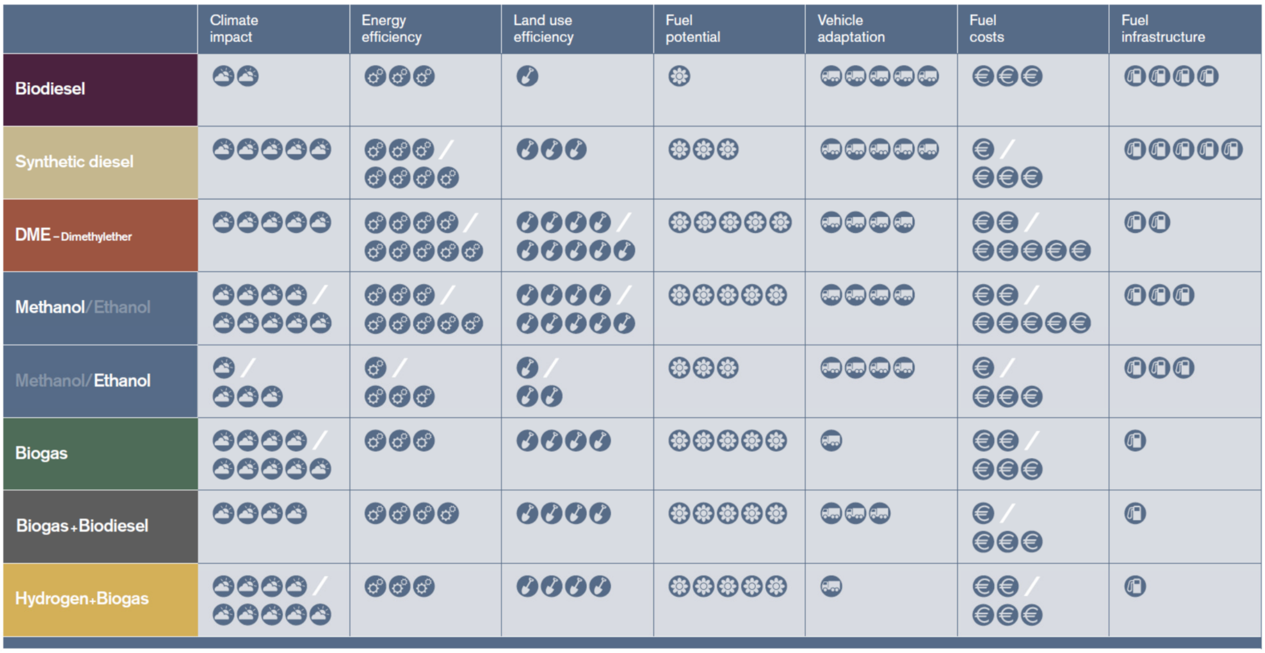


Figure 12: Summary list for biofuel classification according to seven criteria (Volvo 2008).

JEC well-to-wheel analysis

The Joint Research Centre of the EU Commission, EUCAR and CONCAWE[6] have originally published a well-to-wheel (WTW) analysis for future fuels and powertrains in the passenger car transport sector in December 2003. This study has been continuously updated and adjusted with the most recent release being the WTW Report Version 4 from January 2014 (Edwards *et al*. 2014). The study investigates a large spectrum of fuel and powertrain combinations, including both fossil and renewable alternatives and considering liquid fuels, fuel cell and battery electric cars, as well as hybrid solutions. The focus of the latest report is

[6] *EUCAR*: European Council for Automotive R&D, www.eucar.be
CONCAWE: Oil Companies' European organisation for environment, Health and Safety - Environmental Science for the European Refining Industry, www.concawe.eu

on energy and greenhouse gas emissions, leaving out discussions on costs as well as potential availability of both fuels and powertrain technology options. Earlier versions of the study have been criticized for handling the latter issues in an inappropriate manner, resulting in partially misleading results with high uncertainty. The authors therefore decided to concentrate on their core competences in technology evaluation, namely energy and GHG emission performance. A general conclusion on renewable fuels for transportation stressed by the JEC WTW study is the increased energy use in relation to fossil fuels. The greenhouse gas emission performance in relation to standard fossil fuels is strongly dependent on the combination of production pathway and powertrain alternative. These aspects are illustrated in Figure 13 presented in the WTW report (Edwards *et al*. 2014).

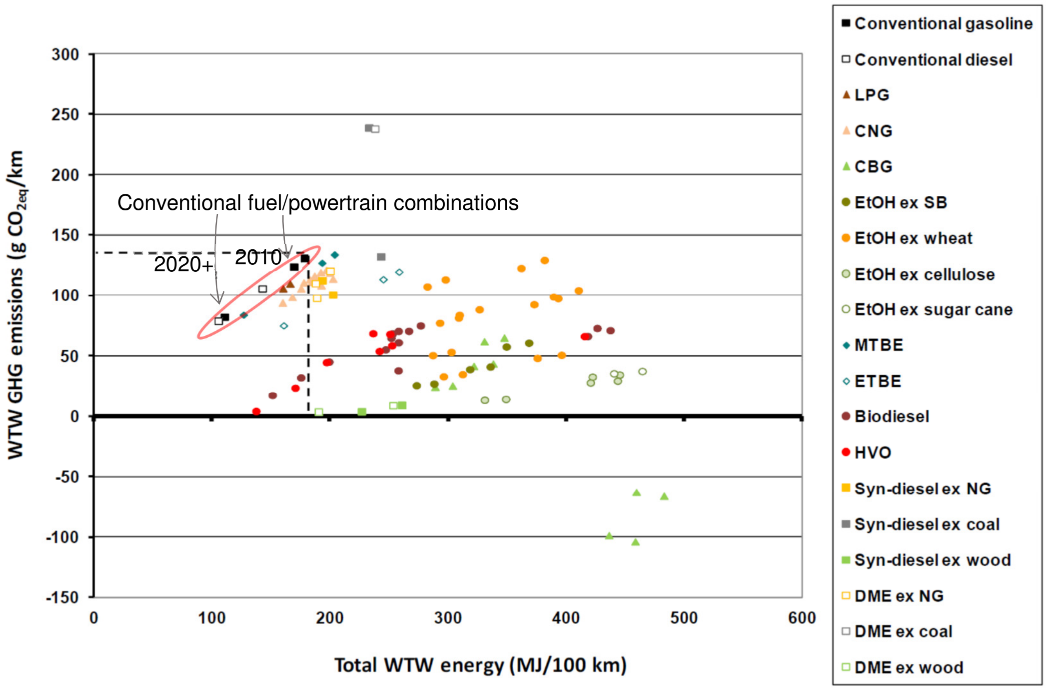


Figure 13: WTW energy and GHG emission performance for various fuel/powertrain combinations in a European perspective (time frame 2020+) as presented in Edwards et al. (2014).

The JEC well-to-wheel report clearly states that the emissions evaluation is not equivalent to a full scale LCA, neither accounting for vehicle production nor end of life disposal. Reference is made to studies (e.g. Bandivadekar *et al*. 2008) indicating that the difference in the emissions allocated to the latter two effects is varying little between different alternatives (21–24 gCO_{2eq}/km for production and 30-31 gCO_{2eq}/km for disposal, respectively). As the numbers in addition are comparatively small in relation to the total emissions from the vehicles (109–178 gCO_{2eq}/km) the authors conclude that well-to-wheel investigations in their sense are still giving proper indications on preferable pathways with respect to the current state of knowledge.

Another aspect that explicitly is excluded in the JEC study is the influence of land use change (LUC) on GHG emission performance for the different biofuel production pathways. As discussed in the earlier sections of this report, LUC may change the ranking of different fuel alternatives considerably even though there is a large uncertainty in the exact magnitude of LUC effects.

Transferability of the WTW results to other vehicle transport sectors such as heavy-duty transports is limited due to the considerable differences in for example duty cycle and thus in powertrain efficiency. The well-to-tank (WTT) data for relevant fuel options to other sectors than passenger cars could however be directly applied.

E4tech: A harmonised Auto-Fuel biofuel roadmap for the EU to 2030

The approach adopted by the E4tech study (E4tech 2013) (commissioned by a consortium of Daimler, Honda, Neste, OMV, Shell and Volkswagen) is represented schematically in Figure 14. Two models are used to represent the biofuel supply on the one hand and the vehicle fleet biofuel uptake on the other hand for four different context scenarios. The output of these models is then matched to assess different biofuel-vehicle options with respect to various criteria.

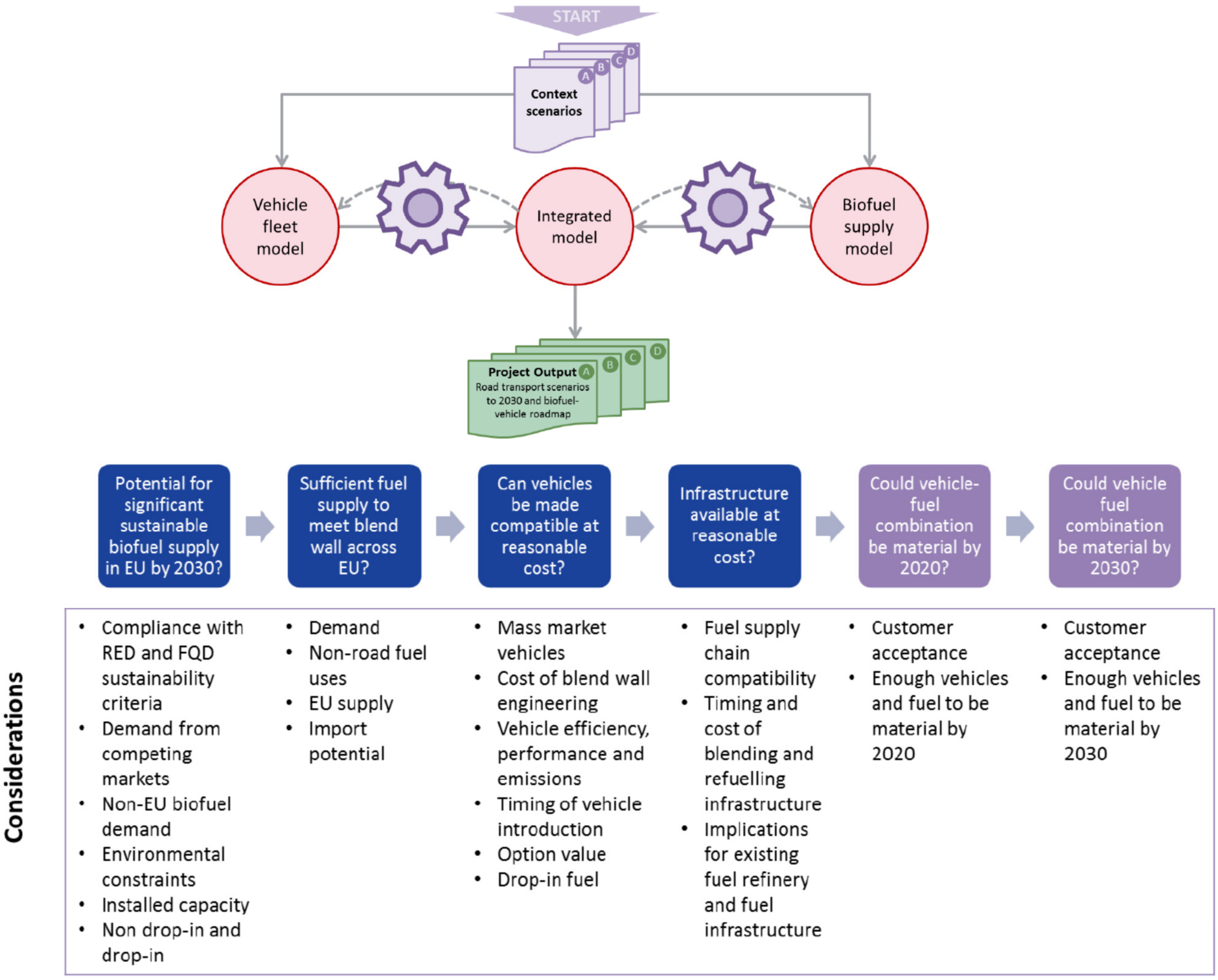


Figure 14: Graphical representation of the methodological approach (upper) and evaluation criteria (lower) for generation of roadmaps in E4tech study (E4tech 2013).

The study estimates an overall energy share of biofuels in the transport sector of 12–15% by 2030 with a 10.6–11.8% in the road transport sector. Corresponding greenhouse gas savings in the road transport sector by 2030 are in the range of 8%. Figure 15 illustrates the distribution of biofuel greenhouse gas savings in the road transport sector (upper) and the overall energy share of biofuels in the transport sector in general (lower) according to the E4tech scenarios.

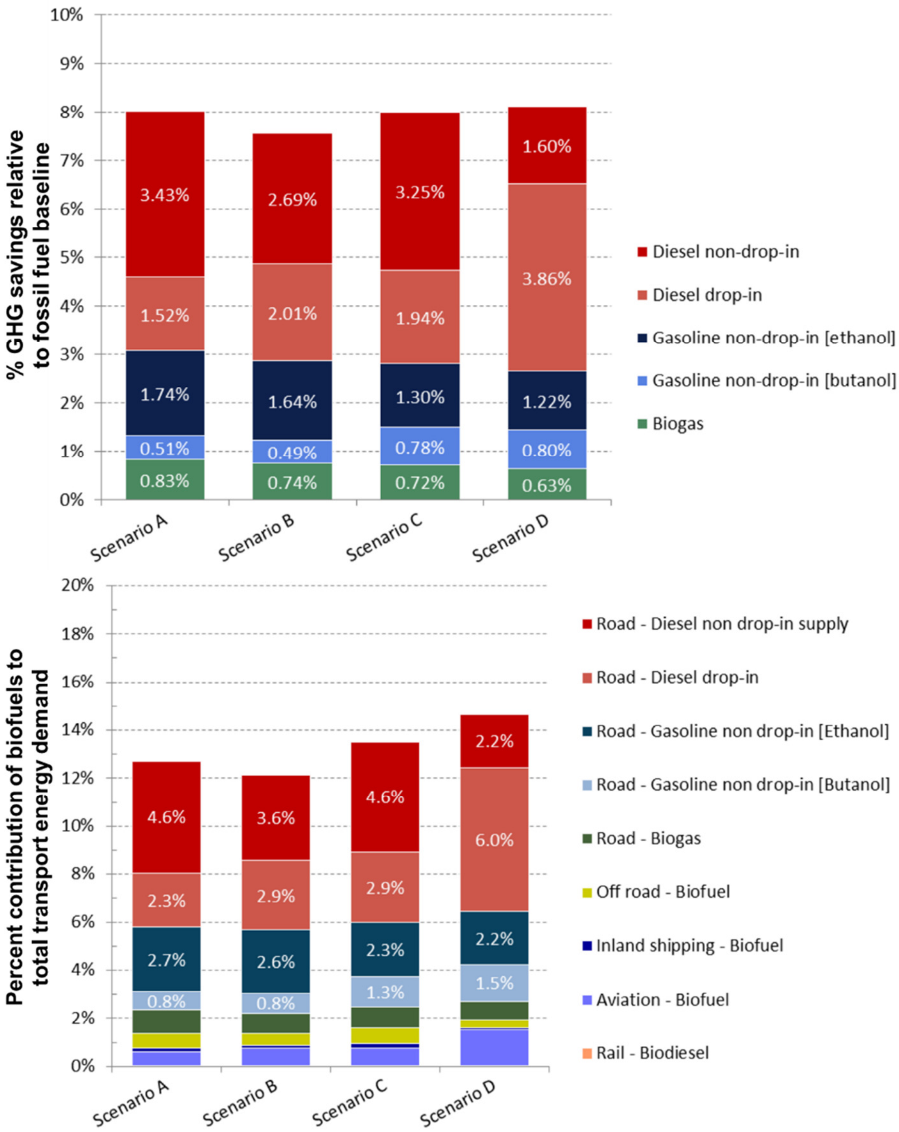


Figure 15: Contribution of biofuels to GHG savings in road transport (upper) and overall energy contribution of biofuels in transport (lower) in 2030 according to different scenarios of the E4tech study (E4tech 2013).

The scenarios are then used as a basis for proposing a roadmap, with a strong focus on blend-in fuels for use in today's Otto and Diesel engines and extending the blend-in limits, as illustrated in Figure 16.

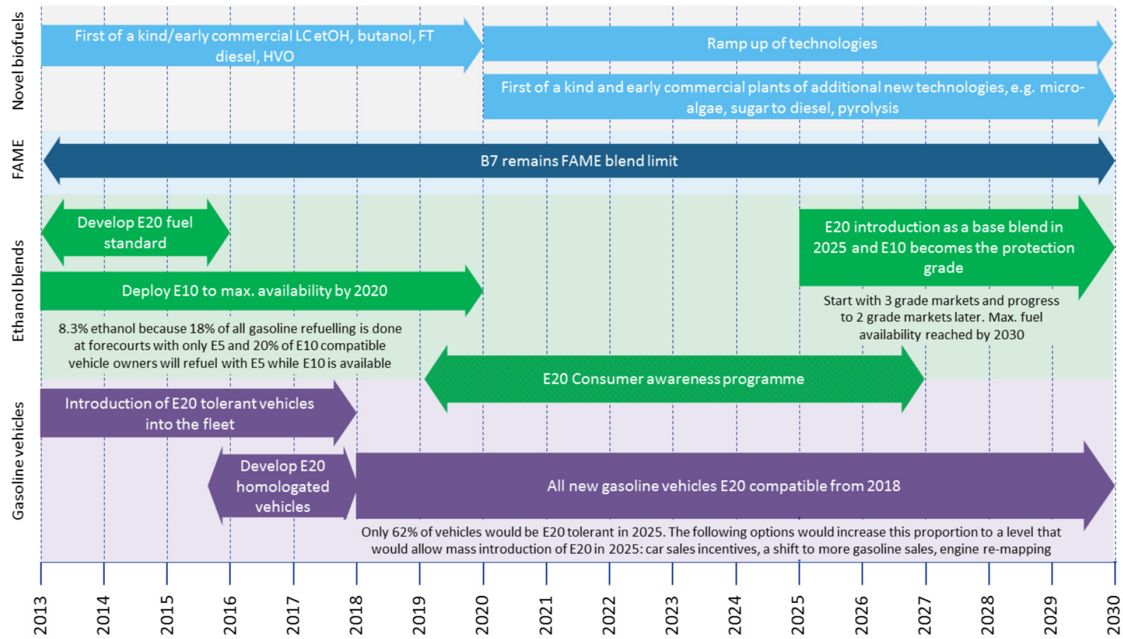


Figure 16: Biofuel roadmap according to E4tech study (E4tech 2013).

FVV study: Future Fuels for Combustion Engines & Gas Turbines

The German Research Association for Combustion Engines (Forschungsvereinigung Verbrennungskraftmaschinen – FVV) issued a report in 2013 on potential future fuels for combustion engines and gas turbines (Albrecht *et al*. 2013). During expert workshops ten fuel alternatives were selected and assessed using a so-called fit-for-purpose matrix (illustrated in Figure 17).

Fuel	Cars	Duty vehicles	Ships	Aircrafts	Power / Stationary machines	Mobile machines
▪ Gas to liquids (GTL) ▪ Hydrotreated veg. oils (HVO) ▪ E-gasoline/E-kerosine/E-diesel ▪ Heavy fuel oil to middle distillates						
Dimethyl ether (DME)	Like LPG	Like LPG				
Oxy-methylene ether (OME)	Blend	Blend	Blend			
Methanol (MeOH)					Handling?	
Compressed natural gas (CNG)		Long distance				
Liquefied natural gas (LNG)	Dor-mancy	Dor-mancy?				Dor-mancy?
Hydrogen (CGH2)				LH2?	Existing fleet?	

Strength/Opportunity
Undefined/Relative
Weakness/Risk

Figure 17: "Fit-for-purpose" matrix used in FVV study (Albrecht et al. 2013).

Various production pathways for the different fuel options were assessed for both cost (€ per liter Diesel equivalent) and GHG emissions from a LCA perspective and set in relation to standard fossil alternatives. Both cost and GHG emission results are presented in the FVV with costs (without taxes) for biofuel alternatives ranging between 2.8 and 6.7 €/$l_{\text{Diesel-equivalent}}$ against a reference price range for fossil fuel of 0.64 to 1.18 €/$l_{\text{Diesel-equivalent}}$. Biofuels are stated to have the potential to almost completely avoid the GHG emissions from fossil fuels (about 90 g CO_2-eq/MJ) but at rather high avoidance costs ranging from about 500 to 1400 €/t CO_2-eq avoided.

The study concludes that there cannot be a single fuel identified as winning alternative, but that a mixture of alternative fuels is to be expected in the near term future (2020+). The recommendations are to investigate e-fuels (using synthesis from hydrogen generated from electrolysis and carbon dioxide from different potential sources such as for example biogas or combustion flue gases) and algae based fuels as both might become important pathways in the long term. The large degree of uncertainty of their actual potential however makes additional research necessary.

ERTRAC Roadmap: Energy Carriers for Powertrains - for a clean and efficient mobility

The European Road Transport Research Advisory Council (ERTRAC) – the European Technology Platform (ETP) for Road Transport – published in 2014 a roadmap providing "an overview of energy carriers and production routes that offer significant potential to contribute to decarbonisation of the transport system's energy supply" in view of the European Commission's target to reduce the transport sector's GHG emissions by 60% in 2050 relative to 1990 (ERTRAC 2014).

The study presents milestones on a qualitative level for efforts considered necessary by the authors to achieve the GHG emission reduction goals within:

- research and development
- production and market and
- regulatory framework.

The analysis is performed for energy carriers (biofuels, natural gas and electricity) as well as for engine powertrain development. In order to achieve the ambitious emission reduction goals ERTRAC advises to focus on a harmonized European framework with reliable and long term overall targets for different industries and sectors. For the transport sector these targets should apply to the fuel (or energy carrier) supply as well as efficient use in vehicles. The major focus – according to ERTRAC – will be on cost-efficient electricity with low carbon intensity and biofuels as key elements in the overall optimization of the whole value chain from well to wheel.

American biofuel roadmaps – GREET model

The Argonne National Laboratory has developed the GREET software (Argonne 2014) – an LCA tool – and used the model to generate a large number of fuel pathways analyzing the well-to-wheel performance in a similar way as the JEC study. Figure 18 gives an illustration of the GHG emission performance of the different pathways generated with GREET. A modified GREET model has also been used to generate the fuel pathways specified under the Californian Low Fuel Carbon Standard Program (LCFS) (ARB 2015).

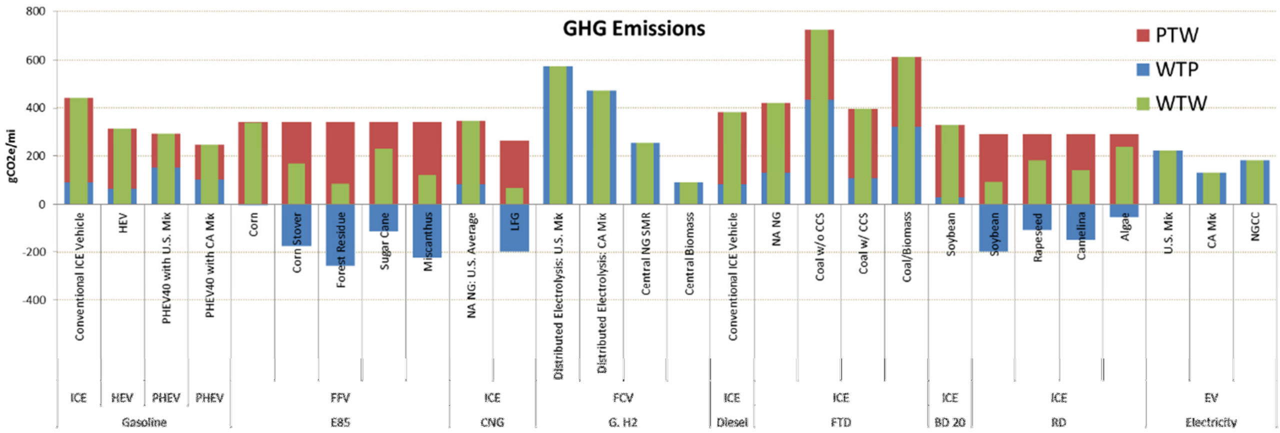


Figure 18: GHG emission performance (pump-to-wheels (PTW), well-to-pump (WTP), and well-to-wheel (WTW)) for a number of pathways generated using the GREET LCA software (Argonne 2015).

Systems studies: reflections on similarities and differences

The systems studies presented, all have adopted a somewhat different analysis approach, presuming different assumptions leading to different results. It needs to be kept in mind that the consortia standing for the different reports are often industry based. This might to some extent influence the basic delimitations adopted as starting point as well as interpretation and presentation of results with industrial interests being prioritized over a holistic and impartial approach. Nevertheless a number of common conclusions can be identified. A general trend in the systems studies – most of them having a time perspective between 2020 and 2030 – is to highlight the importance of increasing the limits for blending renewable fuels or additives to today's major fuels, i.e. diesel and gasoline. HVO and FAME are the major biofuels identified as diesel substitutes, with the latter being limited to the current 7% blending limits according to e.g. the E4tech study (E4tech 2013). Ethanol, butanol, ETBE and MTBE are the major blend-in (or even substitute in case of alcohols) alternatives mentioned for gasoline. Methanol is controversially discussed in the different studies: in the Volvo study (Volvo 2008) with focus on heavy duty engines methanol scores quite well within all categories whereas for example the FVV study is skeptical about methanol, in particular due to its toxicity (Albrecht *et al*. 2013). The JEC study does not consider methanol as an alternative fuel for engines at all within their timeframe (2020+) and only analyses the well-to-tank aspects (Edwards *et al*. 2014).

Liquid fuels are clearly in focus for all studies. This again is related to the time horizon the studies have adopted. As a consequence, the blend-in wall for ethanol is a critical aspect lifted in studies. On the supply side, the E4tech study, for example, concludes that transition to E20 is more likely to be limited by the vehicle fleet transition rather than the sustainable supply of biofuels (E4tech 2013).

Gaseous fuels are identified as very interesting alternatives considering the production processes. In particular biogas from digestion of waste streams performs very well with respect to greenhouse gas benefits (assuming zero or low leakages). Drawbacks for gaseous fuels – renewable methane (or biogas) being the major option – are the lacking distribution infrastructure, vehicle fleet and, to some extent, the limited feedstock potential (in particular for biogas from anaerobic digestion).

Studies extending the timeframe consider algae-based fuels as interesting options, however, big question marks in particular on feedstock availability and costs remain. Electrofuels are seen as a competitive/complementary alternative to electromobility and their interrelation with renewable electricity generation might be very well adapted to future energy markets. But higher costs and a penalty on efficiency due to conversion steps limit their potential in the short to medium term.

Research needs identified

Based on the above mentioned reports and data an attempt to identify research needs within the different areas of biofuel systems analysis is made. In Figure 19 the current state of knowledge, as well as the future research needs, are qualitatively represented for both different biofuel categories and areas of biofuel systems research. Biofuel categories included are:

- **currently available biofuel options**
  such as ethanol, FAME, HVO, biogas etc.
- **conventional (large-scale) biofuel options under development**
  such as FT-Diesel, methanol, DME, SNG etc.
- **non-conventional biofuel options under development**
  such as butanol, furans, etc.
- **future biofuel options that are not yet discussed at large scale or even not yet identified**
  such as algae-based fuels or electrofuels (e.g., power-to-gas)

Obviously, there is no clear distinction between these four categories and different fuels may qualify for more than one category depending for example on their biomass feedstock or production pathway. The goal with this kind of representation is to illustrate the multi-faceted research needs from a systems perspective for both current biofuels as well as for fuels that might emerge in future, without going into detail for specific pathways. The green shading of each field in Figure 19 represents the state of knowledge for the given combination of biofuel category and research area. It should be considered as a qualitative measure for the research work performed to date.

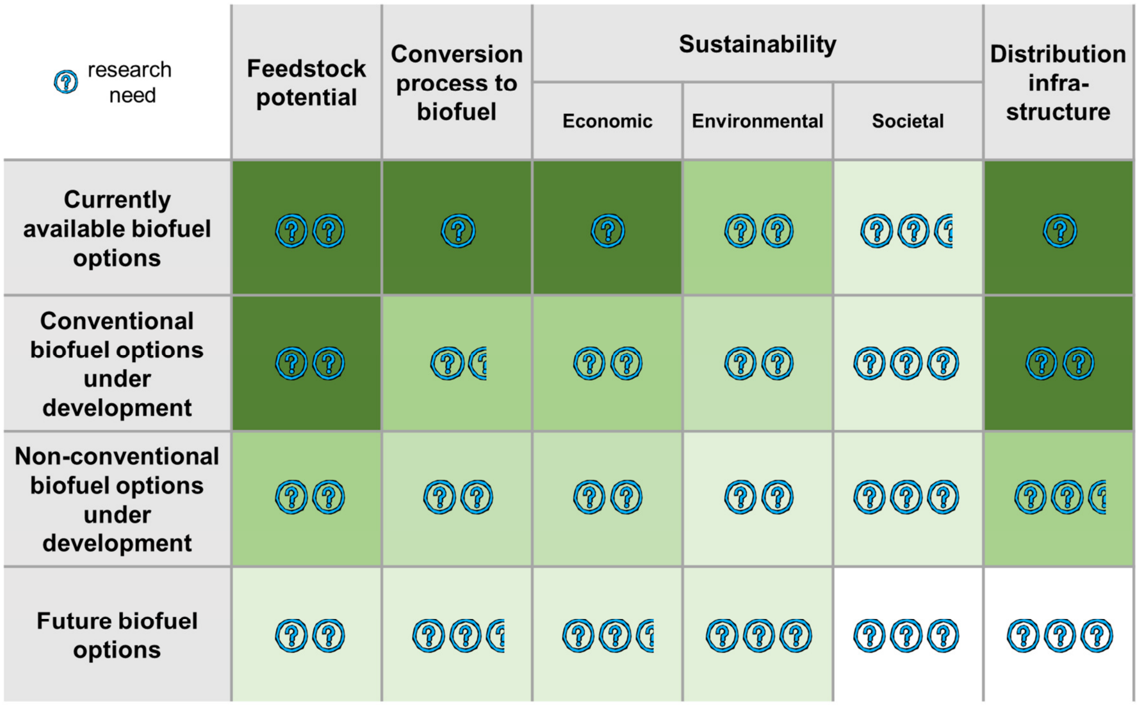


Figure 19: Qualitative assessment of the state of knowledge (shading) and the research need (question mark symbols) for biofuels with respect to production systems analysis. The darker the green the higher the knowledge level.

A darker shade of green indicates a higher state of knowledge or more research work already preformed. The number of question marks in each field indicates on a qualitative level the research need for the given field. No statement with respect to the relevance or importance of the different research areas is made here.

Considering for example the feedstock potential for current biofuels, a lot of research work has been conducted to date. However, there still resides a considerable uncertainty in the estimates and we consider that research efforts are needed to address and reduce this uncertainty. Even for emerging biofuels the feedstock situation is quite well investigated while for future biofuels – e.g. based on algae – the feedstock potential is less well defined. Further research is needed for improving estimates of the feedstock potential for all biofuel categories.

For the conversion processes the state of knowledge is considerably higher for currently available biofuel options that to some extent already are produced at industrial scale or at least in demonstration plants. For future biofuel options the state of knowledge is lower with lab-scale experiments being the major source of knowledge.

Regarding the sustainability aspects, most work has been done on the economic level, followed by environmental investigations. Little work is done so far on social sustainability aspects of biofuels. Research needs are identified as a logical consequence in particular on the social level and on all levels for long term biofuel alternatives.

Finally, with respect to distribution infrastructure, there is an advantage for drop-in fuels that can be blended with current commercial fuels compared to completely new fuels in need of a dedicated infrastructure. For future biofuel options that demand new infrastructure, further work is needed in order to develop possible distribution systems.

Conclusions

In the present review the current state of art in systems analysis for biofuel well-to-tank analysis is presented and future research needs identified with focus on future and potentially tailor-made biofuels for engine applications. In systems analysis, sustainability criteria are important performance indicators that are used to rank different pathways. It has been shown that not all dimensions of sustainability can be evaluated on a quantitative level. Nevertheless, research should focus on multi-objective evaluation and optimization of future biofuel alternatives, even using qualitative measure at some level as they still may serve as a useful tool for policy and decision makers.

From analyzing the reviewed studies we have identified research needs in the following key areas:

- multi-objective optimization accounting for parameter uncertainties to identify robust pathways for the future
- studies accounting for regional differences and opportunities/risks for both feedstock growth and harvest as well as production processes (e.g. integration to existing industry infrastructure)
- interactions between biofuel production processes and the stationary energy sector, again including aspects of regional differences; in particular electrofuels are of interest in that regard
- continuous update of systems studies with most recent developments in production process development
- better understanding of land use change effects and feedback loops to facilitate decision making in order to avoid biofuel production options with negative effects with respect to greenhouse gas emissions and environmental performance from a systems perspective
- social factors – even though not being quantifiable at the same level as economic and environmental ones – need to be included for both fossil and renewable fuels as an additional measure for decision making; work is even needed for developing methods better taking into account social factors

Finally, the systems analysis of biofuel production processes could be extended to a higher level tackling question on how to realize the theoretical potentials of biofuels without interfering with other interests. In particular interference with food production needs to be studied in more detail to avoid negative lock-in situations. Börjesson *et al.* (2013) state in their conclusion that there is room for increasing bioenergy and biofuel production and at the same time reducing impact on agricultural markets and food production by prioritizing a diversification of production technologies as well as types of biofuels and identifying different future options. This in turn requires regional optimization of land use and adapted sustainability policies that are supported by intergovernmental rules and policies. Possible measures for avoiding competition with the food sector could be the intensification of food production, using fallow land for biofuel production, reducing losses in food chain, or changing diet towards less meat and in particular less beef (Börjesson *et al*. 2013). All of these options are interlinked and their effects need to be studied with a holistic approach.

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