RESolve-Biomass

D6.1 Fully updated and verified RESolve-Biomass model

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Report nr. TNO 2018 P10699

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.º 764799.

Deliverable Information	
Grant Agreement Number	764799
Project Acronym	ADVANCEFUEL
Instrument	CSA
Start Date	1 September 2017
Duration	36 months
Website	www.ADVANCEFUEL.eu
Deliverable Number	D6.1
Deliverable Title	Fully updated and verified RESolve model
Expected Submission	M10
Actual Submission	M10
Authors	Marc Marsidi, Ayla Uslu, Joost van Stralen
Reviewers	Jeroen Daey Ouwens, Kristin Sternberg, Ric Hoefnagels, Thuy Mai-Moulin, Panoutsou Calliope, Sonja Germer
Dissemination Level ***Public (PU), Restricted (PP), Confidential (CO)***	PU

Executive Summary

The project ADVANCEFUEL focuses on accelerating the market uptake of RESFuels in the European transport sector. RESfuels refer to liquid advanced biofuels produced from lignocellulosic biomass and other liquid renewable fuels from non-biological origin. ADVANCEFUE will define strategies for the further development of RESfuels and the RESolve-Biomass model of ECN part of TNO will be used for the integrated analysis in the project. It will provide insights in full-chain fuel cost, taking into account feedstock costs and potentials, logistics, technology performance and market demand.

The RESolve-Biomass model has a long track record. It was created in 2005 and further developed and used for impact analysis in a number of projects. It is a cost optimisation model that incorporates electricity, heating & cooling, biofuels and also biobased products. Within the ADVANCEFUEL project, alterations were made to the model to fulfil the specific needs of the project.

A strong feature of the model is the high level of detail regarding conversion technologies and the related feedstock and in-between logistics (including technologies for fuels for the aviation and maritime sectors). The detailed modelling allows for import and export to be explicitly shown, both for feedstocks, intermediates and final products.

The main limitation of the model is the lack of incorporating demand-side dynamics that can influence the cost and supply of feedstock as well as energy prices.

In order to optimise results and better meet the requirements of the ADVANCEFUEL project, the model data sets were updated and the technology sets were expanded to cover the aviation and maritime sectors. In addition, a separate Excel tool was created to mimic the interactions between demand for biofuels and the electrification of the transport sector.

Contents

1 Introduction

The project ADVANCEFUEL focuses on accelerating the market uptake of liquid advanced biofuels and other liquid renewable fuels[1], jointly referred to as RESFuels, in the European transport sector. The project will define strategies for the further development of RESfuels. These strategies, however, should be based on solid insights in full-chain fuel cost, taking into account feedstock costs and potentials, logistics, technology performance and market demand. Acquiring such insights will require research regarding the impacts of accelerated feedstock mobilization, technological progress, and trends of fossil energy prices, using various demand and supply scenarios that take into account both socio-economic and environmental aspects.

ECN part of TNO's RESolve-Biomass model is the main modelling instrument to analyse the future of RESFuels using different scenarios. These scenarios will include assessment of 'innovation cases' related to cropping, conversion technologies and system integration, sustainability safeguards, and market development.

RESolve-Biomass is an extensive model that determines the most optimal (least-cost) set of bio-conversion routes to meet the demand for biobased sectors. All relevant biofuels and all the major transport modules are covered in this model. See Figure 1 that shows the lignocellulosic feedstock based biofuels. This document describes the RESolve-Biomass model and reviews key developments and improvements that have been made to the model specifically for this project.

1 Liquid advanced biofuels are defined as all liquid biofuels produced from lignocellulosic biomass. Other liquid renewable fuels refer to all renewable fuels that do not use biomass as feedstock.

Biofuel type					
2G ethanol	√				
ATJ jet				√	
ATJ gasoline	√				
ATJ diesel	√	√	√		√
DME	√	√	√		
FT	√	√	√		√
FT jet				√	
HTL gasoline	√				
HTL diesel	√	√	√		√
HTL jet				√	
Pyrolysis diesel	√	√	√		√
Pyrolysis gasoline	√				
Pyrolysis jet				√	
Bio-CNG/LNG	√				√

Figure 1: Advanced biofuels covered in RESolve-Biomass (van Stralen 2017)

The RESolve-Biomass model is described in chapter 2. In chapter 3 the adaptations made to the model for this specific project are explained.

2 RESolve-Biomass

There is a clear need for dedicated modelling of biobased sectors that covers the complete value chains for different sector; from feedstock(s) to product(s), with details regarding both the feedstock supply chains as well as the conversion technologies, and including country specific production and end-use. Standard integrated assessment models (IAMs) (Loulou et al. 2004, Loulou et al. 2016) are well suited to addressing questions regarding the role of biomass at a system level (e.g. the competition of biobased options versus other options for low-carbon and clean transport). However, given the inherently generic description of biomass chains, IAMs face difficulties in addressing questions that require a more detailed coverage of biobased supply chains and markets.

The RESolve-Biomass model is designed to predict trade flows of biomass and biobased products between countries, and makes analyses of specific technological developments or innovations in feedstock mobilisation. It is, therefore, able to tackle the complex questions regarding biobased supply and demand and is more suitable than IAMs to be used in this project.

2.1 Modelling framework

'RESolve-Biomass' is an optimisation model programmed in AIMMS. The key (exogenous) inputs of this model are the demand for final bioenergy (in electricity, heating & cooling and transport sectors) and biobased products (biochemicals). The model determines the least-cost configuration of the entire biobased production chain, given the demand projections for biofuels, bioelectricity, bioheat and biochemicals, and taking into account the cost-supply curves of various biomass feedstocks and conversion technologies (including technological progress), under several possible conditions and constraints (van Stralen et al. (2012), van Tilburg et al. (2005), Lensink et al. (2007)). An overview of the model characteristics is provided in Figure 2. By doing so, this model mimics the competition among the four sectors demanding biomass feedstocks. The model optimises each year within a given timeframe.

RESolve-Biomass model

System components	Exogenous model components (input)	Endogenous model components (output)
Biomass supply	• Domestic and imported biomass supply potentials • Key constraint: feedstock mobilization rate	• Feedstock portfolio

Energy system	• Conversion technologies
	  • Technology scope and techno-economic data
	  • Greenhouse gas performance thresholds
	  • Technological learning system and introduction year
	• Key constraint: technology deployment rate and blend wall
		• Technology portfolio
		• System cost*
		• Greenhouse gas reduction (post-analysis)
		*the model minimizes total *additional* system cost

Biomass demand	• Demand for bio-based electricity, heat, chemicals and transport fuels • Regulatory framework (biofuel targets and multiplier for aviation and marine)	• Biofuel use in aviation, marine, and road transport

Figure 2: Exogenous and endogenous model components of RESolve-Biomass (de Jong et al. 2017)

The RESolve-Biomass model covers the entire supply chain, including: raw feedstock production (for example energy crop cultivation), (pre)processing, conversion, transport and distribution to final end users. One of the most important features of the model is the ability to simulate international trade of both intermediates and final biobased products. By providing the trade attribute (between EU member states and imports from third countries), future cost of bioenergy and biochemicals can be estimated in a much more realistic way compared to evaluating costs in each country separately. The most recent functional description of the model derives from the Biomass Futures project (van Stralen 2012). The most recent updates and expansions can be found in the S2Biom Integrated Assessment (van Stralen 2016).

While the model has been developed and adapted over time, some characteristics have remained identical, but with regular updates of the datasets. Those are:

1. Description of the full supply chains of biobased energy and materials, from feedstock to end use, in a step by step approach: This allows the model to choose optimal combinations of feedstocks, logistics (including international trade), conversion, logistics again (with trade options) and end use;
2. Statistical data: A meaningful analysis of future trends starts with a good reproduction of historical trends. Statistical data is used to calibrate the model;
3. Prevention of radical changes from year to year ('flip-flop-behaviour'): This is a feature frequently observed in models that optimise from year to year. By introducing logical constraints (the impact of sunk costs, maximum rates of feedstock and technology growth and a vintage approach), the model has gradually become more robust in this respect;

4. Impact of technology learning: This has always been an important feature of the model (see de Wit et al. (2010)). For established technologies, the model applies (endogenous) cost reductions through a learning curve approach. For novel technologies, for which such an approach is less adequate, technology cost reductions are dependent on, among other factors, a maximum rate of upscaling and a related scale factor for the impact on costs;
5. Policy impact: As most biobased options require policy incentives to be economically feasible, the model has always had ample attention for the impact of policies. The basis mechanism (least cost solution for a given volume target) most closely resembles obligation policies, but the model can also assess the impact of feed-in support, and accompanying measures such as investment subsidies, specific support for feedstock mobilisation, caps on specific biofuels and the double counting mechanism for advanced biofuels;
6. Additional costs related to biofuel distribution: Some of the biofuels require technical or structural adjustments in the distribution stations (i.e. the extra costs for safety measures) (Lensink et al, 2007). These distribution costs are included for biofuels for road transport and aviation. They are further differentiated according to the type of biofuel, i.e. CNG, DME and renewable jet fuels. Such costs for shipping has not yet been included in the model;
7. Additional costs related to vehicle adaptation: The drop-in biofuels, in principle, do not require adaptations to the vehicle fleet[2]. For other fuels vehicle adaptations will be needed and these costs are included in the model as follows:
    - Additional car costs related to E85. E85 will require flex fuel cars that can run on ethanol blend of 85%. The cost difference of a flex fuel car in comparison to a conventional (gasoline) car is included in the model as additional cost;
    - Modest modifications will be needed to convert a diesel engine to run on DME. These costs are included in the model for trucks and busses.

[2] The model also includes additional costs incurred for 1st gen biofuels: in case of B100, the car engine will need to be modified to run on 100% FAME), B30 for trucks has also additional costs due to adaptations.

2.2 Key input

The key input data to conduct scenario analyses using the RESolve-Biomass model are:

- The biomass cost-supply data;
- The techno-economic data related to conversion technologies (both pre-treatment and final conversion);
- Input data for logistics of feedstocks, intermediate products and fuels.

Generally, the number of feedstock types and conversion routes (see Annex 1: Techno-economic table) is always a compromise between level of detail and refinement, and practical considerations such as model runtime and data collection efforts.

2.3 Historical development of the model

Table 1 shows the list of various projects in which RESolve-Biomass has been used (the model was named BIOTRANS in the past). It illustrates the model scope expansion. Initially, the model was covering only biofuels for road transport in the Viewls, REFUEL and ELOBIO projects. The model was expanded to cover also electricity and heating & cooling sectors within the Biomass Futures and Biomass Policies projects. Finally, in the S2Biom project the use of biomass to produce biochemicals was also included in the model. Through all these projects, the modelling of competition and synergy effects were gradually improved (note, however, that the benefits of complex biorefinery systems that provide a wide array of outputs is not yet within the modelling scope). Some previous assessment examples conducted through the RESolve-Biomass model are presented below.

- Analysis of potential future biofuel development pathways using the modelling approach (setting up roadmap for biofuels in 2030);
- Analysis of impacts of different policy instruments on biofuel deployment and related costs;
- Assessment of the role biomass can play in meeting EU energy policy targets up to 2030 (with intermediate 2020) by bringing biomass demand and supply trends together;
- Integrated assessment of lignocellulosic biomass chains, for energy as well as chemicals and materials.

Table 1: Assessment of demand for biobased energy carriers and products: coverage and assumptions in the course of the projects.

Project	Demand sectors covered[1]	Combinations modelled	Sources for demand assessment	Overall energy reference scenario
ADVANCEFUEL	HEFC	CHP, Heat and power as co-products of several value chains of biofuels and biobased chemicals. Biomass also covers biofuels for aviation and maritime	For transport - PRIMES2013 and WEO2018	PRIMES2013 reference scenario.
S2Biom (2016) Kraan (2015), Mozaffarian (2016)	HEFC	CHP, Heat and power as co-products of several value chains of biofuels and biobased chemicals	HEF:GREEN-X modelling, and NREAPS, consistent with RED targets (2020) and Climate package (2030) C: Market review (2020/30)	2030 Energy & Climate package impact assessment, GHG40 scenario.
Biomass Policies (2016) Uslu et al. (2016), van Stralen et al. (2016)	HEF	CHP, Heat and power as co-products of several biofuel value chains	HEF:GREEN-X modelling, and NREAPS, consistent with RED targets (2020) and Climate package (2030). However, for HE further refined by interaction with the RESolve-E model	2030 Energy & Climate package impact assessment, GHG40 scenario.
Biomass Futures (2012) van Stralen et al. (2012)	HEF	CHP, Heat and power as co-products of several biofuel value chains	HEF: NREAPS and PRIMES 2009 Ref. For E further refined by interaction with the RESolve-E and -H/C models	PRIMES 2009 Reference
Elobio (2010) Bole et al. (2010)	F	Heat and power as co-products of several biofuel value chains	2020: RED (10%) 2030: project-defined ambition (15%)	PRIMES 2006 Reference
REFUEL (2008) Londo et al. (2008)	F	Heat and power as co-products of several biofuel value chains	2020: RED (10%) 2030: project-defined ambition (25%)	PRIMES 2006 Reference
Viewls (2005) van Thuijl et al. (2005)	F	None	2010: BFD (5.,75%) 2030: project-defined ambition (20%)	PRIMES 2003 Reference

[1]: Demand sectors: H: Bio-Heat, E: Bio-Electricity, F: Biofuels, C: Biobased chemicals

2.4 Key strengths

The RESolve-Biomass model has the following key strengths:

1. It covers supply chains with a relatively fine level of detail in regard to feedstock types, conversion technologies and the logistics in-between (see Figure 3 for an example of technology mixes). Especially when compared to other integrated energy models or models covering all renewable energy options on a European level, RESolve-Biomass offers more detailed insights into the biobased sectors;
2. The inclusion of aviation and maritime sectors and related supply chain elements of biofuels;
3. Import and export between countries can be explicitly shown, both for feedstocks, intermediates and final products. Import/export between countries is explicitly modelled.

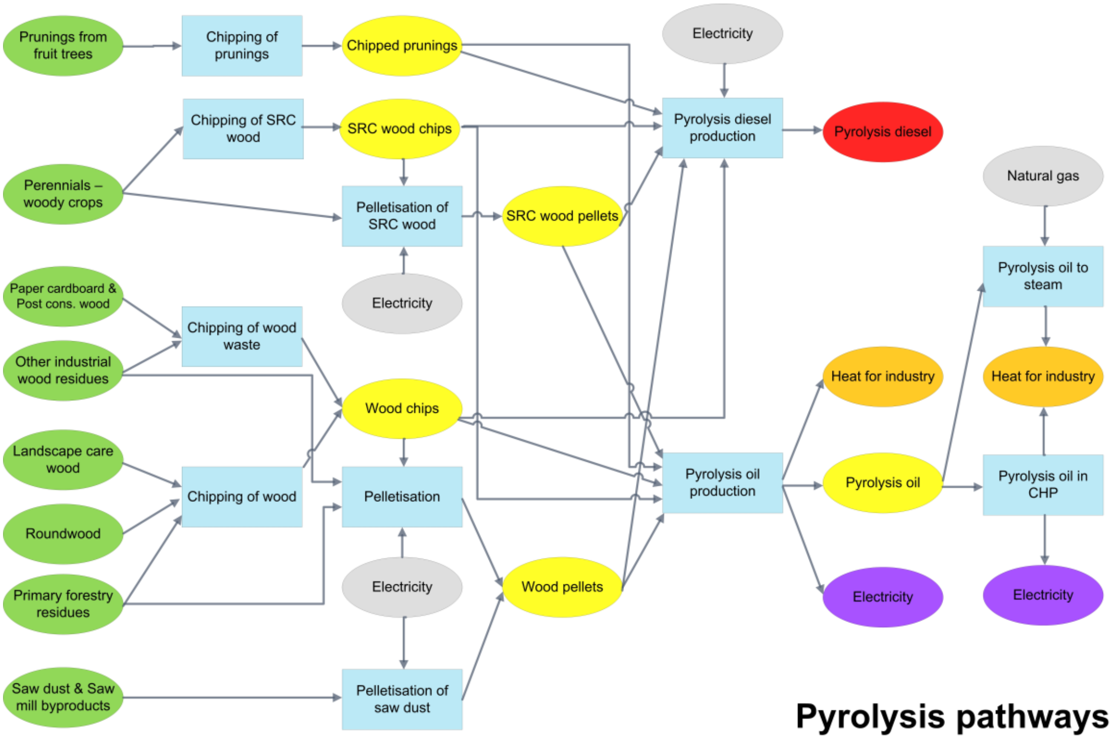

Figure 3: Example of the level of detail modelled in RESolve-Biomass

2.5 Model limitations

As with any model, knowledge of its limitations is pivotal for adequate application and interpretation of its outcomes. Key limitations we observe in (the current version of) RESolve-Biomass are:

1. The cost-supply data of the various feedstocks are fixed for the years 2020 and 2030 (although they may change over the years). Especially for feedstocks that can also be

used for other applications than energy (e.g. food crops), this is a strong simplification: demand-side dynamics in other markets than energy and chemicals will directly influence feedstock prices. However, through the information on marginal feedstock costs, to what extent these costs deviate from current or expected market prices can now be checked;

2. The model does not include explicit land use dynamics or competition with other types of land use. This also means that it is not suited to assess complex systemic effects such as indirect land use change (ILUC). For such analysis, macro-economic models and land use change models need to be used in combination with RESolve-Biomass;
3. The demand for final biobased energy and chemicals is fixed, which means that the model does not have any dynamic interaction with:
    a. other RES options such as wind, solar and geothermal. This interaction, however, can be simulated in a simplified way by transferring marginal costs of biobased options from RESolve-Biomass to its sister models RESolve-E and RESolve-H, in which they compete with other renewable options for electricity and heat, respectively. However, these models are less elaborate and up-to-date in terms of data;
    b. fossil options. Although fossil energy prices are included in the model (also in order to calculate overall system costs compared to a reference with more use of fossil energy and fossil-based chemicals), fossil energy prices are not affected by a decrease in demand because of the growth or renewables. With low shares of renewables this is acceptable, but with the foreseen significant growth of renewables this becomes problematic;
    c. other greenhouse gas (GHG) reduction options like electric vehicles (EV's), carbon capture storage (CCS), and energy savings. The key denominator of the model is energy, and euros per PJ of final energy. This means that the model is not fit to find optimal balances in terms of least costs per tonne avoided CO_2-equivalents, although the model contains GHG data for most of the value chains.
    d. biofuel types included in the model. The biofuel types considered for transport sector is more representative for the time frame up to 2030. Beyond 2030, other types of biofuels may be ready for the market uptake such as biobutanol and biomethanol. In the current version biomethanol is included as a building block for biochemicals. Biobutanol is not included. Technologies readiness levels (TRLs) of several technologies will be analysed in WP3. When the result indicate other promising biofuel options beyond 2030 these will included into the model in the course of the ADVANCEFUEL project.

3 Model adaptations for ADVANCEFUEL project

In order to optimise results and better meet the requirements of the ADVANCEFUEL project, the model data sets were updated and the technology sets were expanded. In addition, a separate Excel tool was created to mimic the interactions between the demand for biofuels and the electrification of the transport sector.

3.1 Database update

The following datasets were updated and/or expanded:

- Eurostat data: Statistics on the use of different fuel types in the transport sector were updated;
- HVO and 2nd generation ethanol production[3]: These statistics could not be obtained from Eurostat and were updated separately (Neste, 2014; IRENA, 2018; Ecofys, 2015; EurObserv'ER, 2018);
- New end-users: Aviation and marine were added to the end-users in the transport sector;
- Renewable jet fuel targets: The target for biofuels for airplanes can now be set independently. This allows for simulations in which the renewable jet fuels can either have a separate target or are included in the general RES targets for transport;
- Output flexibility: The ratio of the outputs, for technologies that have multiple outputs, is not fixed but can be optimized (within the constraints of a fixed range);
- Timeframe: The model timeframe was extended to include the period up to 2050;
- 2nd generation ethanol: This technology has been split into two processes: straw and wood based.

[3] There is currently no production of 2nd generation biofuels other than ethanol.

3.2 Aviation and maritime biofuels

One of the main changes made to the RESolve-Biomass model for the ADVANCEFUEL project was the inclusion of aviation and marine sectors as end-users. To this end, a set of new technologies was added to the model's database that enables the model to include the production of jet fuel and marine fuel.

Table 1: Aviation biofuel for kerosine

Biofuels	Process
Alcohol-to-Jet (ATJ) for jet	Alcohol-to-Jet (ATJ)
Fischer-Tropsch (FT) for jet	Fischer-Tropsch-DJ (diesel jet)
Hydroprocessed or Hydrotreated Renewable Jet (HRJ) from Used frying oils (UFO)	Hydrotreated Esters and Fatty Acids (HEFA) - (HRD/HRJ)
Hydrothermal Liquefaction Jet (HTLJ)	HTL-DJ (diesel jet)
Pyrolysis jet	Pyrolysis diesel+jet production
Hydroprocessed or Hydrotreated Renewable Diesel (HRD) from UFO	HEFA-HRD using UFO

Table 2: Marine biofuels for heavy fuel oil

Biofuels	Process
1G biofuel	Various
Biodiesel from UFO	Various
Bio FT diesel	FT production
HRD from UFO	HEFA-HRD using UFO
Hydrothermal Liquefaction Diesel (HTLD)	HTL-D
Pyrolysis diesel	Pyrolysis diesel production
ATJ diesel	Alcohol-to-Jet (ATJ)
Pyrolysis heavy fuel oil (HFO)	Pyrolysis diesel production
Pure vegetable oil	Pure vegetable oil
Bio-HFO	HTL-D/HTL-DJ

Table 3: Marine biofuels for sulphur heavy fuel oil and marine gas oil

Biofuels	Process
1G biofuel	Various
Biodiesel from UFO	Various
Bio FT diesel	FT production
HRD from UFO	HEFA-HRD using UFO
HTLD	HTL-D
Pyrolysis diesel	Pyrolysis diesel production
ATJ diesel	ATJ

Table 4: Marine biofuels for liquid natural gas

Biofuels	Process
Bio-LNG	LNG process

3.3 Detailed yearly fuel consumption for each transport mode per member state

The RESolve-Biomass model requires the fuel consumption input data in the transport sector per country per year. In previous model versions the total fuel use in transport per country was extracted from PRIMES2016 (reference scenario) and the division in fuel type (gasoline, diesel) for passenger cars was based on PRIMES2013[4] (reference scenario). The following assumptions are made to make the distinction between fuel types based on the PRIMES2013 data:

- Motorcycles only consume gasoline;
- Aviation only consumes kerosene;
- Inland navigation consumes diesel and residual oil;
- Public transport consumes diesel, electricity, gas and hydrogen;
- Rail consumes electricity and diesel;
- Trucks only consume diesel.

For the ADVANCEFUEL project, the data for the reference scenario was extracted from the fuel consumption in transport as presented by PRIMES2013[5]. In addition to the previous version of the model, the division in fuel types for passenger cars was expanded to also include

[4] The PRIMES2016 results do not allow for such a distinction between fuel types to be made, so therefore the PRIMES2013 results had to be used.

[5] PRIMES2013 does not include the most recent development in policy making since the analysis stems from 2012. However, it is the most detailed publicly available PRIMES data and therefore the best fit for the ADVANCEFUEL project.

hydrogen, electricity, LPG, methanol and ethanol, and gas. Furthermore, the activity per transport mode (expressed in vehicle kilometres) was also extracted. The activity per transport mode will act as the basis for future scenarios to be constructed, and analysed using RESolve-Biomass. In the scenarios the total energy demand for biofuels will vary, depending on the assumed efficiency improvements of the vehicles, penetration of electrification and use of electric vehicles, etc. The total distance (vehicle kilometres) per transport mode, however, remains the same, which will allow for direct comparison of the scenario results.

4 Concluding remarks

The RESolve-Biomass model has been updated so that it can be used for the integrated assessment of innovative approaches related to biomass feedstock supply, conversion technologies and polices promoting RESFuels. This document briefly introduces the model and the additional updates. It is, however, necessary to emphasise that the datasets related to feedstock supply and conversion technologies will again be evaluated over the course of this project. The work packages (WPs) focusing on the analysis of feedstock supply (WP2), conversion technologies (WP3) and end use (WP5) will yield new information and the model database will be cross-checked and updated as new information is obtained.

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Annex 1: Techno-economic table

Technology	feedstock	main fuel type	Efficiency main product			Introduction year	Life-time (yr)	Investment cost (€$_{2010}$/kW)			Fixed O&M cost (€$_{2010}$/kW/yr)			Market-driven learning	Scale-driven learning				
			2010	2020	2030			2010	2020	2030	2010	2020	2030	Progress ratio %	Initial plant capacity (MW input)	Maximum plant capacity (MW input)	Scale factor	Doubling time (vii) (years)	Source
Starch-Ethanol	Starch	Gasoline	55%	55%	55%	2005	20	1,060	Learning	Learning	433	Learning	Learning	80%	n/a	n/a	n/a	n/a	Deurwaarder, 2007
Sugar-Ethanol	Sugar	Gasoline	45%	45%	45%	2005	20	659	Learning	Learning	272	Learning	Learning	80%	n/a	n/a	n/a	n/a	Deurwaarder, 2007
Transesterif-oil seed	Seeds oil	Diesel	99%	99%	99%	2005	20	201	Learning	Learning	81	Learning	Learning	90%	n/a	n/a	n/a	n/a	Deurwaarder, 2007
biomethane from gas(AD)	Manure	Gas	60%	60%	60%	2005	12	898	714	586	56	44	36	exogenuous	n/a	n/a	n/a	n/a	
Biomethane conversion to BioLNG	Biomethane	LNG	92%	92%	92%	2010	20	423	423	423	21	21	21	exogenuous	n/a	n/a	n/a	n/a	2016 World LNG report
Cellulose-EtOH	Lignocellulosics	Gasoline	39%	39%	39%	2015	20	3,673	Learning	Learning	363	Learning	Learning	95%	100	2,000	0.8	5	Deurwaarder, 2007
Alcohol-to-Jet (ATJ)	Lignocellulosic ethanol	Diesel/Gasoline/Kerosine	89%	89%	89%	2023	20	401	Learning	Learning	54	Learning	Learning	100%	100	2,000	0.8	5	de Jong, 2015
Hydrotreated Esters and Fatty Acids (HEFA)	Oils and fats	Diesel/Kerosine	109%	109%	109%	2007	20	543	543	543	80	80	80	70%	n/a	n/a	n/a	n/a	de Jong, 2015
FT liquid production	Lignocellulosics	Diesel	50%	50%	50%	2023	20	1,894	Learning	Learning	192	Learning	Learning	95%	100	2,000	0.8	5	de Jong, 2015
FT-kerosin	Lignocellulosics	Kerosine	45%	45%	45%	2023	20	1,894	Learning	Learning	192	Learning	Learning	98%	100	2,000	0.8	5	de Jong, 2015
DME production	Lignocellulosics	DME	65%	65%	65%	2023	20	1,369	Learning	Learning	55	Learning	Learning	0.98	300	2000	0.8	5	Hannula, 2013
Hydrothermal liquefaction (HTL) and full hydrodeoxygenation	Woody biomass	Diesel/Gasoline/Kerosine	56%	56%	56%	2025	20	833	Learning	Learning	109	Learning	Learning	98%	50	400	0.8	5	Tews, 2014
Pyrolysis diesel production	Woody biomass	Diesel/Gasoline/Kerosine	58%	59%	60%	2023	25	1,345	Learning	Learning	220	Learning	Learning	98%	50	400	0.8	5	Tews, 2014
Gasification for SNG	Lignocellulosics	SNG for transport	65%	65%	70%	2017	20	2,930	Learning	Learning	306	Learning	Learning	98%	32	3,200	0.8	5	Lensink et al. (2017)