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Biofpr Biofuels Bioproducts & Biorefining

Emerging bioeconomy sectors in energy systems modeling – integrated systems analysis of electricity, heat, road transport, aviation, and chemicals: a case study for the Netherlands

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Abstract: Several studies that have assessed the role of bioenergy in the energy system have primarily focused on electricity, heat, and road transport. However, sectors that have few alternatives to biomass, namely aviation and the chemical industry, are expected to become increasingly important. We have extended a bottom-up energy systems model with fossil-based and bio-based chemicals and with renewable jet fuels to assess the deployment of biomass conversion technologies in the Netherlands until 2030. The model comprises detailed cost-structures and mid-term developments for the energy system with detailed cost-supply curves for biomass, renewable energy technologies, and carbon capture and storage. The framework incorporates multi-output processes, such as biorefineries, to address cross-sectoral synergies. To capture the uncertainty in technical progress, technology development scenarios are used to assess cost-optimal biomass utilization pathways over time. Slow technical progress (LowTech) leads to biomass applications for heating, first-generation biofuels from hydrotreated oils, and bio-based chemicals based on first-generation fermentation systems. Enhanced technology development (HighTech) allows the production of second-generation biofuels, large volumes of diverse bio-based chemicals and renewable jet fuels. The required biomass may range from 230 PJ (LowTech) to 300 PJ (HighTech) in 2030, supplied primarily from imported resources. Both

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scenarios show that, under existing policies, CO_2 emissions will only gradually be reduced to reach 1990 levels (140–145 Mt CO_2). Further scenario analysis is recommended to assess model sensitivity and the necessary preconditions for future biomass conversion pathways and robust directions towards the required greenhouse-gas mitigation pathways. © 2018 Society of Chemical Industry and John Wiley & Sons, Ltd

Supporting information may be found in the online version of this article.

Keywords: energy systems analysis; bio-based chemicals; renewable jet fuels; bioeconomy; bio-based economy; cost-optimization

Introduction

The role of biomass in the global energy mix is frequently highlighted for its potential to mitigate greenhouse gas (GHG) emissions and diversify energy supply.[1–3] In contrast to other renewable sources, biomass can substitute fossil fuels in sectors for which there are no or few other alternatives (e.g. shipping, aviation, feedstock for chemicals). In the European Union (EU), biomass is the largest source of renewable energy and it is expected to remain so, increasing from 4 EJ in 2010 to 5.8 EJ in 2020, accounting for almost 55% of the EU renewable energy target.[4–6] A similar growth can also be expected post-2020, based on the European Commission's (EC) proposal to reduce GHG emissions in the EU by 40% in 2030 compared to 1990 under an EU-wide target of 27% supply of renewable energy by 2030.

The role and contribution of biomass is ambiguous in view of the EU's intention to expand its bioeconomy sectors strategically.[7,8] According to the EC,[9] 'the bioeconomy includes the sectors of agriculture, forestry, fisheries, food and pulp and paper production, as well as parts of chemical, biotechnological and energy industries.' The present study only assesses the energy, biotechnological, and chemical sectors and excludes food, feed and traditional material sectors. The development of the bioeconomy sectors, especially those that deliver raw materials (biomass feedstocks), energy, and industrial products, is seen as key to meeting societal challenges.[9] The EU addresses the need for a fair comparison of resource efficient uses of biomass across all sectors including bioenergy and biochemicals that will allow for improved biomass policies.[10] However, there is little understanding of how biomass will be distributed across the bioeconomy sectors or where it will be used most cost-effectively. To date, this gap impedes the design of improved biomass policies that promote its optimal deployment. One of the most notable omissions has been the use of biomass for bio-based chemicals. The potential contribution of selected bio-based chemicals to future GHG emission reduction ranges from 2 to 246 Mt CO_2/year per bio-based chemical, assuming complete replacement of the fossil counterpart.[11] At a global level, biomass demand for bio-based chemicals may potentially reach 18 EJ, achieving emission reduction of about 1.2 Gt CO_2/year, thus contributing to climate goals.[12] Despite their high added value, bio-based chemicals have so far been excluded from renewable energy policy frameworks and their diffusion in the market is limited.[12–15] The second key omission is the use of biomass for production of renewable jet fuels (RJF). Direct emissions from aviation account for more than 2% of global and 3% of the EU's GHG emissions.[16] The EU has the ambition to consume 2 Mt of RJF by 2020.[16] However, their uptake has been negligible, primarily due to limited production capacity and high production costs.[17,18] More insights are needed on market-based measures that may address the growth of RJF.[19]

An integrated systems perspective is required to overcome the knowledge gap on synergies and trade-offs of fossil energy reduction and GHG mitigation options beyond 2020, both in energy sectors (electricity, heat, transport fuels) and in non-energy applications (e.g. feedstock for bio-based chemicals). Several models have been used to provide such a perspective. A MARKAL (MARket ALlocation) model focusing on the power sector was used to assess the impact of international climate policies on carbon capture and storage (CCS) in the Netherlands.[20] The same model was used to assess the potential deployment of hybrid vehicles and of synthetic fuels with electricity generation and CCS, thus expanding the model to the road transport sector.[21] Other studies analyzed biomass deployment in the electricity, heat and transport sectors in the context of the EU's National Renewable Energy Action Plans.[5] However, none of these studies assessed biomass use for chemicals or RJF, even though these products had been analyzed in dedicated studies.[22–24] One study used a MARKAL framework to assess competitive uses of biomass for energy and materials in Europe.[25] However, this study was conducted in 2001 and new insights are required that take new policies and technology developments into account. More recently, non-energy uses of biomass have been assessed from a global systems perspective.[12] Nevertheless, interactions with the rest of the energy system have been ignored and a large temporal and geographical scope has been applied, which is not suitable to capture short-term developments. Other studies have used linear programming to model system interactions but they included only a limited number of products.[26] Large-scale production of bioenergy and bio-based chemicals in the Netherlands has been assessed; however, parallel developments in the deployment of fossil and renewable energy technologies were ignored.[27] Moreover, a critical aspect has not been sufficiently assessed: the multi-output production from biorefineries that can supply different sectors. The above omissions indicate the need for a comprehensive framework that considers a timeframe to 2030 and that includes the required sector-specific and region-specific details to assess the optimal uses of biomass across all competing sectors.

The main goal of the present study is to design a modeling framework that accounts for competitive and synergetic uses of biomass for energy (electricity, heat, fuels) and non-energy applications (bio-based chemicals). The framework should be able to capture future uncertainty regarding the technical progress of advanced conversion technologies. This uncertainty influences production costs and thus the competition of alternative technology options. Furthermore, the framework should address how the competitiveness of different biomass value chains is affected by the development of other renewable energy technologies. This extends the scope of other studies that assess comparative performance of biomass with a single competing technology.[28] The emphasis of this article is on the method applied. To demonstrate the modeling framework, it is applied in a context with sufficient regional and temporal detail. The Netherlands has been selected on the premise that it can support large-scale bioeconomy developments. The country has one of Europe's most efficient and advanced agricultural sectors, which is nevertheless limited by the domestic supply of biomass and land availability; it therefore relies heavily on trade. Moreover, the Netherlands has developed a competitive logistics infrastructure over the years and it holds a strong global position in the production of chemicals. Between 2025 and 2030, the gradual depletion of natural gas reserves will change the country from a net gas exporter to a net gas importer; a transition to a more resource-secure and sustainable energy system is therefore required.[29]

Methods

Model description

We employed MARKAL, a bottom-up, technology-rich and technology-explicit model, which uses linear optimization techniques to calculate an intertemporal partial equilibrium on energy and non-energy markets.[30] MARKAL and its successor, TIMES, are widely used to assess the dynamics of energy systems under different scenarios (e.g. the UK,[31] the US,[32] and the EU[33]), similar to the assessment aimed at in the present study. MARKAL generates a least-cost pathway for the total system by minimizing the system's present value to deliver demand services: electricity (PJ$_e$), heat (PJ$_{th}$), vehicle-kilometers, jet fuel (PJ), and chemicals (Mt).[30] Fossil fuel and renewable energy conversion technologies are deployed within the system ensuring that the available energy supply meets the demand for energy and non-energy applications. Supply and demand conversion technologies are represented by detailed cost-structures and process efficiencies. They are deployed in 5-year intervals within scenario constraints such as feedstock supply at a specific cost-price, the maximum total capacity of a specific technology or the minimum supply of a specific fuel, e.g. biofuels (Fig. 1).

This study builds on an existing model for the Netherlands (MARKAL-NL-UU). The Dutch electricity sector in MARKAL-NL-UU was developed by van den Broek *et al.*[20,34] based on the West European model originally developed by ECN.[35] It was expanded to include the road transport sector by van Vliet *et al.*[21] To assess the aviation and chemical industry sectors, we extended the model to include jet-fuel production and the Dutch

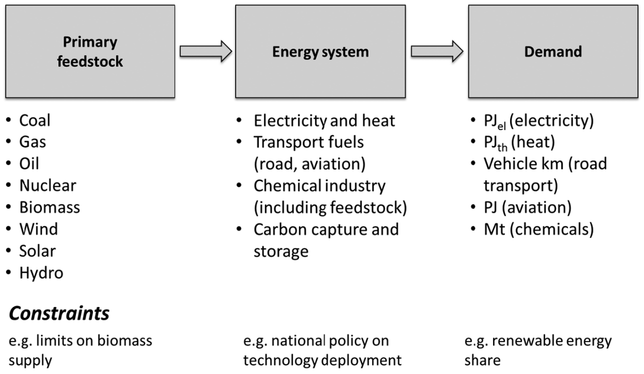


Figure 1. Illustration of the key modules of the MARKAL-NL-UU modeling framework: supply, conversion, and demand.

Table 1. Overview of electricity and heat technologies included in MARKAL-NL-UU.[a]

Fossil conversion	Biomass conversion	Other renewable conversion
Electricity[a,b]		
Combined-cycle power plant on natural gas	Steam-cycle power plant on biomass	Onshore wind turbine
Gas-turbine power plant on natural gas	Pulverized coal-power plant on biomass co-firing with coal	Offshore wind turbine
Pulverized coal-power plant	Integrated gasification combined cycle power plant on biomass co-gasification with coal	Solar photovoltaic panel
Integrated gasification combined-cycle power plant on coal	Gas engines on biogas	Hydroelectric power plant
Nuclear power plant		
Electricity and co-generated heat[a,c]		
Small-scale gas engine combined heat and power (CHP) on natural/landfill gas	Steam cycle CHP on biomass	
Combined cycle CHP on natural gas	CHP[d,e] on biogas	
Gas turbine CHP on natural / landfill gas	Integrated gasification combined cycle CHP on biomass co-gasification	
Steam turbine CHP on natural gas	MSWI – organic waste fraction[f]	
MSWI – fossil waste fraction[f]		
Heat		
Natural gas boiler[g]	Industrial biomass boiler	
	Wood stove (fuelwood for space heating)	
Electricity/heat other		
	Grid injection of green gas[c,h]	

[a] Production costs of electricity and co-generation technologies have been updated by Brouwer *et al.*[50]

[b] All large-scale electricity production technologies can be coupled with CCS. Exceptions are dedicated biomass steam cycle plants and municipal solid waste incinerator (MSWI).

[c] Electricity and/or heat is also co-produced by CHP units of transport fuel or chemical conversion technologies. These are not included in this table.

[d] Added in the present study.

[e] Upgrade of biogas from anaerobic digestion of liquid manure to green gas is also included. Green gas is assumed to substitute natural gas only for heat applications. Synthetic natural gas from biomass gasification can be another direct natural gas substitute; however, it has been excluded from the analysis.

[f] MSWI (fossil, organic fraction) are aggregated to a single technology. In this table, the fossil and organic fractions of municipal solid waste are referred to separately for categorization purposes.

[g] Natural gas-based boilers are implicitly included (i.e. without incorporating detailed cost-structures) by assuming a process efficiency of 90%, which is representative for industrial heat generation in member-countries of the Organisation for Economic Co-operation and Development (OECD).[45] This is a simplification, as efficiencies may vary per sector (within industry or across other end-users such as households) or fuel type. Furthermore, input fuels may vary; however, for the Netherlands, natural gas is the main energy carrier for heat.

[h] Green gas is injected into the natural gas grid and can substitute natural gas applications such as electricity, as listed in this table.

chemical industry, thus also taking into account energy use as feedstock (otherwise referred to as non-energy use). Furthermore, we expanded the model's existing technology portfolio of electricity, heat, and road-transport fuel production technologies.

The extended version of MARKAL-NL-UU covers a substantial number of biomass conversion technologies. Tables 1–3 give an overview of all the technologies included in the extended model. The model extension is described below. An explicit characterization of all technologies is included in the supporting information documents (SI).

Model extension with chemicals, aviation fuels, and other biomass technologies

Structure of the chemical industry and model representation

The chemical industry converts fossil *feedstocks* such as naphtha, liquefied petroleum gas (LPG), natural gas liquids, and heavy gas oil to key organic *basic chemicals* such as olefins (ethylene, propylene, butadiene) and aromatics (benzene, toluene, xylene). Natural gas is used as a fossil feedstock to produce hydrogen, mainly for methanol and ammonia synthesis. In the Netherlands, steam cracking

Table 2. Overview of road and jet fuel production technologies included in MARKAL-NL-UU.

Fossil conversion[a]	Biomass conversion	Other renewable conversion
Road transport		
Refining of crude oil to petrol	Fermentation of sugar to first-generation ethanol[b]	Supply of renewable electricity to electric vehicles
Refining of crude oil to diesel	Pretreatment of biomass followed by extraction of lignocellulosic sugar and fermentation to second-generation ethanol[b]	
Reforming of natural gas to hydrogen	Esterification of vegetable and/or used cooking oil to biodiesel[b]	
	Gasification of biomass to syngas followed by Fischer–Tropsch (FT) synthesis to FT fuels (diesel, petrol, and jet fuel)[b]	
	Gasification of biomass followed by methanol synthesis	
	Gasification of biomass followed by dimethyl ether synthesis	
	Gasification of biomass followed by hydrogen synthesis	
	Pyrolysis of biomass to bio-oil followed by hydrotreatment to petrol[b]	
	Co-production of petrol from methanol-to-olefins synthesis[b] Supply of biomass electricity to electric vehicles	
Aviation[b]		
Refining of crude oil to kerosene	Hydrotreatment of used cooking oil to renewable diesel (HRD)[c,d] Hydroprocessing of used cooking oil to renewable diesel (hydroprocessed esters and fatty acids; HEFA)[c,d]	
	Hydrothermal liquefaction of biomass to renewable diesel[c]	
	Catalytic pyrolysis of biomass to diesel[c]	

[a] Coal-gasification and FT synthesis to FT-fuels (petrol, diesel, jet fuel) have been excluded from the present study.
[b] Added in the present study.
[c] Biomass conversion technologies for aviation also applicable to road transport.
[d] Renewable diesel supplied to road transport may also use vegetable oil.

of naphtha is the most important production process in terms of production volume and energy use.[36,37] Fluid catalytic cracking (FCC) and catalytic reforming are refinery processes that produce propylene from gas oil and aromatics from naphtha-based reformate, respectively. In this study, refinery processes are not modeled explicitly, however; FCC propylene and catalytic reforming aromatics are assumed to be import commodities. In 2012, industrial final energy use in the Netherlands was 1214 PJ (energy and non-energy use) of which 672 PJ was feedstock.[38] Fossil feedstock use in organic basic chemical and fertilizer production accounted for 80% of the Dutch non-energy use (Table S1, SI). Since 2000, non-energy use has increased at a compound annual growth rate (CAGR) of 1.3%. In 2012, the main feedstocks used for the production of basic chemicals were naphtha (330 PJ), LPG (36 PJ) and natural gas liquids (86 PJ). During the same year, natural gas consumption for nitrogen fertilizer production reached 64 PJ.[38] Figure 2 shows how these sectors are captured in MARKAL-NL-UU. Basic chemicals are further converted to key commodity chemical *intermediates*, which are synthesized to a range of *final products* such as polymers, rubbers, adhesives, solvents and fertilizers.

The products and (interlinked) processes of the chemical industry are complex and numerous. In MARKAL-NL-UU we used a simplified representation based on the description of Petrochemicals Europe,[39] which describes basic chemicals as building blocks, intermediates as derivatives and final products as everyday products. Such a distinction has also been used in other studies that apply a systems perspective.[26] Studies with a different scope include different products in these categories (e.g. Neelis *et al.*[37] describe 22 different products as basic chemicals). We included biomass conversion technologies that produce a direct naphtha substitute as feedstock for the chemical industry and bio-based chemicals that are identical or functionally equivalent to fossil-based chemicals. Thus, bio-based alternatives can be provided at the following four levels: feedstock, basic chemical, intermediate and final product (Fig. 2. For an expanded flowchart see Fig. S1 in the SI. Box S1 and Box S2 in the SI describe the structure of the model in detail).

Selection of chemicals

The focus of the present study is on chemicals from naphtha and natural gas due to their significant contribution

Table 3. Overview of conventional and biomass conversion technologies to chemicals included in MARKAL-NL-UU.

Feedstock level	Basic chemical level	Intermediate chemical level[b]	Final product level[b]
Conventional conversion technologies			
Refining of crude oil to naphtha[a]	Steam cracking of naphtha to olefins and aromatics Fluid catalytic cracking (FCC) of crude oil fractions to propylene[a] Catalytic reforming of reformate to aromatics[a] Steam reforming of natural gas to hydrogen	Oxidation of ethylene to ethylene oxide (EO) Hydrolysis of ethylene oxide to ethylene glycol (EG) Oxidation of aromatics to terephthalic acid (PTA) Oxidation of aromatics to phthalic anhydride (PA) Isomerization, hydroformylation and hydrogenation of propylene oxide (PO) to 1,4-butanediol (BDO) Synthesis of hydrogen to ammonia	Polymerization of ethylene to polyethylene (PE) Polymerization of propylene to polypropylene (PP) Esterification of PTA and EG to polyethylene terephthalate (PET) Dehydrogenation of EB[c] to styrene Oxidation and dehydration of propylene and EB to styrene and propylene oxide (PO) Synthesis of ammonia to urea
Biomass conversion technologies			
Fermentation-based chemicals			
		Fermentation of sugar to succinic acid (SA) Hydrogenation of SA to BDO[d]	Fermentation of sugar to lactic acid followed by polymerization to polylactic acid (PLA) Fermentation of sugar to 1,3 propanediol (PDO) followed by esterification of PTA to polytrimethylene terephthalate (PTT)
Ethanol-based chemicals			
	Catalytic dehydration of ethanol to ethylene Catalytic dehydration of ethanol to butadiene		
Thermochemical-based feedstock and chemicals			
Gasification of biomass followed by FT synthesis to fuels and naphtha	Steam cracking of FT-naphtha to olefins Gasification and water gas shift reaction to hydrogen for ammonia synthesis Gasification and separation of aromatics, ethylene[e]		
Methanol-based chemicals			
	Catalytic conversion of methanol to ethylene and propylene		
Catalytic pyrolysis-based chemicals			
	Catalytic conversion of pyrolysis oil to olefins and aromatics		
Catalysis-based chemicals			
			Catalytic conversion of sugar to 2,5-Furandicarboxylic acid (FDCA) and polyethylene furanoate (PEF)

[a] Refinery operation, modeled as import commodity.

[b] In this table, downstream conversion technologies at an intermediate and final product level that are reported under conventional conversion technologies are common for chemically equivalent bio-based feedstocks such as olefins and aromatics.

[c] Also modeled as import commodity.

[d] SA can also be used as a direct phthalic anhydride substitute. As no conversion technology is assumed for this process, it is not listed in this table.

[e] Co-produced SNG is used for electricity generation.

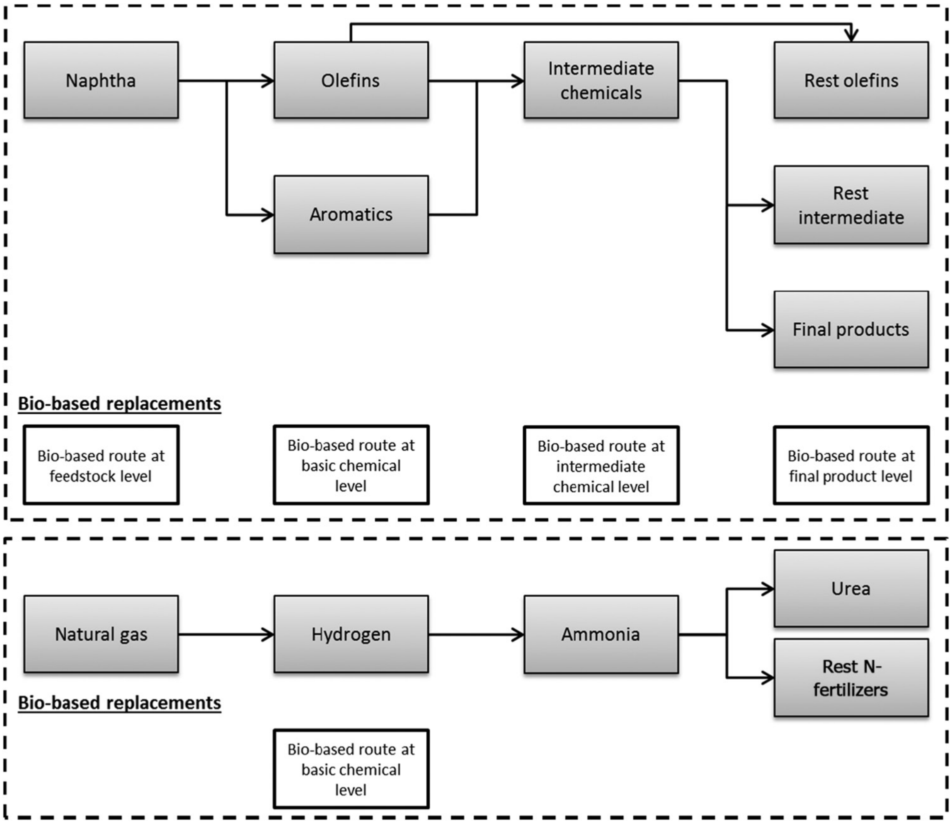


Figure 2. Representation of fossil-based and bio-based chemical routes and products in MARKAL-NL-UU (a detailed flowchart is provided in the SI).

to the Dutch non-energy use. As reference chemicals, we select downstream fossil-based chemicals from naphtha (i.e. basic and intermediate chemicals as well as final products) based on volume according to historic consumption of basic chemicals by derivative in Western Europe (as defined by Petrochemicals Europe) and production capacity in the Netherlands.[39] Large-volume chemical products (Table S2, SI) are responsible for 80% of the global chemical industry's energy demand and for 75% of its CO_2 emissions.[40]

Besides basic chemicals, those that are modeled explicitly in MARKAL-NL-UU are the intermediates, ethylbenzene (EB), ethylene oxide (EO), propylene oxide (PO), terephthalic acid (PTA), ammonia, and the final products polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP) and urea. Together, these products account for 72–81% of ethylene, 56–73% of propylene and 45–53% of aromatics (benzene) consumption in Western Europe in 1994–2013 (Table S3, SI). Intermediate or final chemicals from butadiene are not modeled as most of these are used for the production of synthetic rubber. Higher added-value chemicals (e.g. specialty or fine chemicals) are not included in the analysis.

Selection of bio-based chemicals

We select processes that produce drop-in bio-based chemicals that may replace their fossil-fuel based counterparts directly in the existing infrastructure, and processes that produce new bio-based chemicals as indirect replacements, which may also compete in new markets. The products are summarized as follows:

- fermentation-based chemicals (direct sugar to chemicals): lactic acid (and polymerization to PLA), 1,3-propanediol (PDO) and succinic acid (SA);
- ethanol-based chemicals: ethylene and butadiene;
- thermochemical-based feedstock and chemicals: naphtha from gasification and FT synthesis (feedstock), hydrogen (for ammonia), aromatics and ethylene;
- methanol-based chemicals: olefins (ethylene, propylene);
- catalytic pyrolysis-based chemicals: olefins and aromatics;
- catalysis-based chemicals: polyethylene furanoate (PEF) from sugars.

Cascading of biomass from high-value applications such as materials to energy recovery is another efficient option of biomass utilization but this has not been included in this analysis. Table 3 presents in detail the chemical industry processes included in MARKAL-NL-UU.

Structure of the aviation sector and model representation

Kerosene from crude oil refining is the reference jet fuel. Renewable jet fuel conversion technologies are selected based on de Jong *et al.*[17] The conversion technologies able to produce a RJF fraction are hydroprocessed esters and fatty acids (HEFA), hydrothermal liquefaction (HTL), pyrolysis (PYR), gasification and FT-synthesis (Fig. 3). Hydrotreated renewable diesel (HRD), a closely related but slightly less complex compound than HEFA diesel, is also included as it is currently reviewed as a blend with fossil kerosene.[41] Alcohol-to-jet and direct sugars to hydrocarbons have been excluded due to high production costs.[17] Only used cooking oil (UCO) and woody biomass are included as feedstocks, which is in line with the industry's intention to use only non-food biomass.[42] The RJF conversion technologies, besides RJF, may produce additional products, such as diesel and LPG (in the model, diesel and LPG are assumed as petrol). These products can be used in the road transport sector.

Depending on the technology and the chemical composition of the products, maximum blending constraints (blend walls) for RJF are established by the American Society for Testing and Materials (ASTM) and are included in the model (Table 4). This entails that technical requirements for biofuels and blends with petroleum kerosene are met for RJF use in aircrafts.

Table 4. Blending constraints of renewable jet fuel and renewable diesel with total jet fuel.

Technology	Fuel	Maximum share blended with jet fuel[a] (%)
HEFA	Renewable jet fuel (HEFA jet)	50
HEFA	Renewable diesel (HEFA road)	10
HRD	Renewable diesel (HRD road/jet)	10
HTL	Renewable jet fuel (HTL jet)	30
PYR	Renewable jet fuel (PYR jet)	30
FT	FT jet fuel (FT jet)	50

[a] Only the blending constraints for HEFA jet and FT jet are defined according to the specifications of the ASTM, as these are the only RJF with an official specification.[91] The blending constraints for HRD, HTL and PYR jet are anticipated blending constraints.

Other technologies

Feedstocks based on sugar or starch crops make up a large share of the total production costs of fermentation or enzymatic processes. Lignocellulosic feedstocks for sugar production may demonstrate improved sustainability and cost performance, which is why we included cost structures for solid biomass conversion to C5 and C6 sugars, thus providing demand sectors with the option to use or import raw sugar or starch from crops or invest in domestic lignocellulosic sugar production capacity. We also enriched the technology portfolio of the transport fuel

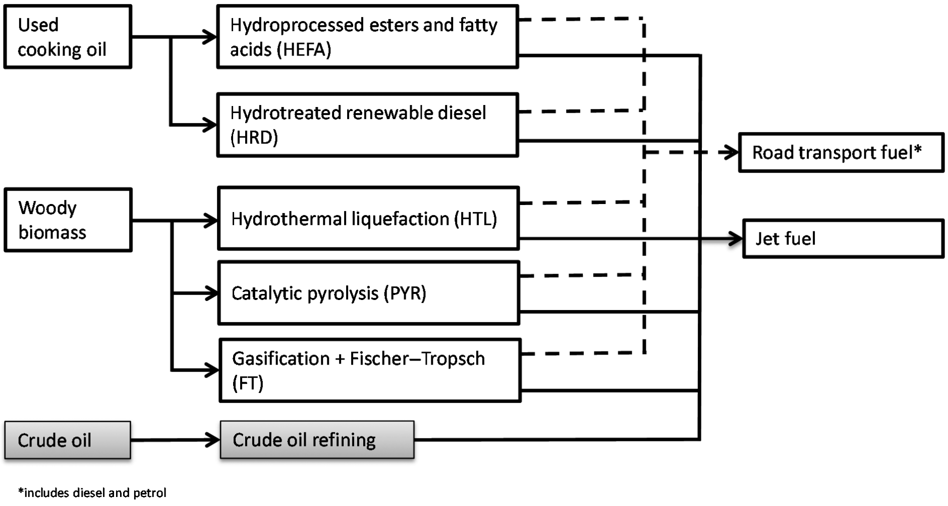


Figure 3. Representation of aviation sector in MARKAL-NL-UU along with other biomass conversion technologies.

sector in MARKAL-NL-UU with cost structures for conversion processes of lignocellulosic ethanol, starch-based ethanol and biodiesel production from vegetable oil and UCO. We also implemented market constraints for biomass conversion technologies to fuels. Individual second-generation technologies were assumed to supply no more than 5% of fuel demand in 2020 and 10% in 2030, based on de Wit *et al.*[43] As these technologies are early in the development or commercialization stage, these restrictions are necessary to prevent a single technology from being scaled up rapidly and supplying an unrealistic high market share even if it is found to be cost competitive. Furthermore, we included cost-structures for the anaerobic digestion of sewage water, manure co-digestion, and wet organic waste. Biogas can then be used in small-scale combined heat and power (CHP) plants for the production of electricity and heat. We also included the option of upgrading biogas to green gas, which can replace natural gas in heat applications (Table 1). Electricity production from synthetic natural gas (SNG) was included only as a co-production option of the specified technology (Table 3). Finally, we included biomass boilers as an alternative to heat supply from natural gas in the industry sector.[44,45] Heat from wood stoves was included assuming a constant supply of fuelwood for domestic heating from wood stoves because no substantial growth is expected.[46]

Multiple process outputs

Several technologies produce multiple outputs, which can be used across the different sectors. For example, a CHP plant generates both electricity and heat, delivering to the electricity and heat sector. Biorefining is the processing of biomass into a spectrum of marketable products and energy. Several biomass conversion processes fall under this definition. In this study, we refer to advanced biochemical biorefineries if enzymatic processes are used to convert solid biomass to lignocellulosic sugar and ethanol, and we refer to advanced thermochemical biorefineries if biomass is gasified to syngas for further conversion to products such as FT-fuels.[11] Lignocellulosic sugar biorefineries convert solid biomass to C5 and C6 sugars and lignin. Lignin is supplied as solid biomass feedstock to the electricity or heat sector. Biomass gasification and FT-synthesis generate fuels (diesel and petrol, used as transport fuels), electricity (supplied to the grid), and FT-naphtha (feedstock for the chemical industry). Conventional coal gasification and FT-synthesis to road transport fuels is excluded from the model. In MARKAL-NL-UU, co-production has been taken into account by linking all process outputs to the sector modules involved, either as feedstock or as end products, thus achieving valorization of biomass constituents and improving overall efficiency.

Input data and scenarios

Current and future techno-economic performance

Production costs

Competition between technologies is based on the performance characteristics of the energy and non-energy products they deliver. Their cost structures consist of capital investments for a given capacity, fixed costs (supplies and administrative costs), and variable costs (feedstock, labor, and other material inputs and utilities). The discount rate is set at 7% under a central planning perspective similar to other studies.[20,21] For investment decisions on technologies from a private perspective different discount rates should be used on a case-by-case basis, related with the sectors, technologies and the risks involved. All nominal costs are deflated to real costs in €2010 terms, based on exchange rates and price indices.[47–49] The production costs of technologies included in MARKAL-NL-UU prior to the model expansion have been described in the literature (Table S4, SI).[20,21,50] Cost structures of technologies that have been introduced during the model's update are based on the following method:

- *Capital investment costs* are the aggregate of inside battery limits (ISBL; e.g. key process components), outside battery limits (OSBL; e.g. utilities, control systems, buildings, storage) and contingency. We use data from available literature and company announcements. For technologies for which only ISBL costs are provided, OSBL costs are assumed as 35% of ISBL and contingency as 25% of ISBL and OSBL costs (Table S5, SI). To estimate the capital investment costs of technologies at different scales, we apply 0.7 as the scaling factor in the formula in Eqn (1):

$$\frac{Cost_{base}}{Cost_{scaled}} = \left(\frac{Capacity_{base}}{Capacity_{scaled}}\right)^{Scaling\ factor} \tag{1}$$

  Location factors are used to convert capital investment costs that refer to regions other than Europe to capital expenditures for the Netherlands (Table S6, SI).

- *Fixed costs* for technologies that are not provided by the data source are estimated based on Hermann and Patel[51] (Table S7, SI). If fixed costs are provided by the data source, these are used instead. Labor costs are either included in reported operational expenditure or are estimated based on an annual full-time salary of €56 210 (wage of 28.7 €/h and 2080 h/year for industry in the Netherlands in 2005. Converted to 2010 wages using labor cost indices for the Netherlands.)[52] If labor hours or labor costs are not provided by the data source, they are assumed as 5% of variable costs. Labor costs are scaled using Eqn (1) and a scaling factor of 0.2 (similar to Patel *et al.*,[53] where a 0.25 scaling factor is applied).

- Biomass feedstock and energy are typical major cost components of *variable costs*. Based on process efficiencies, feedstock costs are calculated using feedstock prices (Table S8, SI). For technologies that require external energy input (electricity, heat), the model takes the additional demand into account and supplies it by conversion technologies based on the system's least cost pathways. Variable costs of technologies that are self-sufficient on energy are indirectly accounted for as additional capital investments (e.g. CHP, boiler). Other variable costs taken into account are cellulase in lignocellulosic sugar and ethanol technologies, catalyst costs in pyrolysis technologies, and acetic acid costs in PTA production.

Production costs are related to the nth plant, and thus exclude the potentially higher costs of the first unit installed due to operation at a low utilization rate.

Technological development and scenarios of bio-based technologies

Future technology costs linked with learning rates are associated with operational experience, design, and the construction of the technology.[54] Unit costs decline by a percentage (learning rate) for each doubling of installed production capacity. This method has been extensively studied and applied on bioenergy conversion technologies.[43,55,56] Learning rates are associated with capacities on a global scale.[56] Compared to the rest of the world, the Netherlands does not represent a sizeable market for most technologies, which is a limitation for applying endogenous technological learning in this study. We therefore take into account technology development exogenously, by relying on estimations of future costs from bottom-up engineering studies and expert judgments on potential improvements of various technology components such as yield and energy efficiency. In addition, we take into account scaling of technologies that may achieve cost reduction through economy of scale. Furthermore, as several technologies are in different developmental phases, the moment of commercialization (start year) becomes highly relevant. Technical improvements, scale-up, start year and technology availability are determined exogenously and are applied to capture the cost development of technologies (Table 5, Table S9 in SI, Fig. 4). These improvements and the consequent cost reductions over time depend on various factors, such as research and development (R&D) efforts and stimulating policies, and involve substantial uncertainties regarding development pathways.

To capture the uncertainty in technology development, we incorporate two scenarios: low- and high-technology development (LowTech and HighTech).

- *LowTech* takes into account technologies that are commercially available today. Based on existing or announced capacities, it assumes the capacities of the technologies to be small. There is a low rate of incremental improvements in process yields and autonomous efficiency improvements (Table 5). This scenario describes a business-as-usual case.

Table 5. Incremental yield and autonomous annual energy efficiency improvements in chemical conversion technologies of the low- and high-technology development scenarios (Table S9 in the SI presents the different assumptions in detail).

Product (process)	Improvement	Range in scenarios	
		LowTech (% p.a)	HighTech (% p.a)
Lignocellulosic sugar/ethanol (various pretreatment methods/ fermentation)	Sugar extraction	1	2–3
	Fermentation	0.05–1	0.1–2
Bio-based chemicals (fermentation and catalytic conversion of methanol)	Yield improvement	0.25	0.5
	Process energy efficiency	0.5	1
FT-naphtha (gasification and FT-synthesis)	Yield improvement	0.25	0.5
Basic chemicals (steam cracking)	Process energy efficiency	1	1.8
Ammonia and hydrogen (steam reforming)	Yield improvement	0.25	0.5
	Process energy efficiency	0.5	1

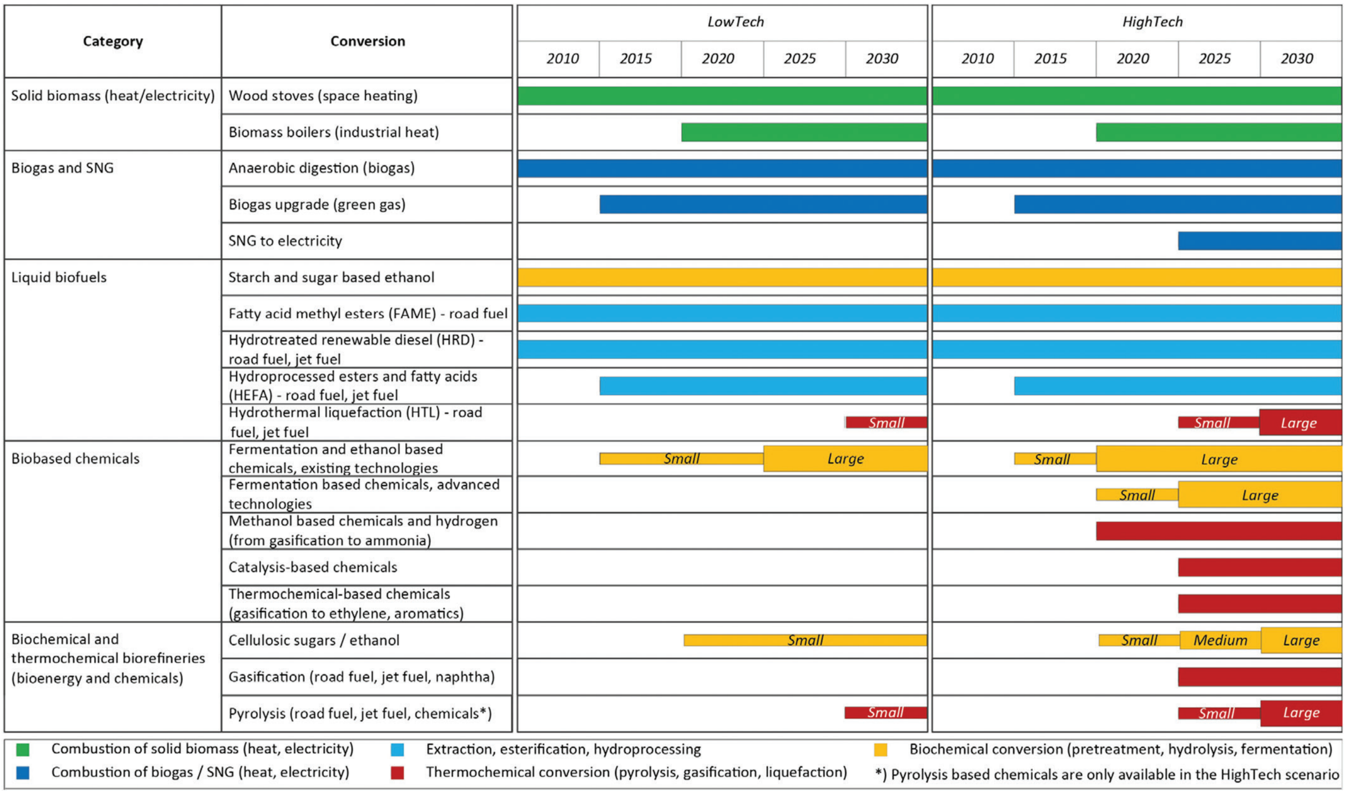


Figure 4. Bioeconomy technology development scenarios in MARKAL-NL-UU with the start year, type of technologies, and capacities.

- *HighTech* assumes that more technologies may be implemented and on a larger scale. There is a high rate of incremental improvement in process yields and autonomous efficiency improvements (Table 5). Preconditions for this scenario are strong R&D efforts, investment at the early stages of development, support of technologies to pass the valley of death (e.g. required for gasification), and commercial success of existing installed capacities.[57]

In this study, technology developments based on technology improvement, scale-up, start years and availability are incorporated in the different scenarios as follows:

- *Technology improvements*. We assume technical improvements for bio-based and fossil-based processes for conversion yields and process energy efficiency. Assumptions are made exogenously regarding the improvement in production costs, yields and efficiencies from the start year t_0 of a technology to year t_{0+n}. For technologies that are mature (e.g. esterification of vegetable oils, downstream technologies, industrial biomass boilers) or where there is no available information on future performance, the cost and efficiency are assumed to remain constant throughout the modeling period. Increases in capital investment costs due to process or energy efficiency improvements have been ignored. For technologies that were included in MARKAL-NL-UU prior to the present study, developments have been based on literature and no differentiation has been made between LowTech and HighTech scenarios (e.g. technologies for the power sector).[20,21,50] Table 5 presents different improvement rates assumed per technology in each scenario. Table S9 in the SI presents the different assumptions in detail.
- *Scale-up*. For biofuels and bio-based chemicals, the LowTech scenario assumes small-scale production capacity, depending on the technology. For example, for pyrolysis fuels up to 91 $MW_{\text{feed in}}$ can be deployed and for lignocellulosic sugar and ethanol up to 400 $MW_{\text{feed in}}$ (e.g. lignocellulosic sugar ethanol). Scale-up of bio-based chemical technologies occurs in time steps of 10 years. By contrast, the HighTech scenario assumes that technologies may be scaled up to 2 $GW_{\text{feed in}}$ (e.g. gasification, lignocellulosic ethanol) and the scale increases every 5 years (using a scaling factor of 0.7 in Eqn (1)).

- *Start year and technology portfolio.* The 'technology readiness level' can be used to determine the start year of technologies. However, it is uncertain how fast a technology can advance through the different development levels (from concept to commercial deployment; see e.g. Peisen *et al.*[58]). Furthermore, even technologies at an advanced readiness level will not always pass the valley of death. In addition, for bio-based chemicals that are not chemically identical with their fossil counterparts, but that have different technical functions and complex supply chains, it could take more than 20 years to emerge at large production scales.[11] Start year and technology portfolio are therefore important parameters to be varied in the two scenarios. Different statuses and ranges of technology development phases are mentioned in literature.[59,60] The start years of biomass gasification that supply fuels in earlier versions of MARKAL-NL-UU[21] are aligned with the start years of biomass gasification technologies.

Figure 4 presents the start year, technologies and the capacities (small scale, medium scale, and large scale) assumed in the two scenarios for the chemical and transport fuel conversion technologies.

Biomass cost-supply

In this study we incorporate cost-supply curves of biomass from domestic resources (i.e. the Netherlands) and intra-EU resources that could be exported based on projections of the economic potential of biomass from 2010 to 2030 of the Intelligent Energy Europe (IEE) project Biomass Policies (Table S10, SI).[61] Excluded from intra-EU trade are low-quality biomass, liquid, and solid manure, which are assumed to be utilized in their country of origin, and household waste, with the exception of paper, wood and UCO. Types excluded from the domestic potential do not contribute significantly to the total potential. From the total EU28 potential, we allocate a specific share available to the Netherlands based on the share of the Dutch total primary energy supply relative to the EU28.[2] For 2010–2030, this has been estimated at approximately 5%. For simplification purposes, the different feedstocks have been aggregated to broader categories (Table S10, SI). In addition to domestic and European biomass, we assume an extra-EU supply of liquid biofuels (first- and second-generation ethanol, biodiesel), vegetable oil, sugar, and solid biomass (wood pellets). The amount of imported wood pellets is constrained to 400 $\mathrm{PJ_{prim}}$ (23.4 $\mathrm{Mt_{wpe}}$; wood pellet equivalents assuming 17.1 MJ/kg lower heating value (LHV)). Imported biofuels, vegetable oil, and sugar amount to 50 $\mathrm{PJ_{prim}}$, which is sufficient to meet the 10% blending target of road transport in 2020. Each feedstock category is associated with specific conversion technologies included in MARKAL-NL-UU as shown in Fig. S2 (SI). Table 6 presents the available domestic and imported biomass potential in MARKAL-NL-UU.

Logistic costs biomass production and transport

The supply costs of intra-EU feedstock categories in MARKAL-NL-UU are summarized in Table S11 (SI) and are estimated based on the following approach:

The logistic costs of EU supply are calculated from NUTS2 (Nomenclature of Territorial Units for Statistics) regions to Rotterdam, assuming transport as wood chips.[62,63] These costs are added to the cost of biomass feedstocks derived from the IEE project Biomass Policies; they are assumed to be constant throughout the modeling period using 2015 oil prices.[61]

- The national cost-supply potential from the NUTS2 level is estimated by aggregating the biomass supply potential of each country's NUTS2 regions. The biomass cost of supply to the Netherlands is their weighted average.
- The regional cost-supply potential per biomass feedstock for four EU regions (North, South, East, West, according to the United Nations' classification; Table S12, SI) is estimated by aggregating the national

Table 6. Available domestic and imported biomass potential in MARKAL-NL-UU for the Netherlands (NL) in 2010-2030 (rounded figures, in PJ).

(PJ)	2010		2020		2030	
	NL	EU	NL	EU	NL	EU
Crops	2	32	13	89	22	101
Crop residues	8	52	7	50	7	51
Wood crops	0	0	1	15	2	16
Forestry products and residues[a]	46	235	52	235	59	254
Waste domestic	88		80		83	
Used cooking oil EU		5		5		5
Extra-EU imports solid biomass			400		400	
Extra-EU imports liquid biomass			50		50	
Total domestic	144		153		172	
Total import	772		843		878	

[a] Fuelwood for wood stoves is added ad hoc to the total domestic potential. It is 15, 18, and 20 PJ for 2010, 2020 and 2030, respectively, and is reported under forestry products and residues.

potential of each biomass feedstock. Regional costs are determined based on the weighted average of the national feedstocks.
- Each region's cost-supply potential per biomass category is estimated by aggregating the supply potential of the different feedstock types of the same category. Their costs are determined based on the weighted average of these types.

The cost of supply of extra-EU categories is summarized in Table S13 (SI) and is estimated based on the following:

- The wood pellet price is based on average free-on-board biomass prices over a 10-year period (2006–2015), and other literature sources were used to estimate the cost-price development of the extra-EU feedstocks (Table S13, SI).
- Transport costs to the Netherlands are assumed, based on fossil-fuel prices and consumption in the logistics chain. These were determined based on Hoefnagels *et al.*[62,63] For extra-EU sugar, transport is assumed to be similar to wood pellets. Transport costs of extra-EU ethanol are added to the cost-price of first- and second-generation ethanol produced in Brazil, based on fuel consumption in the chain.[64] Extra-EU vegetable oil and biodiesel transport costs are included, based on shares of transport costs over the import values of the commodities to Rotterdam according to OECD.[65]

The costs of sugar from inside and outside the EU are assumed to be identical and are based on the Food and Agriculture Organisation of the United Nations,[66] as prices are expected to converge after the abolition of the sugar quota in Europe.

The transport costs assumed in this study are conservative, as they are based on wood chip logistics for long-distance supply chains, leading to overall conservative costs of biomass supply and ignoring the development of fossil fuel prices up to 2030. The literature indicates that significant cost gains can be achieved in biomass transport if biomass is processed to pellets in the sourcing region. Furthermore, biomass densification leads to higher efficiencies on the conversion side. Such improvements can lead to more cost-effective biomass supply chains than assumed in this study, thus improving the cost-competitiveness of biomass deployment in the energy system.[67,68]

Emissions from biomass production and transport

As the GHG emissions of biomass production and transport may be significant, they are accounted for using the same method as for the cost-supply estimates (i.e. weighted average of NUTS2 regions to four geographic regions). Emissions from domestically produced biomass contribute to the national CO_2 emissions. Emissions from production and transport of biomass outside the Netherlands (i.e. intra-EU, excluding the Netherlands and extra-EU) are estimated and presented separately as they do not contribute to national emissions. Nonetheless, due to activities of the Dutch bioeconomy, they contribute to global GHG emissions. Emission factors are presented in Table S14 (SI).[69] Other positive or negative environmental impacts from biomass production such as those induced indirectly by land-use change have not been taken into account.

Final energy and non-energy demand

Energy demand

Final energy-demand projections for electricity and heat are presented in Fig. 5 and Table S15 (SI). The trajectories are based on the latest projections made by the Energy Research Centre of the Netherlands,[70] taking into account policies established in 2012. Demand for road transport fuel (vehicle-kilometers) is based on van Vliet *et al.*[21] and graphically shown in Fig. 5. Demand for aviation fuel has been derived from the average growth projections of the PRIMES model (baseline scenario) and literature for Europe, assuming they are the same for the Netherlands (Fig. 5 and Fig. 6).[71,72] The demand for aviation fuels is based on jet bunker fuel consumption in the Netherlands. This includes jet fuel mainly consumed for international flights, as domestic consumption is negligible. By contrast, in this model, the final demand for electricity, heat and road transport fuel is based on domestic consumption (imports-exports of electricity and road transport fuels are ignored).

Chemicals demand

The level of investment, either as expansion of existing capacity or as deployment of biomass conversion technologies, depends on the production of chemicals in the Netherlands up to 2030 to meet domestic and export demand. We base the demand on the production volume of chemicals in the Netherlands rather than on domestic consumption, as the trade flows of chemical commodities are too complex to take them into account in the model (e.g. re-exports, conversions to different commodities). To determine the production volume of chemicals, we use publicly available information on production capacities in

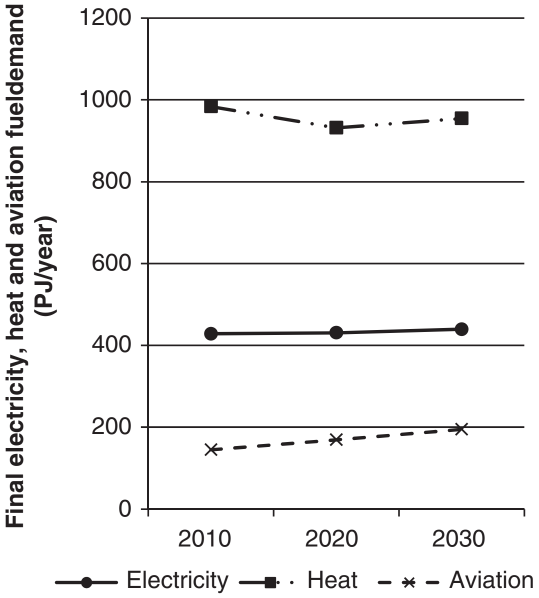


Figure 5. Final demand of electricity, heat and aviation fuel in MARKAL-NL-UU.

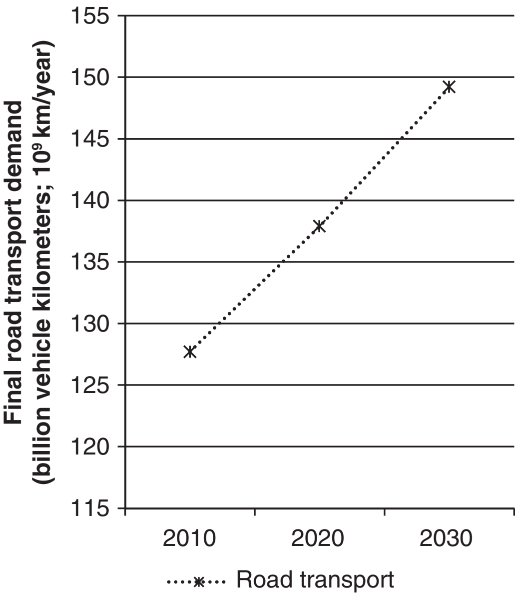


Figure 6. Final demand of road transport in MARKAL-NL-UU.

2006–2011 (Table S3, SI).[73–79] This is extrapolated to 2030 based on high growth rates (Fig. 7; Table S16, SI).[80] Future demand for chemicals is a significant input parameter as it determines the level of capacity investments required, assuming that existing steam crackers will be decommissioned in the modeling timeframe. However, future production demand for chemicals within the Netherlands is uncertain, considering that production capacity in other regions may increase due to competitiveness, uncertain fossil fuel prices and so on. Lower or even negative growth rates may therefore be expected.

To estimate the production volume, we assume capacity utilization rates of 85%.[37] The volume of basic chemicals that are not used for the production of intermediate or final products is defined as the residual demand for each basic chemical (Fig. 2). This demand is based on the total volume of basic chemicals produced in the Netherlands minus the demand for the production of intermediate and final products according to capacity and process yields (Table S17–S18, SI). The residual capacity, which in turn defines the residual demand, is presented in Table S19 (SI).

The demand for energy and chemicals is exogenous and fixed. Efficiency improvements, may reduce resource use, however, because demand-side measures and substitution of demand services are not included, the model does not provide a solution to the cost-minimization problem by reducing or substituting demand services.

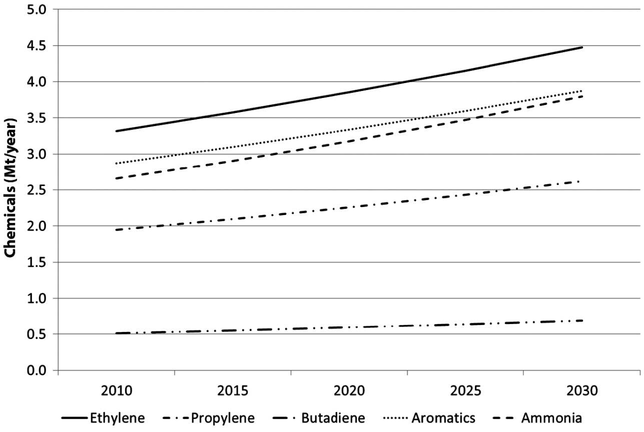


Figure 7. Production demand for basic chemicals and ammonia assumed in MARKAL-NL-UU for the Netherlands in 2010–2030.

Policy targets

Under the EU Renewable Energy Directive (RED), each member state has an obligation to meet country-specific targets to achieve the Union's target of 20% renewable energy share in the final energy demand by 2020.[4] For the Netherlands this corresponds to a minimum of 14% renewable energy in the country's final energy demand (electricity, heat and transport fuels) by 2020. In addition, 10% of the final energy demand in road transportation must be of renewable origin (biofuels, renewable electricity). Biofuels from wastes, residues, non-food cellulosic material, and lignocellulosic material contribute twice and renewable electricity in transport contributes 2.5 times to the blending target. This study excludes the contribution of RJF to the renewable energy share and blending target of the EU RED if these supply exclusively the aviation sector, despite that this is allowed according to the directive and implemented by the Netherlands.[4] In addition, the Dutch Energy Agreement[81] outlines specific goals regarding the use of biomass for co-firing in coal power plants, the deployment of onshore and offshore wind turbines and a renewable energy share in the final energy demand beyond 2020 (Table S20, SI). More specifically, the renewable energy share, according to the Dutch Energy Agreement should be 16% in 2023. In the present study, these targets are incorporated in all scenarios. We have also included CO_2 emission tax based on the International Energy Agency's World Energy Outlook New Policies scenario.[2] The CO_2 tax levels across the years are presented in Table S8 (SI).

Results

Biomass consumption

Figure 8 and Fig. 9 show the development of primary energy consumption of renewable and fossil resources, respectively. Total primary energy increases by 1–2% in the two scenarios. However, fossil energy decreases by 6–8%. The reduction in fossil energy is compensated by an increase in biomass and other renewables. Biomass consumption reaches 230 PJ in LowTech and 300 PJ in HighTech (CAGR of 2.7% and 4%, respectively between 2010 and 2030). Other renewables are not influenced by the two scenarios, as we do not vary technology improvement of non-biomass renewables between LowTech and HighTech and because their deployment is primarily driven by targets. Depending on the technology-development scenario, the growth in biomass consumption and biomass types varies; high technology development consumes large quantities of biomass equivalent to 18 Mt_{wpe}, which would require significant efforts in infrastructure and logistics. At the same time, different types and volumes of feedstock such as agricultural residues are valorized by biorefineries in the HighTech scenario.

Figure 10 and Fig. 11 show biomass resource flows for the LowTech and HighTech scenarios in primary energy terms in 2030. Imported biofuels from global markets are accounted for in final energy terms. Estimation of bio-based chemicals in energy terms is based on the LHV of bio-based chemical output. They also specify the sourcing regions, namely the Netherlands, intra-EU and extra-EU and include consumption per sector and final production of bio-based energy and non-energy in 2030. Biomass consumed in multi-output processes such as biorefineries is allocated based on the LHV of outputs.

While total biomass availability is the same in both scenarios (Table 6) the main differences are observed in total biomass consumption, final supply, sectoral flows, and

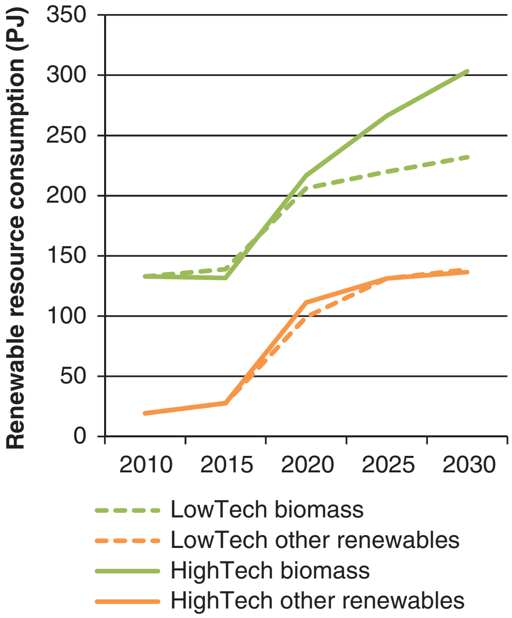


Figure 8. Primary renewable energy consumption: biomass and other renewable energy in the Netherlands in 2010–2030 (wind, solar and hydro PJ_{prim}=PJ_{final}).

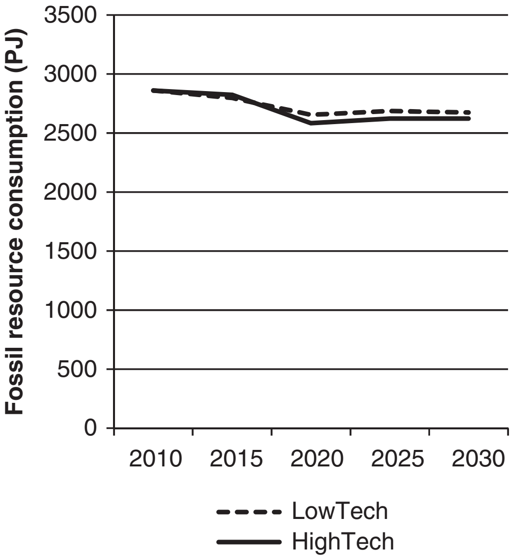


Figure 9. Primary fossil energy consumption in the Netherlands in 2010–2030.

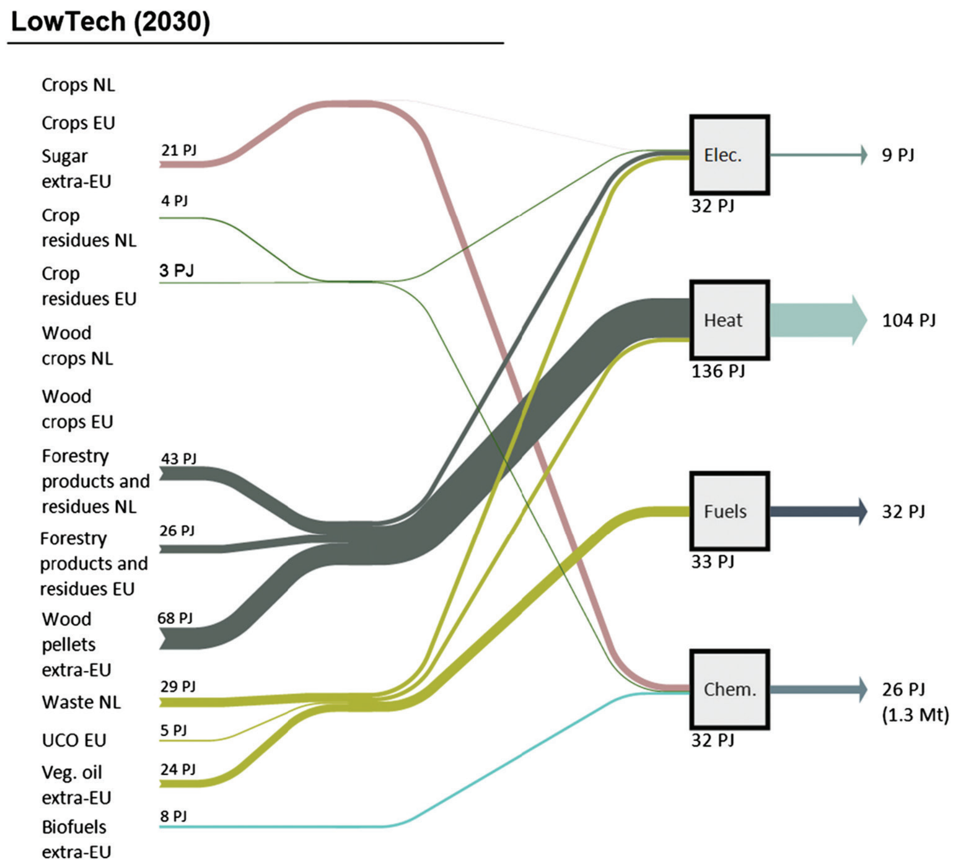


Figure 10. Biomass flows in the Netherland in 2030 under low-technology development scenario assumptions.

utilization of domestic resources. The consumption levels between the two scenarios differ by about 70 PJ (see also Fig. 8) and final supply by about 30 PJ. Biomass consumption for heat is high in both scenarios (highest consuming sector in LowTech, second highest consuming sector in HighTech). Technology development significantly increases the production of fuels and chemicals in terms of consumption and production. Large quantities of biomass are consumed in HighTech in advanced biorefineries, biochemical and thermochemical (160 PJ or approximately 9 Mt_{wpe}). In LowTech, consumption is significantly lower as thermochemical biorefineries are not part of the scenario's technology portfolio due to slower technical progress, and only small-scale lignocellulosic sugar biochemical refineries are deployed (7 PJ or approximately 0.4 Mt_{wpe}). Furthermore, some biomass flows are directed to other sectors. For example, a comparison of Fig. 10 and Fig. 11 makes clear that forestry products and residues used for heat in the LowTech scenario are shifted towards fuels in the HighTech scenario.

Next to sugar and biofuel imports, advanced biorefineries for lignocellulosic sugar production supply the necessary low-cost feedstocks to bio-based chemical conversion technologies in the HighTech scenario. These biorefineries are projected to produce significant volumes of chemicals (up to 1.95 Mt). Without strong technology development however, bio-based chemicals depend primarily on the cost-supply of imported sugar. The preconditions for the deployment of bio-based chemicals are therefore technology development and access to low-cost feedstocks. Moreover, non-energy use from biomass may, in the long term, make a significant contribution to final energy consumption despite the uneven playing field created by binding renewable energy targets. The current policy framework does not include bio-based chemicals, thus possibly delaying early deployment. Biorefineries are shown to drive biomass consumption and bio-based energy and chemical supply, as together they consume approximately one third of total biomass in HighTech in 2030.

In 2030, total biomass consumption for bioenergy and biochemicals ranges between 25% and 35% of the total available resource supply. Domestic biomass accounts for approximately 35–38% of total consumption (44–55% of

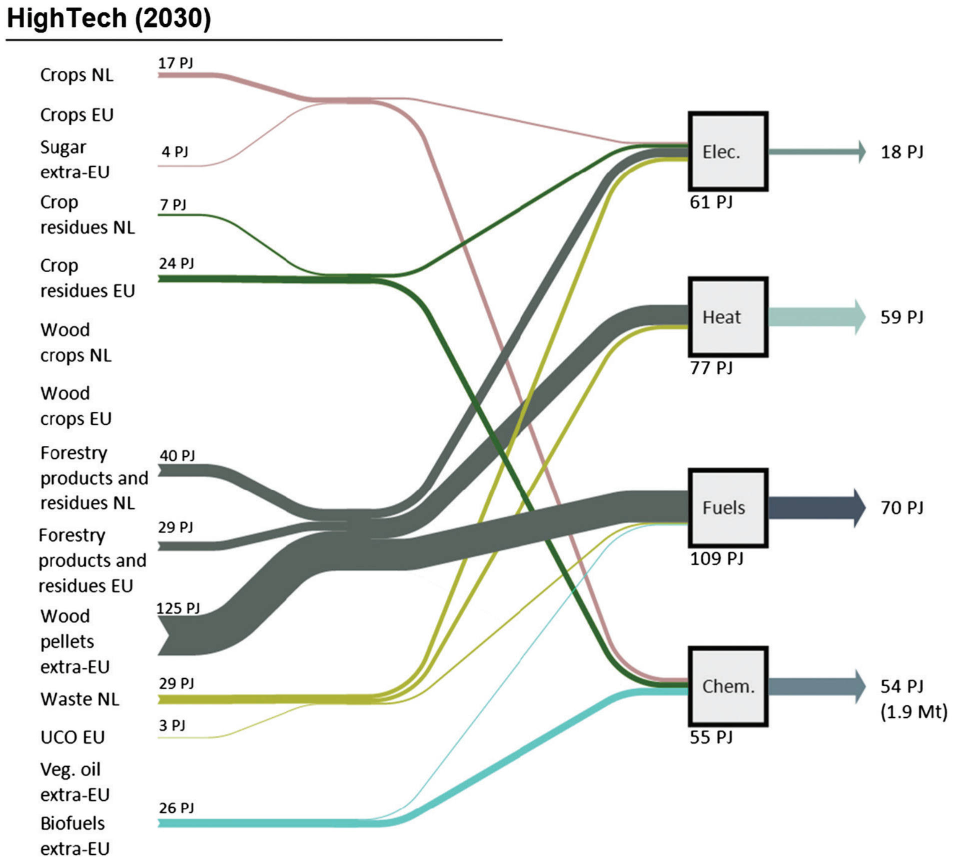


Figure 11. Biomass flows in the Netherlands in 2030 under high-technology development scenario assumptions.

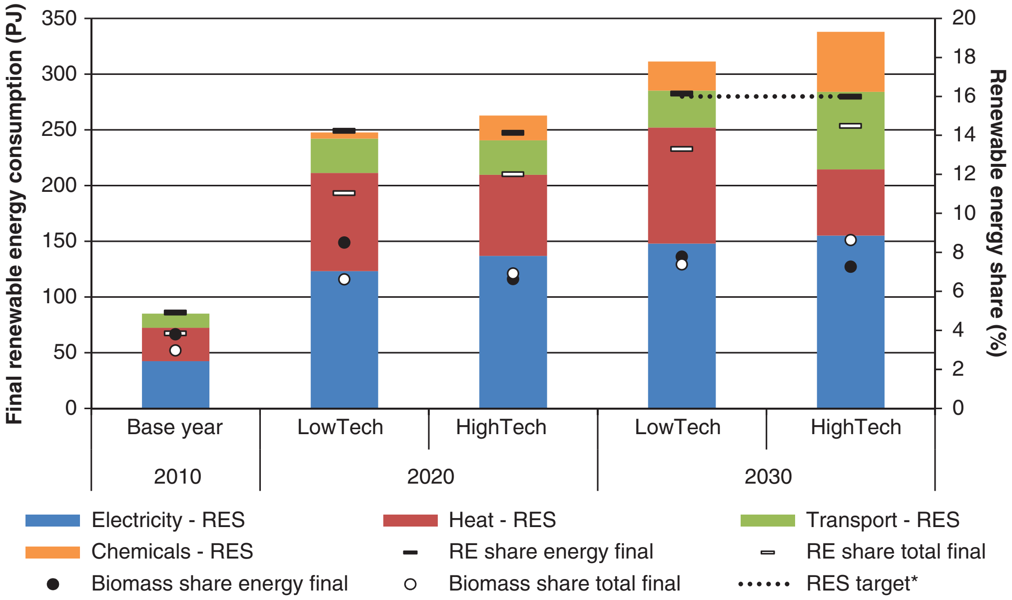
domestic biomass availability) and the remaining volumes are imported. Extra-EU resources account for slightly more than half of total biomass consumption. Forestry products and residues are the most important resources as they account for approximately 60% of total biomass consumption in both scenarios. Rapid technology development makes more use of lignocellulosic feedstocks, such as crop residues. The use of these biomass sources is limited in LowTech.

Final energy consumption

Total final energy consumption in the Netherlands is projected to increase moderately from 1725 PJ in 2010 to between 1766 and 1777 PJ by 2030. In contrast, non-energy use in the Netherlands is projected to increase substantially from 66 PJ in 2010 to between 146 and 147 PJ by 2030. Figure 12 shows the final renewable energy consumption in the Netherlands and renewable energy share in 2010–2030. The renewable target is the key driver for the deployment of renewable energy resources (scenarios do not exceed the renewable energy share target; black rectangular markers in Fig. 12), and limited variation is observed across the scenarios. Greater efforts are therefore required to achieve diffusion of renewables beyond policy targets. Biomass plays a key role in meeting the targets early in the time horizon (black circular markers in Fig. 12). The relative contribution may decrease towards 2030, because of the increase in the contribution of other renewables, especially wind power. In 2020, renewable electricity and heat generation technologies are shown to contribute most to the renewable energy target. By 2030, this pattern continues only in LowTech (see also results per sector below). In HighTech the contribution of biomass heat decreases, as renewable transport fuels grow due to the availability of more efficient technologies, compared to LowTech. Accounting for the non-energy sector, we find that in 2030 and in HighTech, bio-based chemicals contribute more to the shares of renewable energy and non-energy than in 2020.

Electricity

Figure 13 shows electricity output by source in the Netherlands in 2010–2030. Coal-based electricity is



*) Dutch Energy Agreement(23% RES share by 2023, assumed to remain at the same level to 2030).

Figure 12. Final renewable energy consumption in the Netherlands in 2010-2030 (excluding aviation fuel).

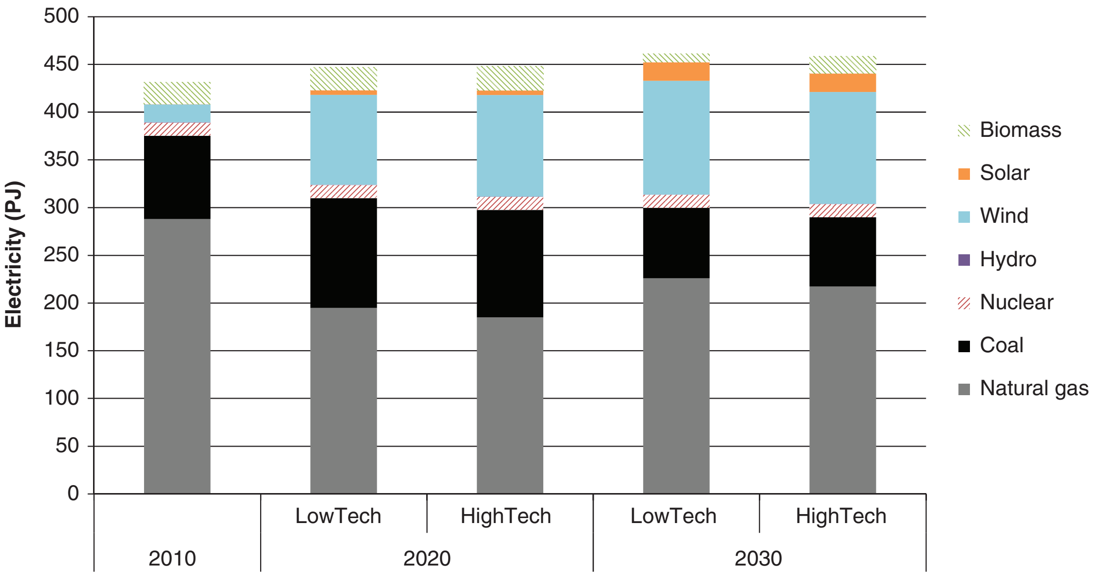


Figure 13. Electricity output in the Netherlands by source in 2010–2030.

increasing between 2010 and 2020. By 2030, natural gas and electricity from other renewable sources (primarily wind) increase compared to 2020, while coal-based electricity has decreased to levels lower than in 2010. The reduction in coal is partly due to the gradual phasing out of old coal-fired power plants in the Netherlands. However, coal-based electricity is still supplied as new coal-based electricity capacity was installed in 2015 (3.5 GW_e[81]). The decrease in coal-based electricity output is also due to higher levels of CO_2 tax in 2030 compared to 2010–2020. The contribution of renewable energy sources in 2030 is highest under HighTech, primarily due to co-production of electricity in biorefineries as electricity output from non-biomass renewables is similar across the scenarios. The output of non-biomass renewables is driven by the Dutch Energy Agreement.[81] Onshore wind turbines of 8 GW_e total capacity is installed as early as 2020 to meet the renewable energy target. As this is 2 GW above the capacity required by the Dutch Energy Agreement, onshore wind is competitive with electricity from biomass.

Heat

Biomass heat contributes significantly to the renewable energy share (21–37%, Fig. 12) and triples between 2010 and 2030 (from 30 PJ_{th} to up to 104 PJ_{th} in 2030; Fig. 14). The highest contribution comes from biomass heat use in industry (52–79% of total biomass heat output). The remainder of the renewable heat is similar across the scenarios and is primarily the output of bio-CHP, MSWI and wood stoves. Heat from co-firing biomass in power plants contributes only in 2020.

Transport fuels

Results for the transport sector (road and jet fuels; Fig. 15, Table 7) indicate (a) a significant contribution of fossil fuels (diesel, petrol, and kerosene) in the transport fuel mix (89–95% across scenarios) and (b) a diversified technology portfolio of biofuels across the technology

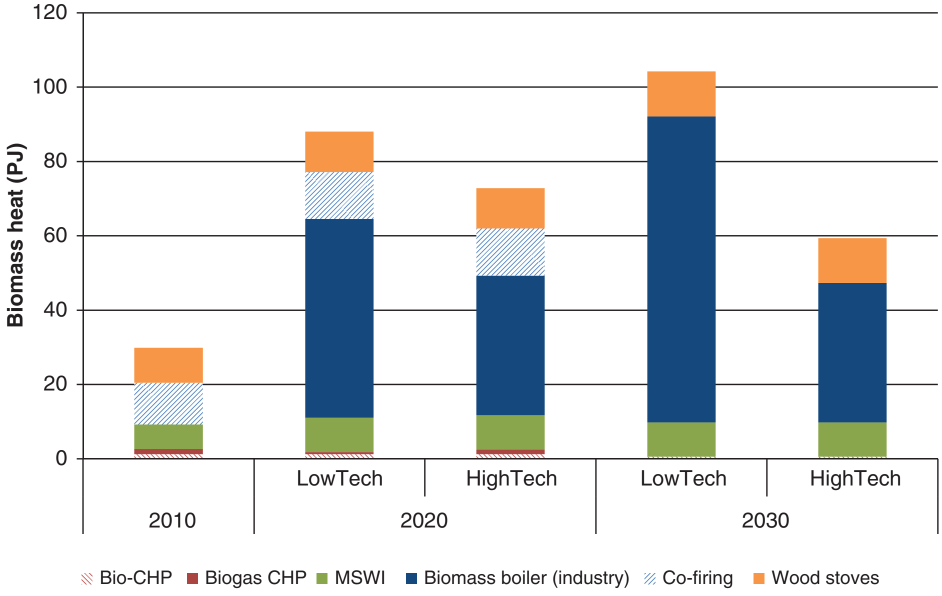


Figure 14. Biomass heat production in the Netherlands in 2010–2030.

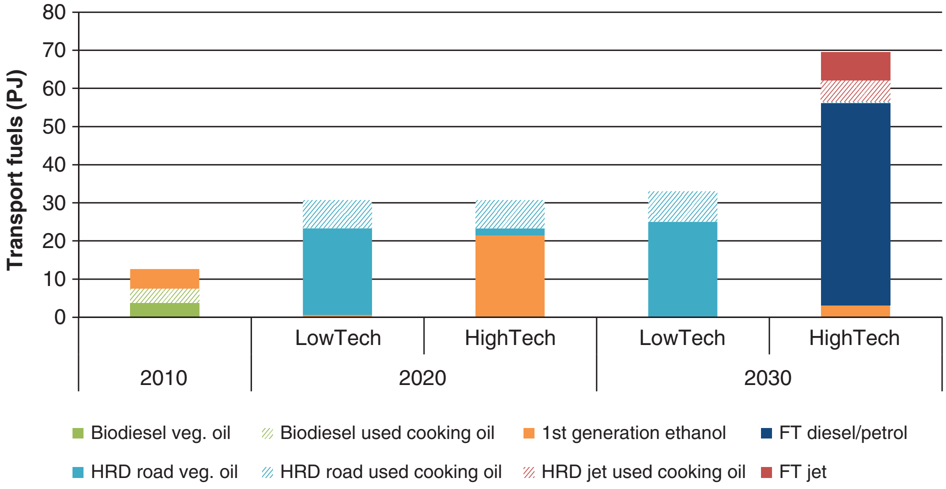


Figure 15. Bio-based transport fuels in the Netherlands in 2010–2030.

Table 7. Blending shares of biofuels in the transport sector (road transport, aviation) in the different scenarios and time periods.

	2010	2020		2030	
	(%)	LowTech (%)	HighTech (%)	LowTech (%)	HighTech (%)
Total biofuel blending	2	6	6	5	11
Biofuel blending road transport (incl. double counting)	4	10	10	10	27
Biofuel blending road transport	3	8	8	8	14
Biofuel blending aviation	0	0	0	0	7

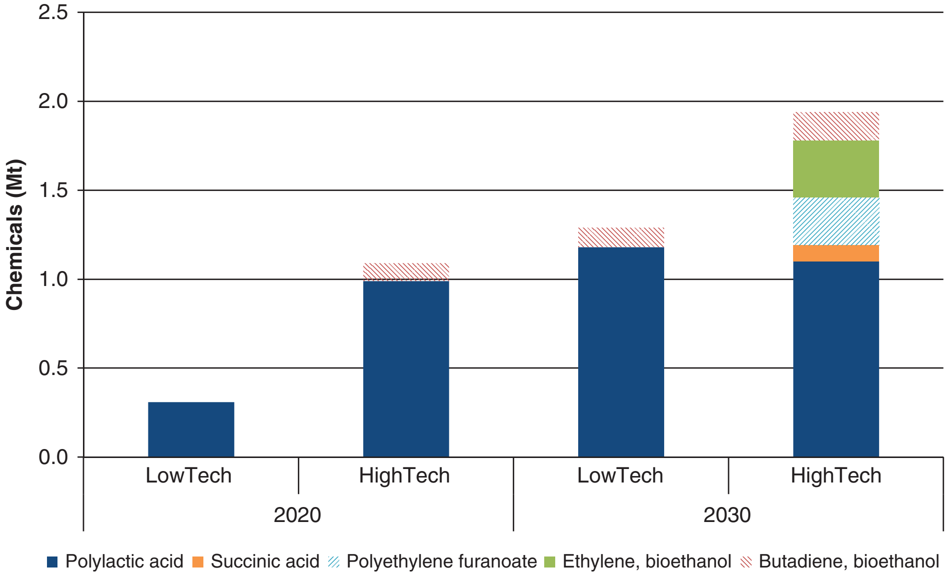


Figure 16. Bio-based chemical production in the Netherlands in 2020–2030.

development scenarios. In 2020, HRD from vegetable oil and UCO are key in LowTech (combined output of 30 PJ). However, in HighTech the supply changes from renewable diesel from vegetable oil to first-generation ethanol as the latter becomes more competitive due to improvements in production costs in supply regions. If these do not occur, HRD from vegetable oil will be produced in HighTech instead. No RJFs are supplied by 2020 in the two scenarios. In 2030, in LowTech, HRD still contributes to the biofuel mix. No RJF is supplied in LowTech in 2030.

In HighTech, biofuel output is more diverse: compared to LowTech, HRD is almost completely phased out from road transport and is supplied to the aviation sector (5.5 PJ). Furthermore, large quantities of FT-diesel and petrol are supplied to road transport (53 PJ) and a small share goes to the aviation sector (7.5 PJ). First-generation ethanol is also supplied in small quantities (3 PJ). The diversification of HighTech in 2030 is due to the access to low-cost feedstocks (imported wood pellets) in combination with technology development (biomass gasification and FT-synthesis), which make biomass conversion technologies competitive; supply is distributed based on cost competitiveness instead of being driven by the blending target (e.g. HRD is supplied to road transport in the LowTech scenario but to aviation in the HighTech scenario, as in this scenario FT-fuels cover a large part of road transport fuel demand). In LowTech the blending target is the main driver for biofuel production across the modeling period. In HighTech, the road transport sector's blending target will have been exceeded in 2030 to achieve the EU RED renewable energy share.

Bio-based chemicals

The output of bio-based chemicals varies significantly across the two scenarios and time periods. Bio-based chemical output increases from 2020 to 2030 in both scenarios (a factor 4 growth in LowTech and almost a factor 2 growth in HighTech). However, in absolute terms, the output in LowTech is 30–70% lower than in HighTech. The bio-based chemical that appears to be competitive in both scenarios and time periods is PLA. In 2030 and in HighTech, bio-based chemicals compete in the same market: the PLA output remains the same from 2020 to 2030 while PEF and ethylene from ethanol is also supplied. These developments are due to take place without policy incentives or support schemes for bio-based chemicals. Their emergence is an outcome of cost competition with fossil-based chemicals as driven by biomass and oil price, the high growth rates of the chemical industry assumed in this study, but also because part of the steam cracker capacity is decommissioned (approximately 3 Mt ethylene, which was installed before 2000). Tsiropoulos *et al.*[82] address the effects of demand and decommissioning of steam crackers. In terms of non-energy use, the share of the bio-based chemicals over the total chemicals ranges from 1–5% in 2020 to 5–10% in 2030 (Fig. S3, SI). The estimation of the bio-based non-energy use is based on the LHV of final products. Fossil non-energy use savings are determined in the same manner, as opposed to deploying a counterfactual scenario where no bio-based chemicals production is allowed.

CO_2 emissions

Figure 17 presents direct CO_2 emissions, i.e. domestic emissions that occur within the geographical boundaries of the Netherlands, including domestic biomass production and transport (grouped under 'Heat and other sectors' in Fig. 17).

Direct CO_2 emissions decrease over time and across the technology development scenarios. The sectors that contribute most to the reduction are *electricity*, due to the deployment of wind and the switch from coal to natural gas, *industry*, due to the use of biomass heat, *heat*, due to the decrease in demand, and *transport* (only in the HighTech), due to the large biofuel supply. However, CO_2 targets are not met in any of the scenarios. This indicates that with the assumed fossil fuel prices, CO_2 tax, and technology portfolio greater efforts will be required to achieve reduction targets.

Figure 18 shows that there are significant indirect emissions, i.e. emissions that occur in the supply chain outside the geographic boundaries of the Netherlands, due to biomass production and transport (approximately 3.5 Mt CO_2) whereas indirect emissions due to import and extraction of oil and gas are approximately 5.5 Mt CO_2. In 2020, indirect emissions may counterweigh the reduction achieved in the Netherlands, but by 2030 there is a net reduction in the range of 8–16 Mt CO_2 (or 5–10%) compared to 2010. Emissions from land-use change have not been taken into account.

Emissions from jet fuels are not included in Fig. 17 and Fig. 18, because they are primarily associated with international flights and are not allocated to the Netherlands. These are in the range of 13.4 Mt CO_2 for both scenarios

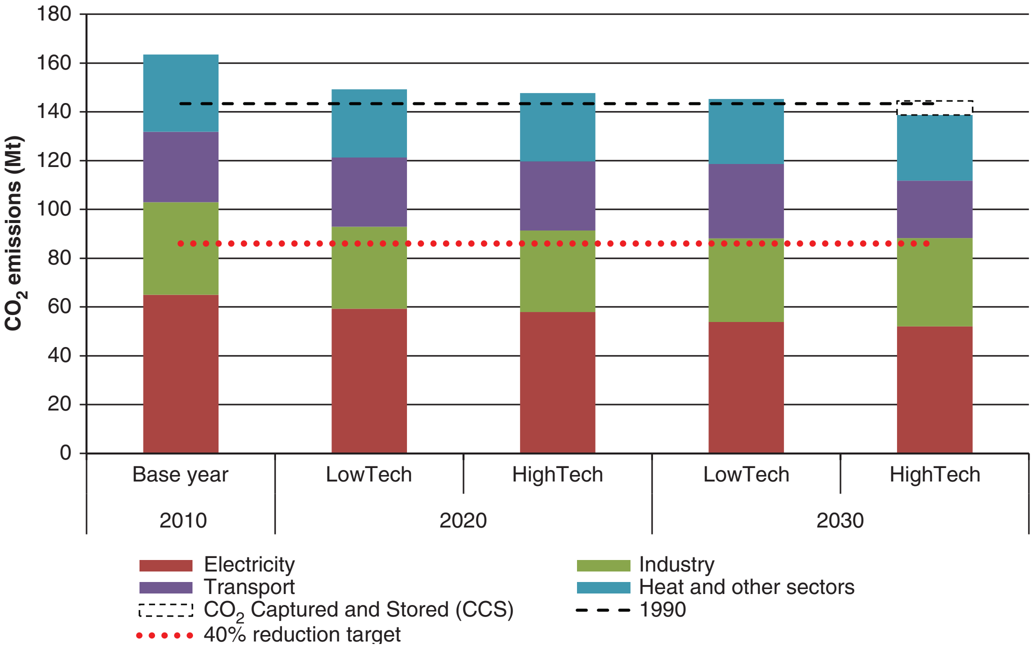


Figure 17. Direct CO_2 emissions in the Netherlands in 2010–2030.

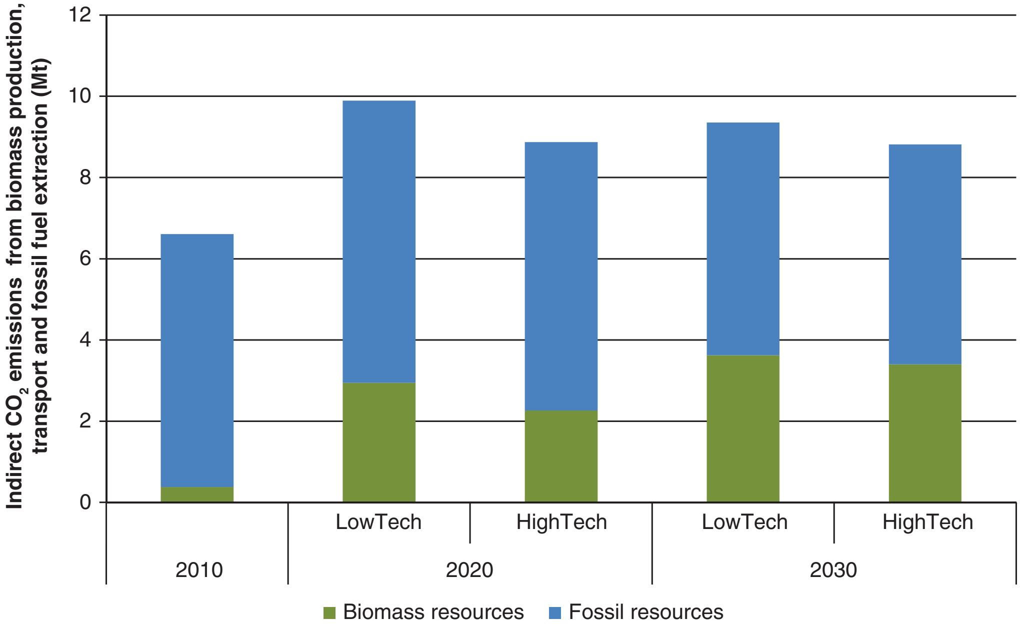


Figure 18. Indirect CO_2 emissions from biomass and fossil resources imported and consumed in the Netherlands in 2010–2030.

in 2020. In LowTech, where only kerosene is used, the emissions reach 15.5 Mt CO_2 in 2030, while RJF blending leads to savings of 1 Mt CO_2 in HighTech during the same year.

Discussion

The results of this study should be interpreted in the context of the input assumptions and the method used. In the following sections we discuss the influence of the modeling approach, technology selection, data limitations, sensitivity and uncertainty analysis. A complementary set of scenario analysis for the Netherlands is provided in Tsiropoulos *et al.*[82]

Modeling approach

Firstly, in MARKAL-NL-UU there are no market constraints that limit the deployment of conversion capacity for the most cost-effective technologies. To some extent, we can account for this limitation by introducing supply constraints in the conversion capacities of advanced biofuels (see above). However, this was not applied to the conversion capacities of bio-based chemicals. On the one hand, the aim of this study is to demonstrate optimal pathways of biomass to end-use sectors, taking chemicals into account. Limiting the production capacity of bio-based chemicals would deviate from this goal. On the other hand, such constraints may be relevant for specific routes, such as PLA or ethylene from ethanol, which were found to reach production volumes of up to 1.95 Mt by 2030. In comparison, today's single plant capacities reach 155 kt/y of lactic acid (for PLA) and 200 kt/y of ethanol-based ethylene.[83] Therefore, it could be argued that similar constraints should be applied for these processes. Nonetheless, while all technologies compete for the same resource (see above) the biomass potential available to the Netherlands is not fully utilized (44–55% of domestic resources).

Secondly, consumers and producers may have different criteria for preferred technologies. For transportation this has already been discussed in van Vliet *et al.*[21] Similar issues are relevant for bio-based chemicals, especially for those that are not chemically identical to their assumed fossil-based counterpart. An example is PLA, which has different barrier properties from PET and PE.[84] End-use consumers (e.g. brand owners) may not encourage such a large-scale shift, which may delay the market penetration of the technologies. Drop-in bio-based chemicals (i.e. bio-based replacements identical to fossil-based chemicals such as ethylene from ethanol) are likely to be less subjected to this.[11] However, other sustainability criteria (e.g. labor conditions, GMO feedstocks) may still form a barrier to large-scale market diffusion.

The existing modeling framework could benefit from decoupling the domestic demand for chemicals from the overall production in the Netherlands, as this would align the demand across all end-uses of energy. It would also enable better representation of organic waste flows from bio-based materials consumed in the Netherlands into MSWI and would allow incorporating end-of-life policies such as recycling and/or incineration in the model.

Closely related are the higher biomass efficiency gains that can be obtained if cascading of biomass is applied to the system, namely the prioritized consumption of biomass for high-value applications such as materials and chemicals, followed by reuse and recycling before being finally consumed for energy.[85] Given the regional boundaries of this study, detailed material flows are required to capture prospective domestic consumption of bio-based materials, reuse practices, recycling and end-of-life practices, as well as the corresponding policies. While these challenges have not been addressed by this study, they are recommended for future research and model improvement.

Another aspect that has been excluded from the modeling framework is implementation and competitiveness of energy efficiency measures that can reduce energy demand, especially in sectors where biomass was shown to play a key role, e.g. industrial heat. To some extent, this has been addressed by autonomous efficiency improvements in the chemical industry and the decrease in the demand for energy due to existing efficiency measures. However, more stringent energy efficiency may contribute beyond what is implicitly included in this study and may influence the size of the renewable energy portfolio. Similarly, in other sectors, minimization or substitution of demand (e.g. tele-working, car pooling) could be pivotal in transitioning to more sustainable energy systems.[86]

Furthermore, oil refineries have not been explicitly modeled. Crude oil is assumed to be an imported commodity and is converted to diesel, petrol, kerosene, and naphtha by ignoring their production co-dependency in refineries. A reduction in fossil fuels, as the results of this study suggest, would entail a reduction in crude oil refining with a consequent reduction in the output of naphtha or other refinery chemicals, and potentially also lower prices due to lower demand. It is recommended as an improvement to the model to better represent the interrelation between on the one hand fuels and naphtha from refineries and on the other hand crude oil and price correlations. This suggestion involves intensive data collection on refinery cost-structures and stock in the Netherlands, which is a rather complex and data-intensive task.

Technology selection and data limitations

Technology development and innovation of bio-based chemicals is ongoing and there are several prospective routes and platform chemicals that could be included in a systems analysis framework.

The technologies included in this study are not exhaustive regarding the several bio-based chemical conversion pathways that exist or are being developed (see above). However, the selected routes can be considered most representative as they are currently produced on a large scale (e.g. PLA and ethanol-based ethylene), are in the ramp-up phase (e.g. SA), or are promising for the future with an expected CAGR to 2020 of over 10%.[87] Besides high-value/low-volume bio-based chemicals (see above), chemicals have been excluded if they were in the early phases of development, e.g. algae-based or fatty acid-based chemicals and lignin-based aromatics. An exception is the production of polyhydroxyalkanoates (PHA), which are already at an early commercial stage. However, the available data for PHAs are limited. Polyhydroxyalkanoates have an estimated high growth potential and may lead to significant emission reduction. Like many other pathways of biomass to materials, they have higher production costs than other polymers.[11]

One shortcoming of the bio-based chemical technologies included in the present study is the limited representation of conversion routes to aromatics. Model outcomes suggest the supply of aromatics from oil refineries at assumed cost prices. As a result, if future biomass conversion routes to aromatics have lower production costs than refinery chemicals, additional fossil fuel replacement can take place. One option would be to incorporate isobutanol from fermentation or aqueous phase reforming and subsequent conversion to paraxylene. However, literature shows that the production costs of paraxylene are 2885–4121 $/t, which is approximately 3–4 times more expensive than fossil-based aromatics.[88] This technology was therefore not included, as it would not compete with alternatives. Gasification and conversion of syngas to FT-fuels was shown to be a key technology in the model results of HighTech, demonstrating synergies between the transport and electricity sector. Supply of FT-naphtha to the chemical sector was not shown as a cost-effective option, due to the additional capacity of steam cracking required for the conversion of naphtha to olefins. Direct conversion of syngas to olefins could potentially offer benefits by avoiding this intermediate step.[89] Lignin valorization technologies, although early in technology readiness, could become an interesting alternative beyond 2030 as large-scale lignocellulosic sugar and ethanol production is included in the technology portfolio, where lignin is produced as a co-product. Potential technologies go beyond the ones addressed above. A key constraint to the extension of the technology portfolio is data availability. In this study we were faced with difficulties in estimating reliable and verifiable cost structures. To be able to assess bio-based chemical conversion technologies in a systems analysis framework, more data should become available. This requires action from bioeconomy stakeholders, including the industry, which typically hold such information. If more data is available, expanding the temporal scope of the model beyond 2030 can be deemed feasible and more insights can be derived.

Additional technologies do not only relate to the bio-based chemical sector. More technology options could be explored, such as the production of synthetic natural gas from biomass gasification in different locations (e.g. Ukraine). However, in a cost-optimization model, such options could dominate the supply because they may potentially have lower production costs than natural gas.[90] Nevertheless, infrastructure, technology deployment (gasification), markets and so on are not expected to be fully operational in 2030. Other industrial sectors where biomass can be utilized are excluded from this study: synthetic fibers, composite materials, natural rubbers and traditional users of biomass such as pulp and paper, construction, and charcoal use in the iron and steel industries.

A major determinant of the deployment of biomass conversion technologies is the cost-supply of biomass. In this study biomass was disaggregated to feedstocks and regions to define detailed biomass cost-supply curves; biomass costs are a major determinant of production costs, and therefore of the deployment of conversion technologies. Nevertheless, modeling of biomass cost-supply could be further improved. For example, feedstock-specific logistics can be applied as a proxy instead of wood chips, thus improving the representation of transport costs from the sourcing regions to the Netherlands. Furthermore, pre-treatment methods such as pelletization or torrefaction could also take place in the sourcing regions, which could increase biomass production costs but may well significantly reduce transport costs to the Netherlands, thus increasing cost-efficiency and stimulating the deployment of biomass conversion technologies.[67,68]

Uncertainty and sensitivity analysis

The primary goal of this study was to design and apply a modeling framework, which accounts for competitive and synergetic uses of biomass for energy and non-energy applications. To assess potential deployment pathways of biomass conversion technologies, we developed two scenarios that account for a key future uncertainty: the rate of technology development.

However, there are several exogenous parameters that may influence model outcomes, which need to be assessed prior to providing robust directions to policy making. First and foremost, fossil fuel prices (Table S8, SI) influence the competitiveness of the reference conversion technologies. Furthermore, as fossil fuels are consumed in biomass supply chains in production (e.g. harvesting) and transportation, any variation in prices may in turn affect biomass costs. However, the latter are subject to influence by other drivers (e.g. supply and demand, weather conditions that affect production). Other uncertainties include, different CO_2 emission mitigation policies such as high CO_2 taxation or an emission cap, constrained biomass supply, with the Netherlands having access to only intra-EU resources, or conversely access to low-cost biomass feedstocks from regions outside the EU (such as Ukraine), stricter sustainability constraints, and specific support for technologies. Furthermore, complete closure of coal-based power plants based on a government decision can significantly influence the fuel mix for electricity generation and the CO_2 emission performance of the system. Additional scenario and sensitivity analysis may provide greater insights if applied to the modeling framework of this study. Biomass sourcing regions (e.g. Brazil) may also move towards the direction of advanced bioeconomy applications, thereby affecting the competitiveness of biomass imports to the Netherlands and the subsequent conversion to bio-based chemicals, or may change the import structure of the country (e.g. from biomass feedstocks to bio-based intermediate or final chemicals). Such scenarios require regional-wide models; however, they are crucial to further assess the implications of bioeconomy developments.

Conclusions

In view of emerging biomass conversion technologies and novel bioeconomy applications, the potential synergies of sectors through valorization of different biomass constituents and the competition with other renewables across the energy system are very important. So far, however, the non-energy sector, and in particular the chemical industry, has been omitted from most mid-term, cost-optimization energy systems models. The present study is one of the first endeavors to shed light on cost-effective uses of biomass in an energy system that includes potential bioeconomy developments. This is achieved by extending a cost optimization model with emerging sectors and biomass conversion technologies, namely bio-based chemicals, multi-output biorefineries and RJF. This model can assess the cost-efficient deployment of biomass in the energy system at a country level, in competition with other renewable energy and CO_2 emission mitigation technologies such as CCS. The modeling framework was demonstrated for the Netherlands.

Two scenarios were applied to address uncertainty in future technology progress. Policy targets, a key driver for the deployment of renewable energy technologies, were applied to both scenarios. They included targets from national (Dutch Energy Agreement) and European (EU RED) policies that were assumed to continue up to 2030. In meeting targets, biomass contributes significantly, especially in sectors where there are limited or more costly renewable alternatives, such as heat and transport fuels. In the electricity sector, wind was found to be a key contributor. It was also found that if technology development is accelerated (HighTech scenario) then biomass might offer cost-competitive alternatives without support from policies on bio-based chemicals from 2020 onwards next to co-produced electricity and supply of biofuels beyond the minimum blending mandate in transport. Rapid technological progress enables bio-based growth of the transport sector, primarily through the supply of FT-fuels, and of the chemical sector, through the supply of diverse bio-based chemicals. Beyond 2020, it also enables the production and supply of RJF through gasification and FT-synthesis pathways. In contrast, under low-technology development (LowTech scenario), policy targets remain the primary driver for renewable energy deployment, with biomass mainly being deployed in low-value applications such as heat. Under these scenario conditions, the supply of RJF would require incentives (such as a blending target or subsidies).

The study revealed important cross-sectoral synergies and shifts of biomass feedstocks in different sectors based on the technology development scenarios. Renewable energy deployment (primarily wind) and biomass (through heat, biofuels and CCS in gasification technologies) reduce CO_2 emissions over time in comparison to the base year (2010). However, CO_2 mitigation targets are not met under the assumed scenario conditions (fossil fuel prices, CO_2 taxation, national and European renewable energy targets). Greater efforts are therefore required to achieve emission reduction targets (e.g. a mandatory cap or higher CO_2 emission taxation), which could potentially highlight a higher contribution from biomass in the energy system.

The dependency of the Netherlands on biomass imports indicates that a more detailed representation of feedstock supply-chain development in the model is necessary to assess the feasibility of access to low-cost biomass feedstocks. The technology portfolio could be enriched as there are several pretreatment (e.g. pelletization, torrefaction) and conversion technologies, especially for bio-based chemicals, which could improve cost-efficiencies of biomass value chains. The product portfolio can also be extended to include high-value chemicals as opposed to mainly bulk products that are included in this study. Furthermore, assessment of other systemic aspects such as biomass cascading, competition induced by other policies (e.g. on energy efficiency), and technical aspects such as process integration of technologies, could lead to improved insights by the model presented in this study.

The cost-optimization model developed and demonstrated in this paper can be used to assess comprehensively the future potential supply of emerging bioeconomy products such as bio-based chemicals and RJF, investment decisions that can avoid lock-in or stranded capital stock, the role and contribution of bioeconomy sectors in GHG emission reduction and national policy targets, and several other scenario-based research questions.

Abbreviations and units

ASTM	American Society for Testing and Materials
BDO	1,4-butanediol
CAGR	Compound annual growth rate
CCS	Carbon capture and storage
CHP	Combined heat and power
EB	Ethylbenzene
EC	European Commission
EG	Ethylene glycol
EO	Ethylene oxide
EU	European Union
FCC	Fluid catalytic cracking
FDCA	2,5 furandicarboxylic acid
FT	Fischer–Tropsch
GHG	Greenhouse gas
HEFA	Hydroprocessed esters and fatty acids
HRD	Hydrotreated renewable diesel
HTL	Hydrothermal liquefaction
IEE	Intelligent Energy Europe
ISBL	Inside battery limits
LHV	Lower heating value
LPG	Liquefied petroleum gas
MARKAL	Market allocation
MSWI	Municipal solid waste incinerator
Mt	Million tons
NL	Netherlands
NUTS	Nomenclature of territorial units for statistics

Mt_{wpe}	Million tons wood pellet equivalents
OECD	Organisation for Economic Co-operation and Development
OSBL	Outside battery limits
PA	Phthalic anhydride
PDO	1,3-propanediol
PE	Polyethylene
PEF	Polyethylene furanoate
PET	Polyethylene terephthalate
PLA	Polylactic acid
PO	Propylene oxide
PP	Polypropylene
PTA	Terephthalic acid
PTT	Polytrimethylene terephthalate
PYR	Pyrolysis
RED	Renewable energy directive
RJF	Renewable jet fuel
R&D	Research and development
SA	Succinic acid
SI	Supporting Information
SNG	Synthetic natural gas
UCO	Used cooking oil

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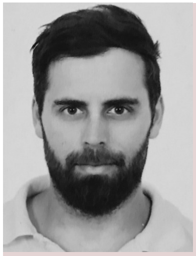

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