THE PRIMES BIOMASS 2012 SUPPLY MODEL

E3MLAB – NTUA

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FIGURES AND TABLES

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Description of Model Version 3.4

1 Introduction

1.1 Model scope and aim

The PRIMES Biomass model is a modelling tool aimed at contributing to the energy system projections for the EU Member-States and the impact assessment of policies promoting renewable energy sources and addressing climate change mitigation. The detailed numerical model simulates the economics of supply of biomass and waste for energy purposes through a network of processes, current and future, which are represented at a certain level of engineering detail for which a very detailed database of biomass and waste processing technologies and primary resources has been developed.

The model transforms biomass feedstock –therefore primary energy- into bio-energy commodities –secondary or final form- which undergo further transformation in the energy system, e.g. as input into power plants, heating boilers or as fuels for transportation.

The model calculates the inputs in terms of primary feedstock of biomass and waste to satisfy a given demand for bio-energy commodities; the model further estimates the land use and the imports necessary and provides quantification of the amount of production capacity required. Furthermore, all the costs resulting from the production of bio-energy commodities and the resulting prices of the commodities are quantified.

The model covers all EU27 Member States individually and covers the entire time period from 2000 to 2050 in five year periods. It is calibrated to Eurostat statistics wherever possible for the years 2000 to 2010. Data from Eurostat is complemented by other statistical sources to fill in the database necessary for the model to function.

The model belongs to the PRIMES model family and was also developed within E3Mlab at the National Technical University of Athens (NTUA). It can work as a standalone model provided that the demand for bio-energy commodities is given exogenously, but is more often used together with the PRIMES Energy System Model[1] as a closed loop system.

1.2 Model development

The PRIMES Biomass model has been developed at E3Mlab of the NTUA over several years. The model databases were improved over the years and were recently harmonised with other European models within the Biomass Futures project[2]. The current model version has been thoroughly

[1] E3Mlab, 'The PRIMES Energy System Model: Reference Manual'. Available online at: http://www.e3mlab.ntua.gr/

[2] The Biomass Futures project: http://www.biomassfutures.eu/

updated in autumn 2011 where the technology and process database was updated. The historical data are updated to the latest available 2010 statistics.

The model has been used for numerous EC projects. Aside from the Biomass Futures project, the model has been used as a tool underlying the Impact Assessment of the EC Roadmaps to 2050 (EC,2011).

1.3 Structure of this document

The scope of this document is to provide a thorough description of the functions and features of the PRIMES Biomass model. The introductory chapter provides a general view into the model. General information about the model is given regarding the scope, the aim and the development of the model.

The second chapter gives an overview of the structure of the PRIMES Biomass model, regarding the biomass conversion chains. In that context, the types of biomass feedstock effectively used in the model are described in detail. Furthermore, the technologies considered in the model for the conversion of biomass feedstock into final bio-energy commodities are analysed, complemented by Annex I, where a schematic representation of all the conversion pathways used in the model is presented.

The PRIMES Biomass model seeks to minimise the total biomass supply chain cost, subject to certain restrictions. In the third chapter, a detailed description of the model methodology is presented, where the cost minimisation problem is described. Other features included in the model, such as endogenous learning-by-doing and final bio-energy product pricing are also described.

The model constitutes a tool for testing the effect of different legislation contexts on the biomass supply system. The next chapter describes the way different policies and measures can be incorporated into the model, so as to determine the way they would affect the structure of the biomass supply system.

The last chapter provides an overview of the databases of the model. The database of the PRIMES Biomass model is classified into categories; the components of each dataset are described in detail.

2 The model: structure, feedstock and conversion technologies

2.1 Structure

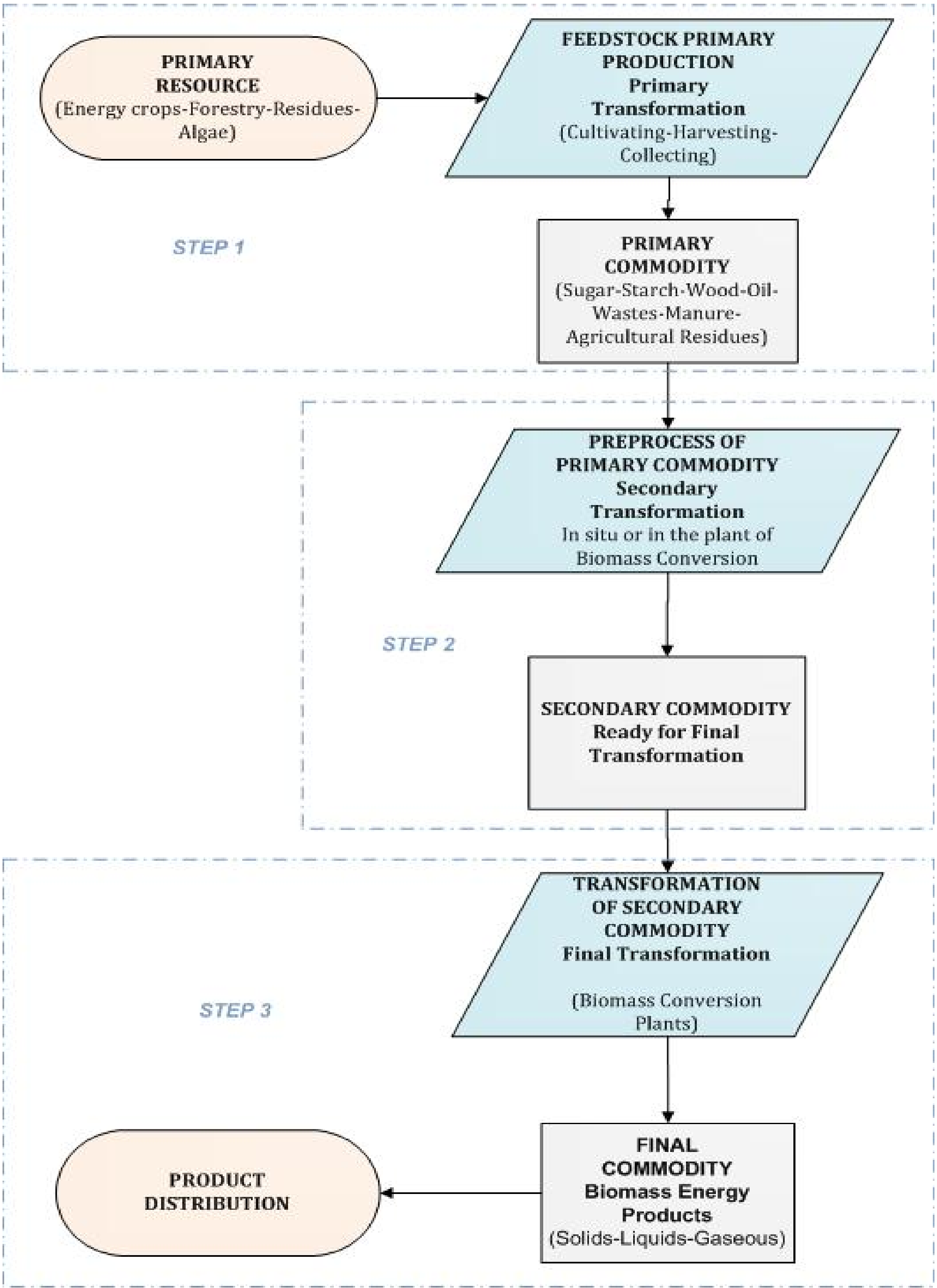
The general structure of the model is illustrated in Figure 1 and can be described in the following way:

Step 1: A primary biomass commodity (e.g., sugar, starch etc) is produced/derived from the primary resource (e.g. energy crops) through a primary transformation stage (e.g. cultivation).

Step 2: The primary commodity is then, passed through a pre-processing stage (e.g. drying) that produces a secondary/intermediate commodity.

Step 3: The secondary commodity is the input to the transformation process from which the final energy product (e.g. biofuel) is derived. Logistics are taken into account as part of the different processes.

FIGURE 1: BIOMASS CONVERSION CHAIN



2.2 Feedstock

The primary production of biomass has been classified into the following categories: energy crops, forestry waste and aquatic biomass (i.e. algae). Depending on the type of the plants that are cultivated, energy crops are further distinguished into starch, sugar, oil and lignocellulosic crops. This classification is dictated by the differentiation of the methods that each plant category may be processed with and the final products that derive from them. Starch crops include resources such as maize, wheat, barley etc, sugar crops refer mainly to sugar beet and sweet sorghum and oil crops consist of rapeseed, sunflower seed, olive kernel etc. Regarding lignocellulosic crops there is a distinction between wood crops, such as poplar, willow etc, and herbaceous lignocellulosic crops like miscanthus, switch grass, reed etc.

Forestry is split into wood platform, i.e. organised and controlled cutting of whole trees for energy use, and wood residues, i.e. the collecting of forestry residues only.

Apart from agricultural residues, several types of wastes have also been identified as potential sources for energy supply. These include industrial solid waste, pulp industry waste (black liquor), used oils and fats, municipal waste, sewage sludge, landfill gas, manure and animal wastes. Table 1 summarises all the types of primary biomass/waste effectively used in the model.

TABLE 1: CLASSIFICATION OF PRIMARY BIOMASS

Energy Crops	*Forestry*	*Wastes and Residues*	*Aquatic Biomass*
Starch Crops	Wood Platform	Agricultural Residues	Algae Biomass
Sugar Crops	Forest Residues	Wood Waste	
Oil Crops		Waste Industrial Solid	
Lignocellulosic Crops		Black Liquor	
• Herbaceous Crops • Wood Crops		Used oils and fats	
		Municipal Waste	
		Sewage Sludge	
		Landfill Gas	
		Manure	
		Animal Waste	

2.3 Biomass Conversion

The PRIMES Biomass model includes numerous production pathways for the production of biofuels for transportation, both for road and non road, as well as pathways producing bio-energy commodities as inputs into electricity and heat generation sectors.

The end products available in the model include bio-energy commodities such as biofuels for road transportation, biogas, small scale solids (mainly pellets) and large scale solids, which mainly are for use in the power generation and industry. Transportation biofuels include diesel and gasoline from biomass (both conventional and advanced biofuels), biokerosene for aviation, bioheavy for navigation, as well as biogass. For gasoline and diesel the model differentiates between conventional and advanced biofuels, which are considered to be fully fungible with conventional fuels and can therefore be used in existing engines. For gaseous bio-energy commodities, the model differentiates between biomethane, which is biogas upgraded to pipeline quality and biogas.

In the following, a brief description of the bio-energy commodity technologies included in the model is presented. Some of them, such as fermentation of sugars for ethanol production or transesterification of vegetable oil for the production of biodiesel, are technological and economic mature processes and are already well established in Europe for the production of biofuels. Other technologies, such as pyrolysis of wood, offer significant benefits, regarding mainly the utilisation of cheaper and abundant feedstock, but need further research in order to become economically competitive.

An extensive literature review was conducted in order to identify those biomass-to-bio-energy commodities conversion technologies that bear some potential for future penetration in the biofuel market. The choice of the technologies that are finally selected to be included in the Biomass Model was made based on the current status of technical and economic development, research efforts and possibilities for future improvements, type of feedstock and type and characteristics of final products. The technologies that are incorporated in the Biomass Model based on the different conversion chains are presented hereafter. Table 2 summarises the technology pathways of primary biomass transformation available in the PRIMES Biomass model, while an extensive schematic representation of the biomass conversion chains is presented in Annex I.

Table 2: Production pathways of bio-energy commodities

FEEDSTOCK	*PRODUCTION PATHWAY*	*END PRODUCT*
Starch crops, Sugar crops	Fermentation	Ethanol
Woody Biomass	Enzymatic Hydrolysis and Fermentation	Cellulosic Ethanol
Woody Biomass	Enzymatic Hydrolysis and Fermentation	Ethanol (advanced)
	HTU process, deoxygenation and upgrading	
	Pyrolysis, deoxygenation and upgrading	
	Pyrolysis, Gasification, FT and upgrading	
Woody Biomass, Black Liquor	Gasification, FT and upgrading	
Aquatic Biomass	Transesterification, Hydrogenation and Upgrading	
Oil crops	Transesterification	Biodiesel
Starch crops, Sugar crops	Enzymatic Hydrolysis and deoxygenation	
Oil crops	Hydrotreatment and deoxygenation	Biodiesel (advanced)
Woody biomass, Black Liquor	Gasification and FT	
Aquatic Biomass	Transesterification and Hydrogenation	

Woody biomass	HTU process and deoxygenation	
	Pyrolysis and deoxygenation	
	Pyrolysis, Gasification and FT	
Woody biomass	Gasification and FT	Biokerosene
	HTU process and deoxygenation	
	Pyrolysis and deoxygenation	
	Pyrolysis, Gasification and FT	
Aquatic Biomass	Transesterification and Hydrogenation	
Woody biomass	Gasification and methanol Synthesis	Biomethanol
Woody biomass	Gasification and DME Synthesis	BioDME
Woody biomass, Black Liquor	Gasification	Biogas/ Biomethane
Organic Wastes, Starch	Anaerobic Digestion	
Woody biomass	Enzymatic Hydrolysis	
	Catalytic Hydrothermal Gasification	
Woody biomass	Hydrothermal Upgrading (HTU process)	Bio Heavy Fuel Oil
	Pyrolysis	
Black Liquor	Catalytic Upgrading of black liquor	
Landfill, Sewage Sludge	Landfill and sewage sludge	Waste Gas
Organic Wastes	Anaerobic Digestion	
Industrial Waste, Municipal Waste (solid)	RDF	Waste Solid
Woody biomass		Small Scale Solid
Woody biomass		Large Scale Solid

2.3.1 Technologies for Bioethanol production

Sugars & Starch Fermentation

Bioethanol is used in spark ignition vehicle engines either blended with gasoline or in pure form if the engines are properly modified. At present bioethanol is mainly produced from sugar crops via fermentation. Currently in Europe sugar beet and sweet sorghum are mainly used as feedstock. Starch crops are also being used as feedstock. In that case an additional pre-process stage is needed to hydrolyse starch into simpler sugars before fermentation that implies a cost difference between sugar & starch fermentation processes (Arumugam et al.,2007). Thus, in PRIMES Biomass Model Sugar Fermentation & Starch Fermentation are treated as separate technologies.

Lignocellulosic Fermentation

Bioethanol can also be produced using as feedstock lignocellulosic crops through the biochemical conversion of the cellulose and hemicelluloses components of biomass feedstock into fermentable sugars. Cellulosic ethanol has the potential to perform better in terms of energy balance, greenhouse gas (GHG) emissions and land-use requirements than starch-based biofuels. Unlike production of bio-ethanol from sugar and starch crops, this process is still under development however a lot of research is taking place both in Europe and in the USA implying significant future potential (IEA,2008).

2.3.2 Technologies for Biodiesel production

Transesterification

Biodiesel is merely produced from vegetable oils by catalytic transesterification with methanol. Biodiesel produced in this way has similar properties with fossil diesel and may be used in conventional engines blended up to a proportion with fossil diesel or in modified engines in higher proportions. Vegetable oils may be produced from several biomass sources, such as rapeseed, soya been, sunflower, olive kernel etc. In Europe the most common feedstock for the production of vegetable oil as feedstock for further conversion into biodiesel is rapeseed. Other vegetable and animal fats as well as used oils may also be used as feedstock to the transesterification process. Transesterification is a well established technology and is largely deployed in Europe (van Thiujl et al., 2003). Additionally, research has been performed to examine algal oil production from microalgae cultivation that could be used as feedstock for the production of biodiesel via transesterification offering various potential advantages when compared with traditional oil crops.

Fischer Tropsch Synthesis

The production of diesel from coal via the Fischer-Tropsch process is a technology with long history. Historically the approach has focused on the conversion of coal-to-liquid fuels and chemicals. Recently the utilisation of biomass derived syngas is proposed for the production of Fischer-Tropsch biodiesel. The thermo-chemical route involves the production of a synthesis gas, which is cleaned, before passed through the Fischer-Tropsch process, to create a range of liquid fuels, but primarily synthetic diesel (IEA,2008). The production of Fischer-Tropsch diesel requires thorough cleaning and conditioning of the biomass derived syngas, which currently bears a lot of technical difficulties and challenges and deteriorates the economics of the technology. However, the combination of the multiple feedstock gasification with the synthesis of Fischer-Tropsch diesel is an attractive alternative for the production of a fossil diesel substitute.

Pyrolysis

Pyrolytic oil is produced by a thermo-chemical conversion process called flash pyrolysis. In order to be used as transport fuel, pyrolytic oil has to be hydro-deoxygenated using catalysts and stabilised to reach specific quality requirements. Since it is not mixable with fossil diesel, the resulting fuel may only be used directly in modified diesel engines. Pyrolytic oil can also be used for co-firing in power and steam generating units, or may be gasified for the production of syngas. The technology has not reached to a maturity status yet and there are significant difficulties that have to be overcome. However, since almost any type of biomass can be used in flash pyrolysis, including lignocellulosic biomass, the technology is attractive and bears significant potential for future deployment (A.V. Bridgwater, 2002).

Hydro Thermal Upgrade

Another substitute of fossil diesel is proposed by converting almost all types of biomass into liquid biofuel via a process called hydro-thermal upgrading (HTU). During HTU process, the biomass is decomposed in water to produce a crude oil-like liquid called 'bio-crude'. The resulting 'bio-crude' is further upgraded through hydrogenation with catalysts to achieve fossil diesel quality and may be blended in any proportion with conventional fossil diesel. The technological status of the HTU process has not reached maturity yet. Furthermore, it is a highly energy intensive process which further reduces its economic performance. Nevertheless, the utilization of a wide variety of feedstock ranks HTU as a candidate technology for future production of biodiesel (van Thiujl et al., 2003).

2.3.3 Technologies for Biokerosene production

Biokerosene is alternative for jet fuel having similar properties to petroleum-derived kerosene. Currently biokerosene production is under research and only test flights have been performed. The airline industry aims not only at replacing fossil with renewable fuels but also to improve fuel efficiency standards and reduce the volume of greenhouse gas emissions (NNFCC,2007).

2.3.4 Technologies for Biogas and Biomethane production

Anaerobic Digestion

A series of biological processes in which microorganisms break down biodegradable material (biomass); in the absence of oxygen, anaerobic bacteria ferment biomass into biogas. Biogas can be produced this way from almost any organic matter such as agricultural residues, animal waste and manure. In the Biomass Primes Model, Anaerobic Digestion is used to produce biogas from every raw material mentioned above. Biogas is a mixture of CO_2 and CH_4. Methane represents approximately a 60% in the total mixture. In order to increase CH_4 proportion in the mixture, biogas passes through an upgrading process where CO_2 is absorbed or scrubbed and finally leaves 98% of biomethane that can be directly injected into the natural gas grid (IEA,2005).

Gasification

Biogas can also be produced via gasification. This route has a much larger potential as a wider range of feedstock as wood can be used. Biomass is gasified at high temperature, producing biosyngas. The biosyngas enters a gas cleaning section and then passes through a methanation unit where CO and H2 are converted into biomethane and CO2. After CO2 removal, the gas is ready for injection into the natural gas grid (Arumugam et al., 2007).

2.3.5 Technologies for Waste Gas production

Waste gas consists of Sewage Sludge Gas and Landfill Gas that could be produced via anaerobic digestion technology using Waste Sewage Sludge and Waste Landfill Gas as feedstock. Anaerobic digestion for the production of waste gas is currently widely used in Europe. Due to the impurity and the lower methane content of waste gas compared to that of the biogas (biomethane) described above, waste gas cannot be injected into the natural gas grid and its main applications are to produce small scale electricity and heating.

2.3.6 Technologies for Bioheavy production

Bioheavy includes 'biocrude' and 'pyrolysis oil' produced via Pyrolysis and Hydrothermal Upgrade. It is mainly produced to be further altered into biodiesel through transesterification, but could also be used for heat generation or as transport fuel in bunkers.

2.3.7 Technologies for Small & Large Scale production of solids

Small & Large Scale Solid consists of wood logs and pellets for small and large scale combustion for power and heating generation, produced from pelletizing and logging processes of wood biomass.

2.3.8 Technologies for Waste Solid production

Waste solid consists of Mass burn waste (MBW) and Refused derived fuel (RDF). Mass burn refers to the incineration of unsorted municipal waste in a Municipal Waste Combustor (MWC) or other incinerators designated to burn only waste from municipalities. RDF is solid fuel for direct combustion and covers a wide range of waste materials processed to fulfil guideline, regulatory or industry specifications mainly to achieve a high calorific value. Waste derived fuels include residues from MSW recycling, industrial waste, industrial hazardous waste, biomass waste, etc. RDF can be produced from municipal solid waste through a number of different processes that in general consist of separation and sorting, size reduction (by shredding, chipping and milling), drying and finally transforming the combustible waste into cylindrical solid fuel (EC-DG Environment, 2003).

2.3.9 Technologies for Biohydrogen production

Biohydrogen is a promising future energy source due to its very high energy content and the fact that it produces almost no emissions when burnt. It could perform either as direct fuel in engines that would burn pure hydrogen or as electric power source for electric motor vehicles (through a fuel cell). Biohydrogen could be produced from bio-syngas, a mixture of H_2 and CO formed from biomass derived char, oil or gas. In PRIMES Biomass model, bio-syngas is derived through biomass gasification, to achieve higher ratios of H_2/CO, an important factor that affects its performance as fuel source. The resulting mixture passes then through a solvent separation system to absorb CO and release biohydrogen (van Thiujl et al., 2003).

3 Methodology

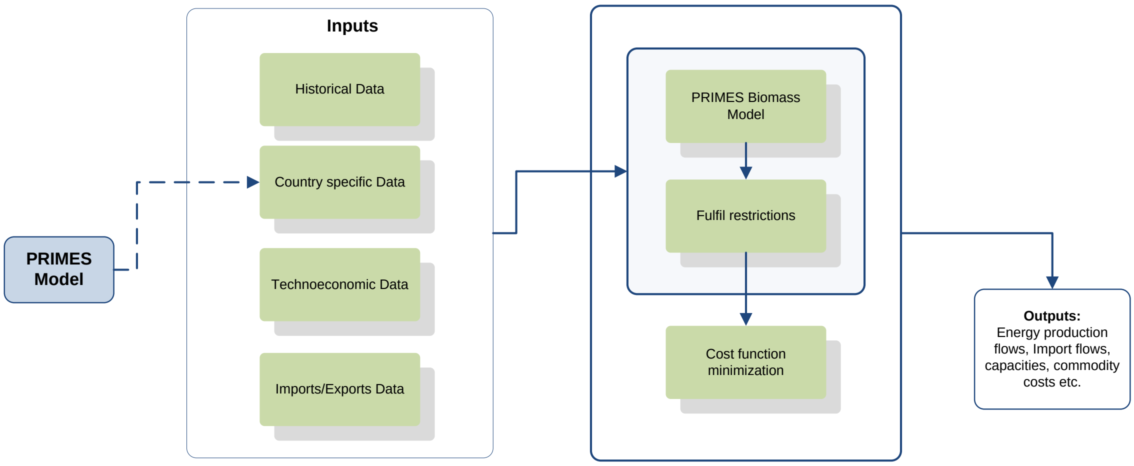
The PRIMES Biomass model is an economic supply model that computes the optimal use of resources and investment in biomass transformation processes, so as to meet a given demand for final biomass energy products under least cost conditions. The PRIMES Biomass model is generally linked with the PRIMES large scale energy system model and can be solved either as a satellite model through a closed loop process, or as a standalone model. When running as a standalone model, the PRIMES Biomass model works as a non linear optimisation model that seeks to minimise total cost to satisfy a fixed demand, derived from PRIMES energy system model. When concatenated with the rest of the PRIMES suite, establishing a closed loop, the PRIMES Biomass model runs as a Mixed Complementarity Problem (MCP) to determine the equilibrium of demand and supply. The time horizon of the model is 2050. The model provides dynamic projections to the future from 2015 until 2050 in 5-year time periods with years 2000 to 2010 being calibration years. The modelling work was conducted using the GAMS modelling tool.

The model solves the cost minimisation problem, so as to fulfil certain restrictions. Consequently, it determines the optimal use of biomass resources and it calculates investments for technologies for biomass conversion to bio-energy commodities, the costs and consumer prices of the final bio-energy products as well as the greenhouse gas (GHG) emissions resulting from the bio-energy commodities life-cycle. The decision on investment for the secondary and final transformation processes is endogenous using technology vintages and dynamics of technology development. Furthermore, endogenous learning-by-doing for all technologies has been included, so as to simulate technological change and decrease of costs of technologies as related to the cumulative experience gained in the process of commodities production. Improvements in each technology are described by one learning-by-doing curve for each technology, uniform for all Member States of the EU; therefore learning-by-doing effects spill over to the whole EU.

The model input data are country specific data, such as data referring to agricultural and land use parameters and data referring to costs and commodity prices (electricity, gas, other liquid fuels), techno-economical data concerning the biomass conversion process and data regarding the biomass and waste resources potential cost supply curves. For the feedstock prices the model uses cost-supply curves which are specific by country and depend on land availability, productivity trends and the use of fertilizers. Exogenous assumptions and estimates are used about land availability and yield improvement possibilities for the various energy crops. The yields are assumed to increase over time due to technology developments and additional agricultural policies.

The model allows trade of both primary biomass and end bio-energy commodities. Tradable feedstock considered are pure vegetable oil, which is mainly imported palm oil, and solid biomass. The end products traded are solid biomass, conventional and next generation biodiesel, bioethanol, biogasoline (meaning cellulosic bioethanol) and biokerosene. The trade takes place both between EU Member States and with other countries outside the EU. Extra EU regions are aggregated into three categories: North America, CIS and the rest of the world. The trade that takes place between Europe and the rest of the world includes as main providers for wood CIS and North America, while for sugarcane bio-ethanol Brazil. Imported oil is for the most part palm oil mainly from Indonesia and Malaysia. Imports from outside the EU are described through cost-supply curves which change in the context of the different scenarios depending on assumptions about biomass use for energy purposes in the rest of the world. Trade within the EU depends on transportation costs which are determined with aggregate spatial information.

FIGURE 2: PRIMES BIOMASS MODEL STRUCTURE



3.1 Mathematical specification of the model

The biomass supply model of PRIMES solves a problem of minimizing total long-term supply costs of meeting a given demand for bio-energy commodities, which is derived from the rest of PRIMES model. The minimization is subject to equilibrium constraints which represent the cost structure of various feedstock supplying possibilities, as well as the cost functions of technology suppliers. Policy-related restrictions are represented as overall constraints, such as for example the sustainability criteria. It is assumed that a variety of biomass producers and transformers acting in all EU Member-States compete with each other in production and in biomass commodity trading among the Member-States. Thus, the optimization solves for all the Member-States simultaneously as well as for the entire time horizon assuming perfect anticipation by all market actors. The model also determines bio-energy commodity prices as a result of maximizing social surplus by Member-State subject to recovering all types of fixed and variable costs of biomass supply.

At a first glance the biomass supply optimization resembles a least cost transport problem consisting of finding the least cost way of meeting demand for bio-energy commodities (denoted by i) through feedstock resources (denoted by s) which are stepwise transformed into final commodities in a variety of processes (denoted by j). The technically feasible transformation pathways are considered to belong to the mapping $h(s,j,i)$. Both demand and supply are located at the EU Member-States (denoted by n), which are linked together through a transportation network used for trading bio-energy commodities among the Member-States. In addition, the Member-States are connected to non EU countries for importing biomass feedstock and/or ready-made bio-energy commodities.

Feedstock can be produced in the EU from crops, residues (agriculture, forestry) and wastes. Owners of resources used to produce feedstock (such as land, residue or waste collectors) are assumed to have different cost structures and to compete with each other. Thus, supply of feedstock is assumed to derive from cost-supply curves, denoted by $f_s(F_s)$, which depend on quantities produced annually (F_s) and exhibit decreasing returns to scale. The cost supply curves are also specified by Member-State (n) and over time (t).

Exporters from outside the EU addressing the Member-State markets are assumed to price feedstock or bio-energy commodities according to their own cost-supply structure which is subject to resource limitations. Thus, import prices increase with imported quantities ($s\ or\ i$) following an ascending cost-supply function: $m_{k,(s\ or\ i)}\left(M_{k,(s\ or\ i)}\right)$ where M denotes imported quantities and k denotes the various non EU importing origins.

The processes (j) transforming feedstock into bio-energy commodities have processing capacities ($K_{j,t}$) which are formed by accumulating investment ($I_{j,t}$). The technology characteristics (unit costs, efficiency, and input/output ratios) are specific to the year of investment, but for new installations they evolve over time depending on technology supply which follows learning-by-doing curves, denoted by $\ell_j\left(\sum_n \sum_t I_{j,n,t}\right)$ exhibiting decreasing costs and increasing performance as a function of total installed capacity in the EU.

Production in time t from a processing unit j built in time τ (i.e. $G_{j,\tau,t}$) is constrained by available capacity ($K_{j,\tau}$). In addition, the rate of use of capacities cannot decrease below a certain level otherwise the capacity is not at all used. As the optimization assumes perfect foresight, obviously only capacities with sufficiently high rates of use will be built. Thus, the model simulates competition between various processing technologies.

Both the decreasing costs due to the learning curves and the capacity usage constraints violate standard convexity requirements and so the optimization is formulated as a mixed-integer programming problem.

The main unknown variables are: $F_{s,n,t}$ the domestic production of feedstock, $G_{i,j,n,\tau,t}$ the production of processes, $M_{k,s,n,t}$ and $M_{k,i,n,t}$ the imports of feedstock and ready-made bio-energy commodities from non EU countries, $K_{j,n,\tau}$ and $I_{j,n,\tau}$ the capacity and investment in processes (of vintage τ) and $X_{i,n,nn,t}$ the exchanges of bio-energy commodities between the EU Member-States (nn being an alias of n).

Market equilibrium is formulated by Member-State and for each bio-energy commodity, requiring that total supply from domestic production and imports (both outside the EU and from other EU countries) meets exactly given demand in each time period. Market equilibrium is thus ensured through the following condition:

$$\sum_j \sum_{\tau \le t} G_{i,j,n,\tau,t} + \sum_k M_{k,i,n,t} + \sum_{nn}\left(X_{i,nn,n,t} - X_{i,n,nn,t}\right) = d_{i,n,t} \quad \forall n, \forall t \qquad \text{Eq. 1}$$

where $d_{i,t}$ is the demand for bio-energy commodities, given from the core PRIMES model.

Production by transformation processes uses inputs and outputs related to each other through a production possibility function, denoted by $g_{s,j,i}$ which determines demand for feedstock ($G^{(f)}_{s,j,i,n,\tau,t}$) and fuel (and electricity) consumption ($G^{(e)}_{s,j,i,n,\tau,t}$):

$$G^{(f)}_{s,j,i,n,\tau,t} = g_{s,j,i}\left(G_{i,j,n,\tau,t}\right) \qquad (\forall s, \forall j, \forall i) \in h(s,j,i)\ and\ \forall n, \forall t, \forall \tau \le t \qquad \text{Eq. 2}$$

$$G^{(e)}_{s,j,i,n,\tau,t} = g_{s,j,i}\left(G_{i,j,n,\tau,t}\right) \qquad (\forall s, \forall j, \forall i) \in h(s,j,i)\ and\ \forall n, \forall t, \forall \tau \le t \qquad \text{Eq. 3}$$

Capacities of processing are determined by investment accumulation, as follows (initial conditions concerning old existing capacities are not shown):

$$G_{i,j,n,\tau,t} \leq K_{j,n,\tau,t} \quad \forall i, \forall j, \forall n, \forall t, \forall \tau \leq t \qquad \text{Eq. 4}$$

$$G_{i,j,n,\tau,t} \geq u_{j,n,\tau} K_{j,n,\tau,t} \; or \; G_{i,j,n,\tau,t} = 0 \quad \forall i, \forall j, \forall n, \forall t, \forall \tau \leq t \qquad \text{Eq. 5}$$

$$K_{j,n,\tau,t} = I_{j,n,\tau} - D_{j,n,\tau,t} \quad \forall j, \forall n, \forall t, \forall \tau \leq t \qquad \text{Eq. 6}$$

where $u_{j,n,\tau}$ is the minimum rate of use of capacities and $D_{j,n,\tau,t}$ denotes the decommissioned capacities, which depend on technical lifetime. The time index τ, which must be lower or equal than current projection time t, denotes the technology vintage for processing units and so production as well as technology characteristics are specific to a vintage.

Total demand for feedstock by type has to be met by domestic production and by imports from non EU countries:

$$\sum_{k} M_{k,s,n,t} + F_{s,n,t} = \sum_{(j,i)\in h(s,j,i)} \sum_{\forall \tau \leq t} G^{(f)}_{s,j,i,n,\tau,t} \quad \forall s, \forall n, \forall t \qquad \text{Eq. 7}$$

The part of domestic feedstock originating from crops is associated with land use ($L_{s,n,t}$) through a production function ($y_{s,n}$) which exogenously assumes yield growth trends, specifically by crop type and by country. Similarly, other feedstock types, such as residues or waste, are using primary resources which are also denoted by $L_{s,n,t}$ and their use depends on productivity trends captured through the function $y_{s,n}$. Total domestic resources by type of feedstock give upper bounds $\overline{L}_{s,n,t}$ which represent technical potentials.

$$L_{s,n,t} = y_{s,n}(F_{s,n,t}) \quad \forall s, \forall n, \forall t \qquad \text{Eq. 8}$$

$$L_{s,n,t} \leq \overline{L}_{s,n,t} \quad \forall s, \forall n, \forall t \qquad \text{Eq. 9}$$

Emissions of greenhouse gases are related to energy consumption in the transformation processes, which include collection and transportation of feedstock, and to emissions related to domestic production of crops. Emissions by type of bio-energy commodities across the chain of production will have to be lower than a threshold (a sustainability criterion):

$$\sum_{(s,j)\in h(s,j,i)} \sum_{\forall \tau \leq t} em^{(e)} \cdot G^{(e)}_{s,j,i,n,\tau,t} + \sum_{(s,j)\in h(s,j,i)} em^{(f)} \cdot a_{s,j,i} \cdot \sum_{\forall \tau \leq t} G^{(f)}_{s,j,i,n,\tau,t} \leq xe_{i,n,t} \cdot d_{i,n,t} \quad \forall i, \forall n, \forall t \qquad \text{Eq. 10}$$

where em are greenhouse gas emission factors, xe is the specific emission threshold (the sustainability criterion) and $a_{s,j,i}$ denote the share of feedstock of type s used to produce bio-energy commodity i through a process of type j.

It is assumed that the actors optimizing total biomass supply anticipate the economics of feedstock supply, as well as the cost functions of imports and the learning curves of technology supply. Thus they take into account the gradients of the corresponding cost-supply curves in their optimization. In this sense, the optimization corresponds to a problem of mathematical programming with equilibrium constraints.

Total biomass supply system cost include in addition the annuity payments for capital investment in transformation processes, the variable and energy costs, the fixed operation and maintenance costs and the transportation costs which depend on distances between the Member-States. The annuity payments depend on a weighted average cost of capital ($\rho_{j,n}$) which may differ by country and by type of process. The aggregation of total costs over time use present values discounted using a social discount rate (δ).

Total intertemporal biomass supply system cost is then defined as follows:

$$\begin{aligned} Cost = \sum_{t=1}^{T} e^{-\delta\cdot t} \sum_{n} \Bigg(& \sum_{s} \Bigg(\sum_{f} f_s(F_{s,n,t}) + \sum_{k} m_{k,s}(M_{k,s,n,t}) \Bigg) \\ & + \sum_{j} \sum_{\tau\le t} n_{j,n}(\rho_{j,n}) \cdot \ell_j \Bigg(\sum_{nn} \sum_{tt} I_{j,nn,tt} \Bigg) \cdot I_{j,n,\tau} \\ & + \sum_{j} \sum_{i} \sum_{\tau\le t} v_{i,j,n}(G_{i,j,n,\tau,t}) \\ & + \sum_{i} \Bigg(\sum_{nn} r_{i,n,t}(X_{i,nn,n,t}) + \sum_{k} m_{k,i}(M_{k,i,n,t}) \Bigg) \Bigg) \end{aligned} \qquad \textit{Eq. 11}$$

where $f_s, m_{k,s}, \ell_j, v_{i,j,n}, r_{i,n,t}, m_{k,i}$ denote respectively the feedstock cost-supply function, the imported feedstock cost-supply function, the technology learning-by-doing function, the variable cost function for processes, the transportation cost function for intra-EU trade and the cost-supply function for imported bio-energy commodities from outside the EU. Annuity payment factors for capital investment are represented by $n_{j,n}(\rho_{j,n})$.

The optimization problem consists in minimizing total cost given by Eq.11, subject to the constraints that are described by Eq.1 to Eq.10 and to non negativity constraints for the unknown variables. The anticipation of the equilibrium conditions by the cost minimizing agent is incorporated directly in the objective function through the cost-supply curves and so it is not needed to solve the model using an

MPEC[3] algorithm. The dual variable of Eq.1 is the long term marginal cost of demand for bio-energy commodities and the dual variable of Eq.7 is the long-term marginal value of feedstock supply.

3.2 Pricing

To determine the prices of bio-energy commodity by type and by country, the model formulates a Ramsey-Boiteux pricing rule. This rule takes the perspective of a multiproduct monopolist which sets the prices so as to maximize social surplus subject to a constraint on profits for which total costs include fixed and sunk costs. Such a rule often applies to regulated utilities which develop new infrastructures and is consistent with regulators aim at maximizing welfare together with ensuring effective investment. For long term planning, as it is the purpose of the model, the Ramsey-Boiteux pricing is appropriate for an emerging industry, such as biomass production for energy purposes. The price setting outcome is also compatible with well functioning markets, which will have to be competitive while providing assurance about fixed cost recovery.

It is assumed that the bio-energy commodities address different markets where they compete against other forms of energy and also that demand for these commodities depend on prices. The numerical values of the price elasticities are known through the use of the core PRIMES model, which among others calculates the demand for the bio-energy commodities. Assume that the implicit demand functions are denoted by $d_{i,n,t}(p_{i,n,t})$ where $p_{i,n,t}$ are the prices of the bio-energy commodities. Let us denote by $\pi_{i,n,t}(d_{i,n,t})$ the inverse demand functions. Cost of supply of bio-energy commodities is known by solving the optimization problem mentioned above, which defines an implicit cost function denoted by $C_{n,t}(d_{i,n,t}, \forall i)$ as depending on the entire bundle of bio-energy commodity demand by country. Consequently, total revenue $R_{n,t}$ by country, profit $\Pi_{n,t}$ and social surplus $W_{n,t}$ can be calculated as follows:

$$R_{n,t} = \sum_i \pi_{i,n,t}(d_{i,n,t}) \cdot d_{i,n,t} \quad \forall n, \forall t$$ *Eq. 12*

$$\Pi_{n,t} = R_{n,t} - C_{n,t}(d_{i,n,t}, \forall i) - \Phi_{n,t} \quad \forall n, \forall t$$ *Eq. 13*

$$W_{n,t} = \sum_i \left(\int_0^{d_{i,n,t}} \pi_{i,n,t}(z) \cdot dz \right) - C_{n,t}(d_{i,n,t}, \forall i) - \Phi_{n,t} \quad \forall n, \forall t$$ *Eq. 14*

Price determination derives from maximizing social surplus $W_{n,t}$ calculated by Eq. 14, subject to profit, calculated by Eq. 13, being equal to a fixed value $\overline{\Pi}_{n,t}$ which is typically set equal to zero. Solving this problem leads to price setting through:

$$p_{i,n,t} = \pi_{i,n,t}(d^*_{i,n,t}) \quad \forall n, \forall t$$ *Eq. 15*

[3] Mathematical programming with equilibrium constraints (MPEC) is the study of constrained optimization problems where the constraints include variational inequalities or complementarities. The lower level optimization problems represent decision by suppliers (of feedstock, imports and technology) for which it is assumed that they have analytical solutions in the form of cost-supply functions.

where $d^*_{i,n,t}$ results from social surplus maximization under the profit constraint. The parameter $\Phi_{n,t}$ may be used to represent a variety of fixed or sunk costs that are needed to develop the emerging bio-energy market, as well as opportunity costs for example in relation to prices of energy commodities competing with bio-energy ones.

4 Implementation of policies and measures

The PRIMES Biomass model is designed to take into account legislation that concerns the use of biomass in energy sector and thus constitutes a tool for the evaluation of the way policies affect the biomass supply system. Additional to current legislation the model is able to simulate other policy contexts, therefore the impacts of different policies, beyond current legislation, and measures can be simulated.

The policy related constraints applied in the model are described hereupon.

4.1 The EU Climate & Energy package

The achievement of the EU 20-20-20 targets is implemented in the PRIMES energy system model and the demand delivered to the PRIMES Biomass model therefore includes these targets. Currently, the model takes into account the RES Directive (Directive 2009/28/EC), the Fuel Quality Directive (Directive 2009/30/EC) and the Biofuels Directive (Directive 2003/30/EC).

4.2 Emissions constraint

Restrictions per bio-energy commodity express that the greenhouse gas emissions (GHG) as percentage of emissions avoided for each biomass commodity have to lie above a certain percentage threshold, determined by current legislation. The threshold imposed by the RES and the Fuel Quality directives is used, but more stringent constraints can be applied as well depending on the scenario.

Carbon emissions are calculated for each final bio-energy commodity as a sum of emissions in all stages of the chain of commodity production and transformations. The emissions are computed by multiplying the quantities of energy forms (oil products, gas, electricity) used in the production and transformation of biomass commodities by specific emissions factors. These factors are obtained from the results of the PRIMES energy system model.

Emissions resulting from indirect land use change (ILUC) can be included in the calculation of the overall emissions, despite the fact that ILUC emissions are not taken into account in current legislation methodologies.

4.3 Sustainability

Additional to the GHG mitigation criterion, other sustainability related restrictions can be effectively applied in the PRIMES Biomass model. The criteria currently used in the model are the ones set out by the RES and the Fuel Quality directive and are related to high biodiversity land and to land with high carbon stock. According to legislation, the raw materials used as biomass feedstock cannot be obtained from high biodiversity areas, such as undisturbed forests, high biodiversity grasslands and nature protection areas, unless the production of that raw material is obtained harmlessly. Furthermore, land with high carbon stock cannot be converted to biomass feedstock cultivation area, thus areas such as wetlands, continuously forested areas and peatlands are excluded from the land that can be used for the production of energy crops. These criteria set restrictions to the total acreage of land dedicated to energy crops used in the model, as the energy crops production can only take place in a sustainable manner.

Other sustainability constraints, beyond the ones set out by the RES Directive and the Fuel Quality Directive or enhancement thereof can also be incorporated in the PRIMES Biomass model, such as constraints concerning sustainable use of fertilizers and the quality of water and air. Extensions of the sustainability criteria to imported fuels can also be incorporated in different ways e.g. by assuming higher prices or reducing the quantities available for imports.

4.4 Further policies

The model can further implement other policies and measures. In different scenario contexts, policies towards climate change mitigation can be simulated, such as policies facilitating the use of Renewable Energy Sources and the application of carbon values to the ETS and non ETS sectors. Furthermore, measures such as subsidies can be effectively incorporated in the model, as well as sensitivity analysis on the effect of various parameters, such as conventional fuel prices, on the biomass supply system.

5 Database

The construction of the biomass database was one of the most demanding and time consuming tasks in the model development process. Extensive literature research has been carried out in order to establish a reliable technical and economic database for each stage of biomass conversion chain. The current model database has been thoroughly updated in autumn 2011, when the technology and process data were updated. The historical data are updated to the latest available 2010 statistics. The model databases were recently harmonised with other European models within the context of the Biomass Futures project, while extensive use was also made of data developed from previous projects, such as VIEWLS, REFUEL, BIOPOL and JRC.

The database of the PRIMES Biomass model has several components which can broadly be classified as: the historical statistical data; techno-economic data related to technological parameters for the processes; country specific data relating to agricultural/land use parameters as well as cost data; and import/export data referring to the trade of commodities outside the EU.

5.1 Historical data

The PRIMES biomass model uses historical data from 2000 to 2010 for calibration and is able to represent the historical biomass situation in the EU. Where data is available the model is, like all PRIMES family models, fully calibrated to Eurostat; as not all data for biomass is available in Eurostat the model uses also further information sources, such as FAOstat and Enerdata. The effort of collecting, analysing and filtering the most reliable data available for the past years, demands a long time endeavour. This process was fully concluded in autumn 2011.

In the following Table 3 lists the parameters which, for the scope of this overview, have been classified as historical data. The table contains the name of the parameter, a description the parameter and the source of the data.

TABLE 3: DESCRIPTION OF HISTORICAL DATA

HISTORICAL DATA	DESCRIPTION	SOURCE
Bio-energy production	Amounts of final bio-energy commodities produced	Key source for the data concerning bio-energy production for historical years is Eurostat
	Production technologies used	The information concerning the production technologies used derive from several sources, such as Aebiom and EurObserver
Land data	Includes the cultivated land per crop for the production of biofuels for historical years.	Aebiom and other sources
Technical data for historical years	All techno-economical information needed for historical years, including costs per processes (capital, fixed and variable costs), heat rate of processes followed, fuel consumption	The techno-economical information used mainly came from ECN and OEKO and were complemented by studies of NTUA and the Agricultural University of Athens
Energy crop production cost	This data set includes all the essential information for the computation of the production cost of energy crops for historical years per crop type and country (land yield, land renting cost, labour cost, cost of equipment, cost and uptake of fertilizers and nutrients, fuel prices)	The data concerning the production crop of the energy crops was derived from various sources such as USDA, FAO and FAOSTAT and several others were consulted such as the International Fertilizer Agency
Imports data	Information regarding the trading activity that took place internally in the European Union and among European Union and the rest of the world.	Data from various sources were used including the NREAPs
Fuel prices	Fuel prices for fossil fuels used during the production process	PRIMES model: based on Eurostat and Enerdata

5.2 Techno-economic data

The techno-economic data specifies the characteristics of the technologies and are updated to reflect the latest technology developments; the projections for the development of technologies to the future were also updated to the latest available data and literature available.

The data underlying the final values used within the PRIMES Biomass model are taken from a large variety of sources including ECN and OEKO; expert judgement as well as external consultation with experts has been used to fill the gap where technology data was not found in literature or where it was not possible to determine the robustness of a data source.

In PRIMES Biomass model numerous conversion pathways are combined to shape the biomass to energy conversion route, producing a variety of bio-energy products. A schematic overview of the biomass conversion technologies effectively used in the model is presented in Annex.

Data was researched for each component of the process in order to have updated data for technologies which currently do not exist or for which data are not available, e.g. data concerning the processes for the conversion of aquatic biomass to final bio-energy commodities.

Table 4 shows the parameters included in the model and gives a description of the parameter.

TABLE 4: DESCRIPTION OF TECHNO-ECONOMICAL DATA

TECHNO-ECONOMIC DATA	DESCRIPTION	SOURCE
Cost per process	Here capital, fixed and variable costs are represented per process, from historical and current years to future estimations of technological maturity.	For the collection of the techno-economical data many sources and reports were consulted. External consultation with experts from the Chemical Engineering Department of NTUA and the Agricultural University of Athens took place. The data that form the PRIMES Biomass model database are harmonised with other European models.
Heat rate	Model heat rate is used to indicate the efficiency of each process.	
Technical Lifetime	Technical lifetime for every transformation process.	
Amortisation	The time period to amortise a process investment.	
Utilisation	Utilization rate of a production facility.	
Technical availability	Estimates about the availability of a technology at a commercially mature level	
Fuel consumption	Amount of energy consumed per technological process.	

5.3 Country specific data

This data refers mainly to agricultural and land use parameters and data referring to costs, including cost supply curves for feedstock as well as commodity prices (electricity, gas, other liquid fuels). The data mentioned in this section refers to country specific data about future developments; past years are covered in the section on historical/statistical data.

Several sources were used to construct the primary biomass potential databases. The available energy crops production is determined endogenously by the model using exogenous assumptions pertaining land availability and land productivity yields. The yields are crop specific and are assumed to increase overtime due to technology improvements in agriculture and additional agricultural policies. The model uses curves to simulate different types of land with different land productivity and fertiliser needs.

Concerning primary biomass potentials, several sources were used to form the model databases. Information on energy crops were mainly derived from EEA studies and EUWood data and estimates was used to determine forestry potential. A thorough analysis was carried out in E3Mlab to determine the municipal waste and landfill potential. The analysis was based on the population growth estimations for each Member State and used data derived from Eurostat waste statistics. Expert judgements were used in order to disaggregate the waste potential derived from Eurostat into the four categories used in waste management. Thus, the amount of waste land filled, composted, incinerated and recycled was determined and therefore the waste potentials that can be effectively used for energy purposes were specified. Regarding black liquor, studies were used to determine current potential, whereas potential projections to future years followed paper and pulp industry growth rates.

Table 5 includes a list of this category of parameters.

TABLE 5: DESCRIPTION OF DATA CONCERNING EUROPEAN MEMBER STATES

EU27 MEMBER STATE DATA	DESCRIPTION	SOURCE
Potentials	Potentials for all biomass types of feedstock resources identified, are available, within the PRIMES biomass model in great detail.	A number of sources were used for the construction of the potentials database, such as EUwood, EEA, Alterra etc.
Demand on biofuels and other bioenergy products	PRIMES biomass model is linked with PRIMES core model as it is determined to compute all the outputs so as to meet a given demand of bioenergy products projected by PRIMES model. The demand is provided by country and by fuel. External sources which give biofuel demand can be used	The most frequently used data source is the PRIMES Energy System Model. Depending on the scenario other external sources can be used, e.g. the National Renewable Action Plans (NREAPs) submitted by the EU Member States
Energy fuel prices	Another input for PRIMES biomass model, are the fuel prices of electricity, diesel oil and natural gas calculated by PRIMES core model, that are being	PRIMES: the costs for the fuels depend on the scenario context in which the

	consumed through the various biomass transformation processes, to produce final bioenergy products from primary biomass feedstock.	scenario is run
Cost supply curves	Estimated economic supply curves for all biomass supply categories in which the initial biomass primary resources have been analysed.	
Land data	Land availability for dedicated energy crops cultivation for every European Member State.	
Energy crops yield	Possible yields for different kinds of energy crops (sugar, starch, oil, wood lignocellulosic and herbaceous lignocellulosic crops) differentiated per European country taking into consideration climate and currently dominant types of crops.	The data concerning energy crops was derived from various sources such as EEA, USDA, FAOSTAT, EUWood, as well as from previous projects such as VIEWLS and REFUEL
Energy crops production cost	Detailed information on land renting cost, land yield, labour cost, cultivation cost, price and crop absorption factor of fertilizers and nutrients and fuel prices for agriculture (given by PRIMES core model), that are available per energy crop type and European country, result in calculating the overall energy crop production cost.	
GHG Emissions	To compute the total CO_2 emissions and emission savings resulted from the extensive use of biomass derived energy, emission factors from PRIMES core energy model for electricity, diesel oil and natural gas are included within the inputs of PRIMES Biomass model. For electricity the values are country specific based on the mix of fuels in power generation and they change over the years based on the scenario projection. Moreover percentages that simulate the abatement of CO_2 emissions that needs to be accomplished according to the EU Renewable Energy Directive are included.	PRIMES Energy System model IPCC methodology for the calculation of N_2O emissions IFPRI, OEKO for ILUC emissions

5.4 Trade & Import data

The Primes Biomass model allows trade of biomass feedstock and end bio-energy commodities between Member States, as well as between the EU and the rest of the world. Information concerning the trading activity of Europe, both internal and international, is covered in Table 6. Historical data sets are collected from the year 2000 to 2010, in order to comply with statistics. The necessary data for the construction of this part of the database were derived from several sources.

TABLE 6: DESCRIPTION OF DATA REFERRING TO INTERNAL EUROPEAN TRADE AND INTERNATIONAL IMPORTS

TRADE & IMPORTS DATA	DESCRIPTION	UPDATES THROUGH BIOMASS FUTURES PROJECT
Potentials	Potentials for all products (biomass feedstock or end energy products) imported internationally are available in detail.	Data from various sources were used to form this part of the database, such as IEA, Enerdata, Eurostat, NREAPs, the U.S. DOE, FERN and FAOSTAT
Imports exports supply curves	Estimated economic supply curves for all international imports and exports activities.	
Distances and trade connections	Trade matrix simulating distances and trade connections between member states and rest of the world.	
Transport	Costs and means used for transportation regarding internal European trade and international imports	

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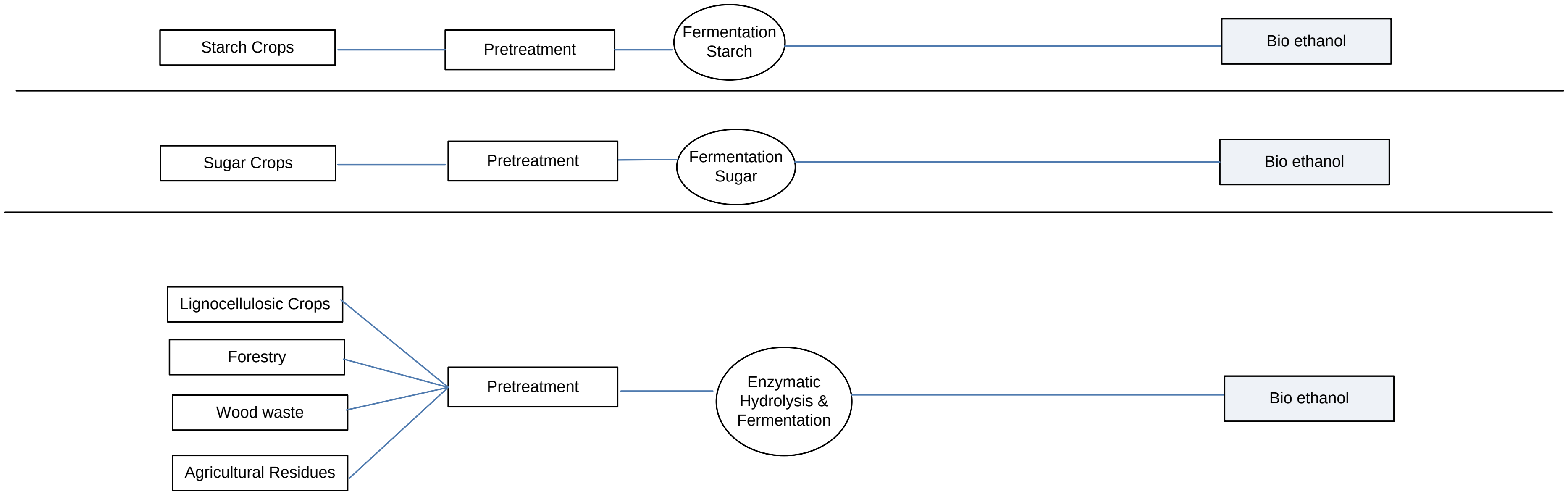
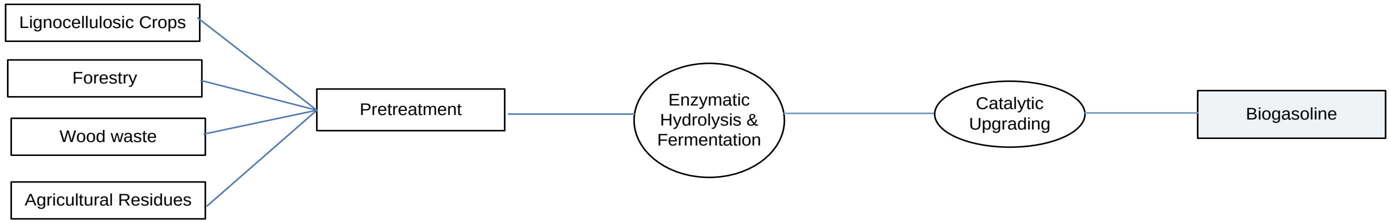
7 Annex I

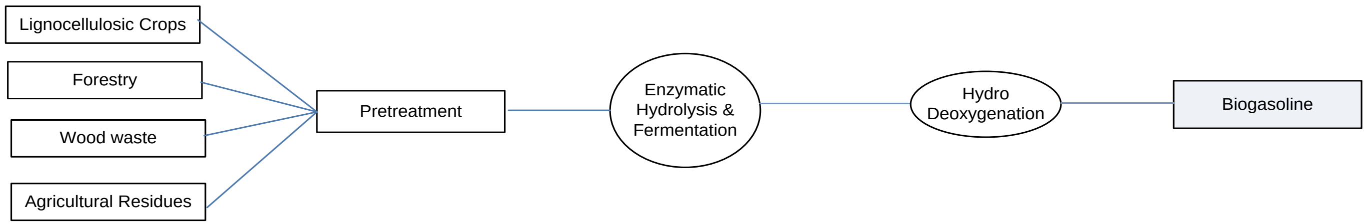
7.1 Biomass Conversion Chains

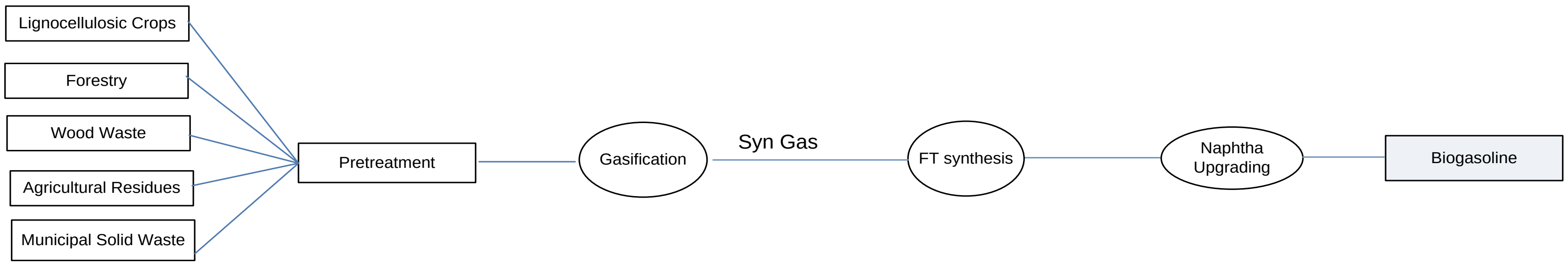
7.1.1 Bioethanol Production Chains

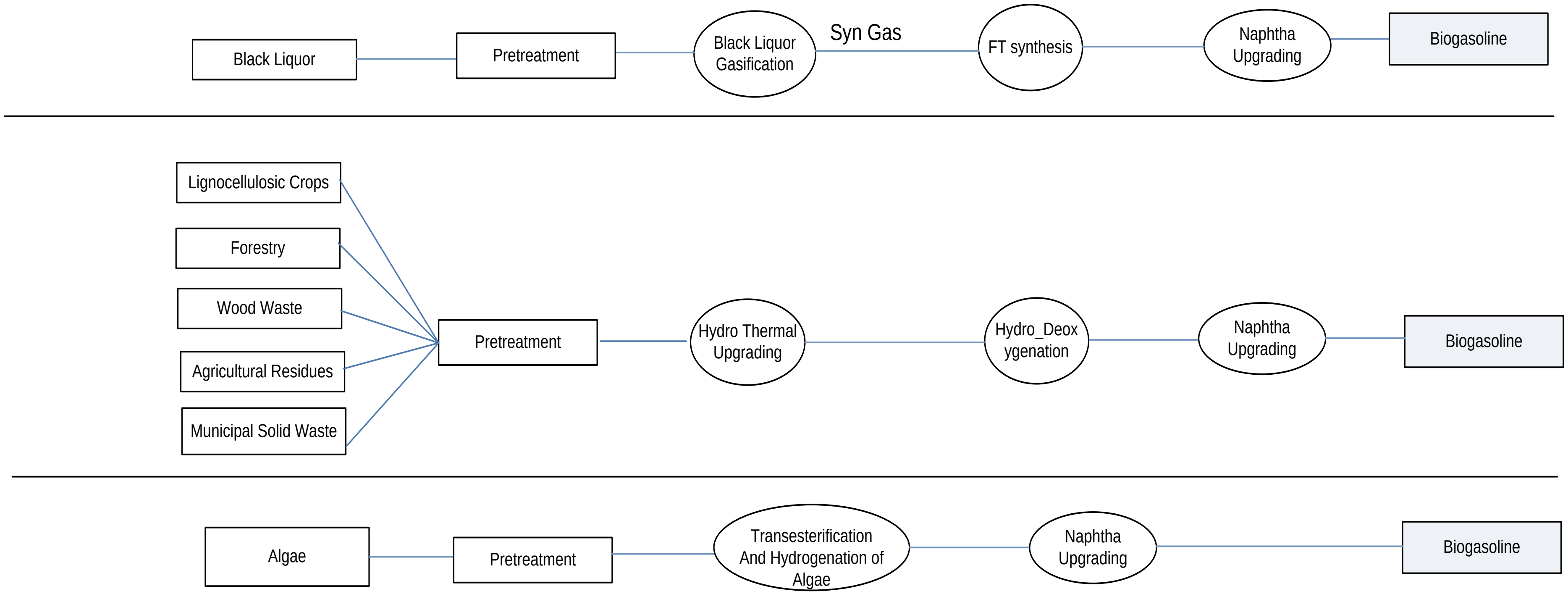


7.1.2 Biogasoline production chains

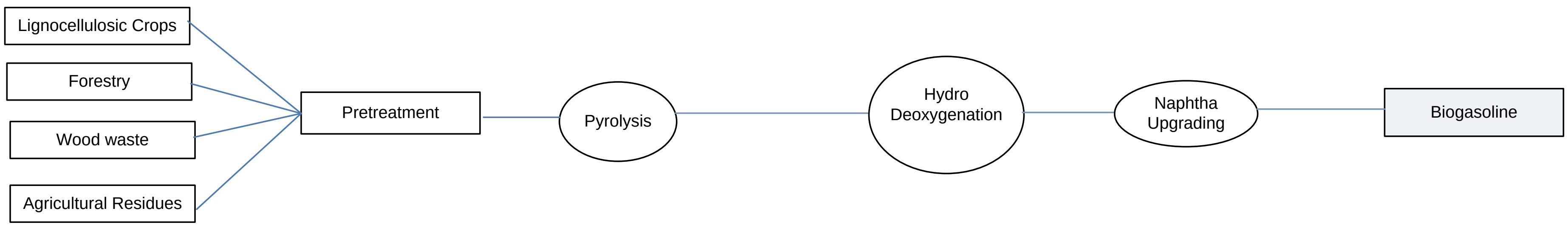


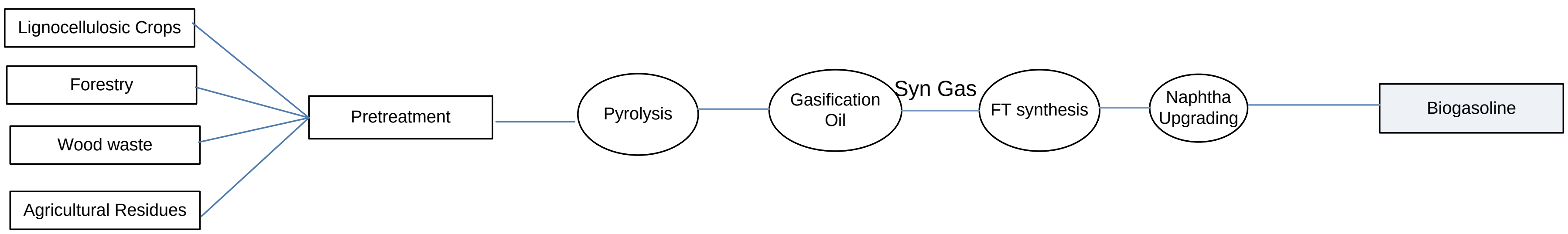




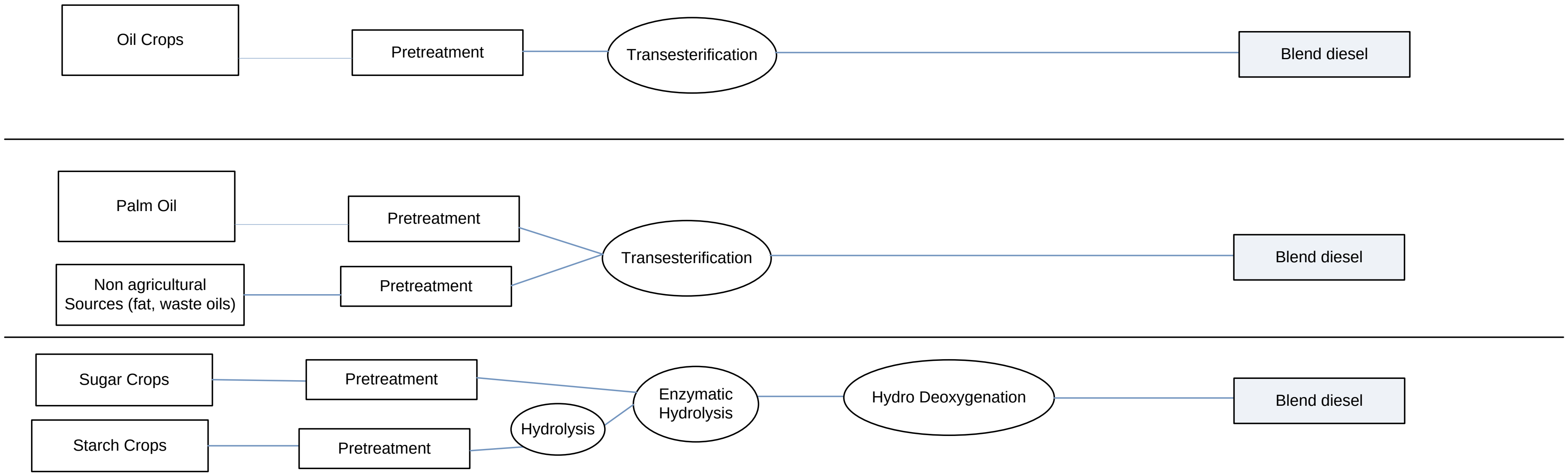


Black Liquor
Pretreatment
Black Liquor Gasification
Syn Gas
FT synthesis
Naphtha Upgrading
Biogasoline
Lignocellulosic Crops
Forestry
Wood Waste
Agricultural Residues
Municipal Solid Waste
Pretreatment
Hydro Thermal Upgrading
Hydro_Deoxygenation
Naphtha Upgrading
Biogasoline
Algae
Pretreatment
Transesterification And Hydrogenation of Algae
Naphtha Upgrading
Biogasoline

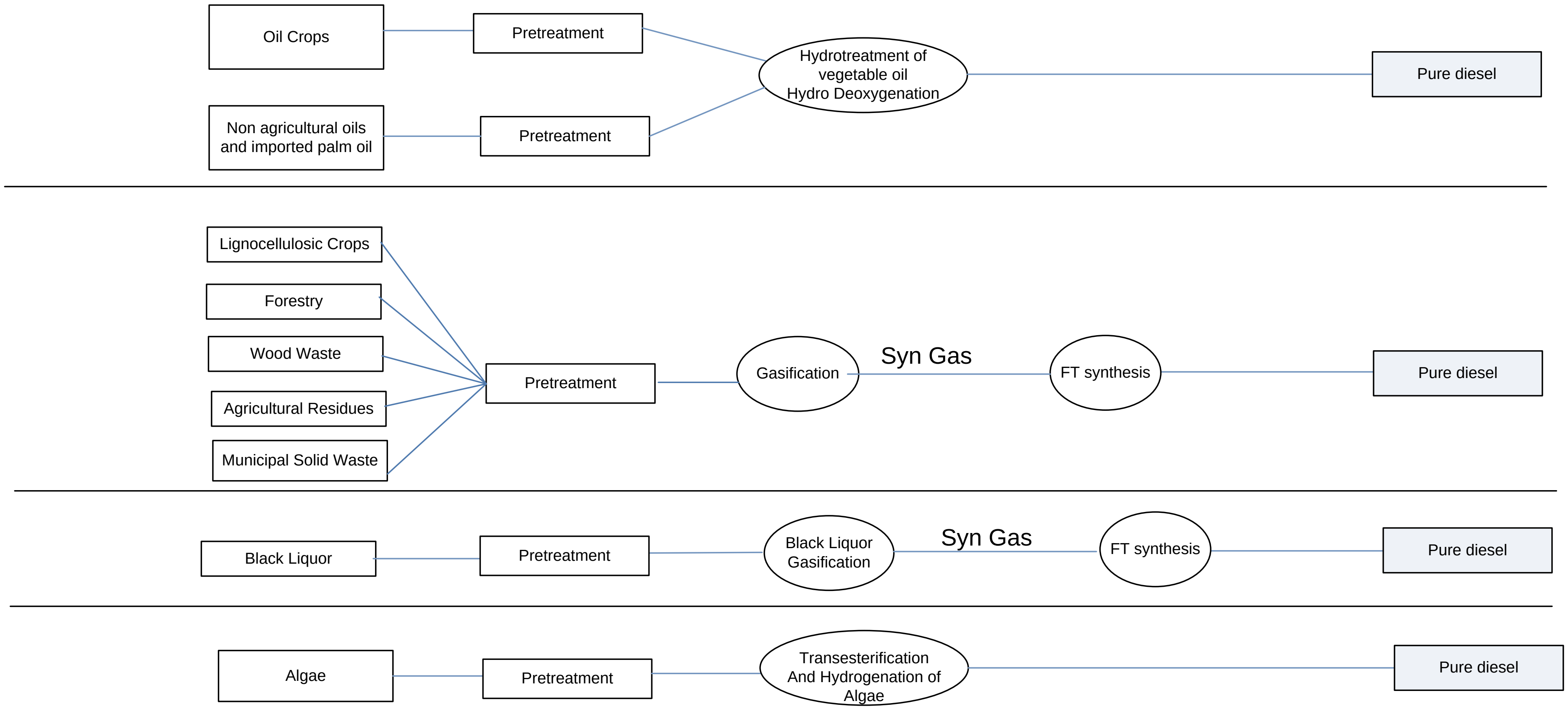

Lignocellulosic Crops
Forestry
Wood waste
Agricultural Residues
Pretreatment
Pyrolysis
Hydro Deoxygenation
Naphtha Upgrading
Biogasoline

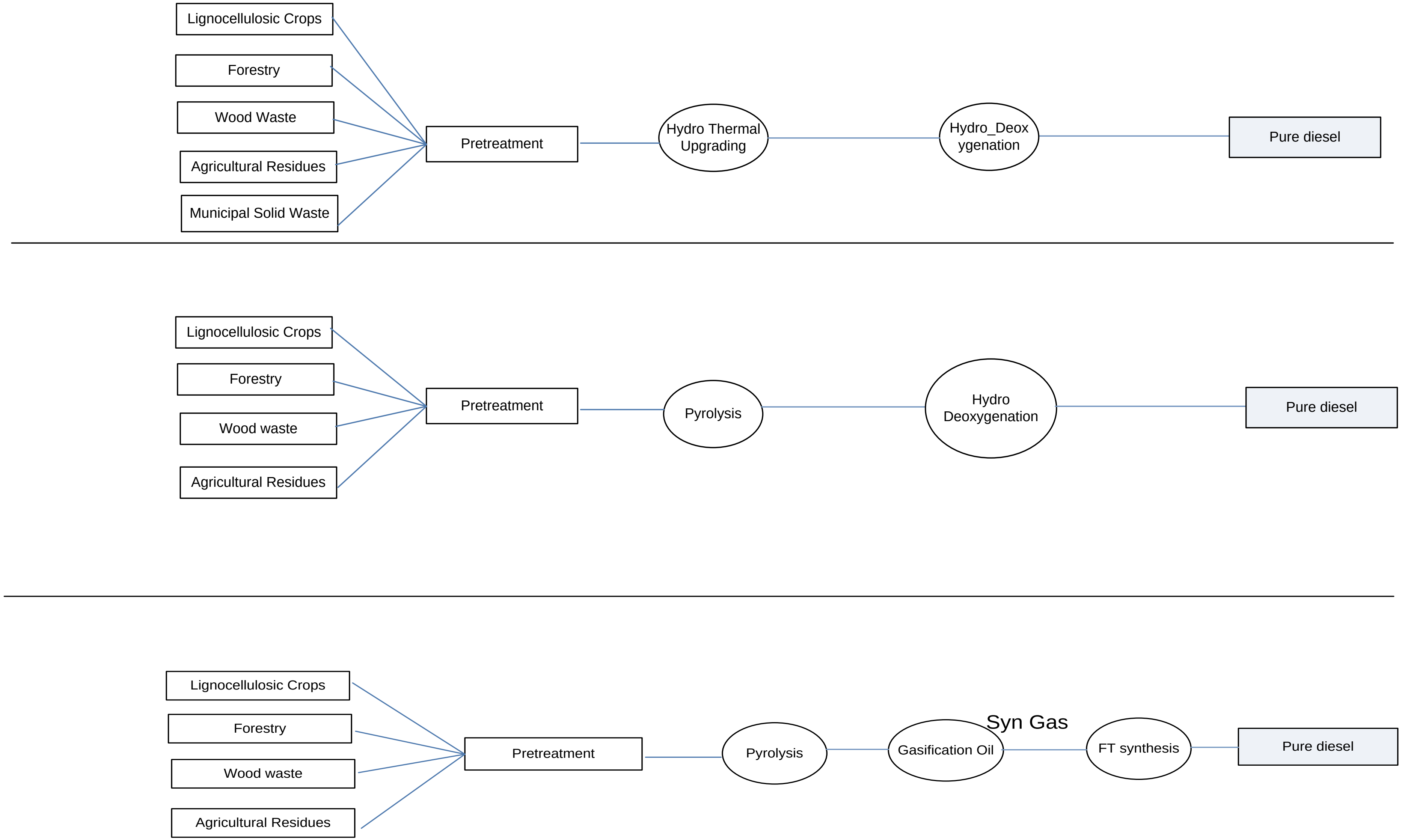

Lignocellulosic Crops
Forestry
Wood waste
Agricultural Residues
Pretreatment
Pyrolysis
Gasification Oil
Syn Gas
FT synthesis
Naphtha Upgrading
Biogasoline

7.1.3 Biodiesel production chains

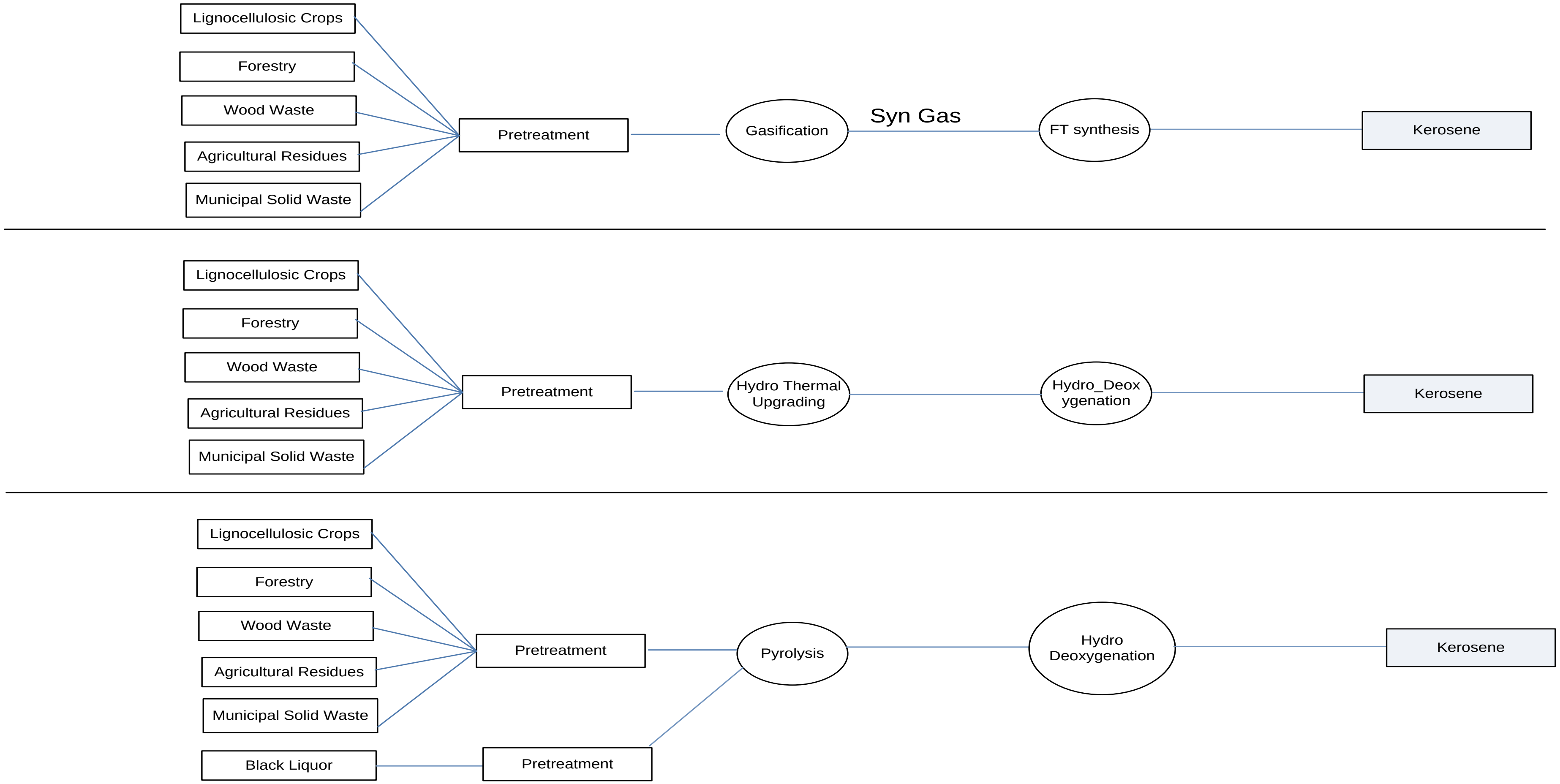


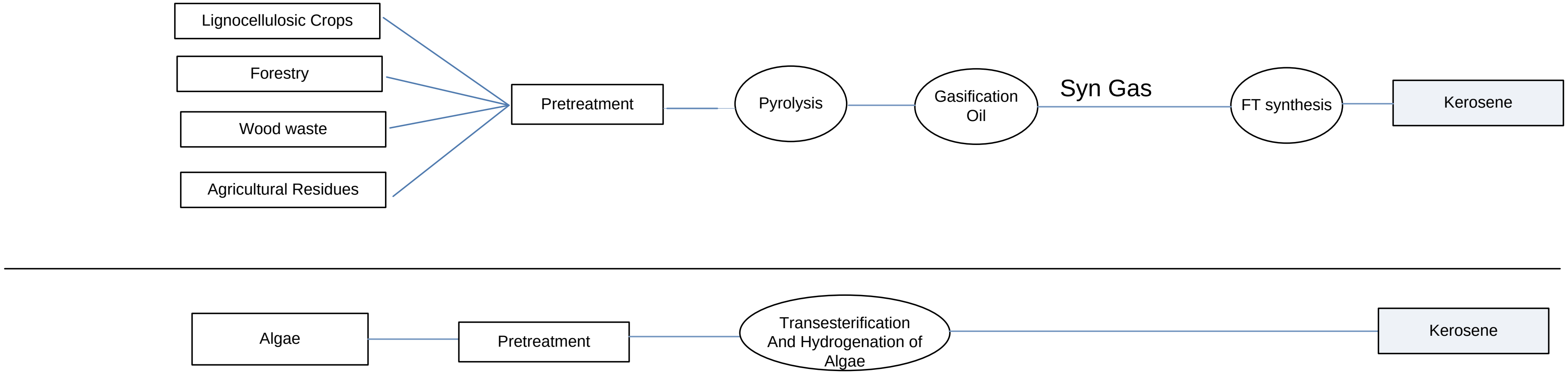
7.1.4 Advanced Biodiesel production chains



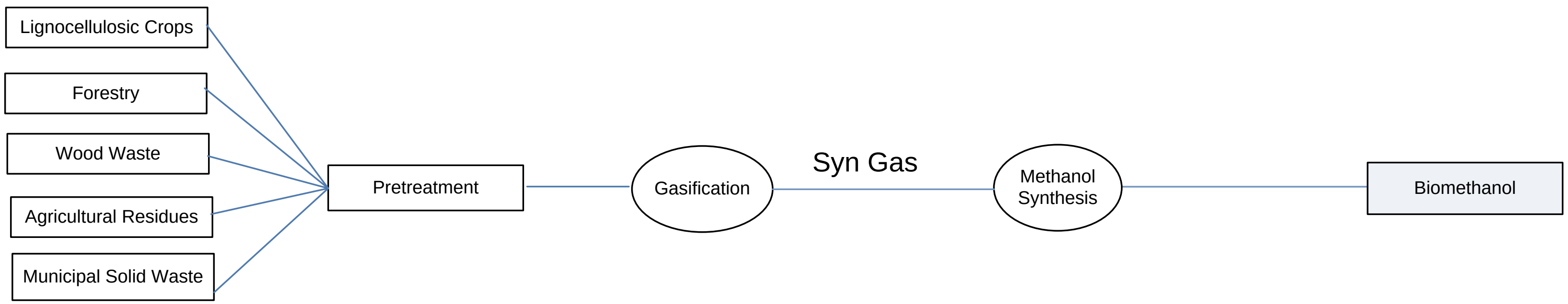

Lignocellulosic Crops
Forestry
Wood Waste
Agricultural Residues
Municipal Solid Waste
Pretreatment
Hydro Thermal Upgrading
Hydro_Deox ygenation
Pure diesel
Lignocellulosic Crops
Forestry
Wood waste
Agricultural Residues
Pretreatment
Pyrolysis
Hydro Deoxygenation
Pure diesel
Lignocellulosic Crops
Forestry
Wood waste
Agricultural Residues
Pretreatment
Pyrolysis
Gasification Oil
Syn Gas
FT synthesis
Pure diesel

7.1.5 Biokerosene production chains

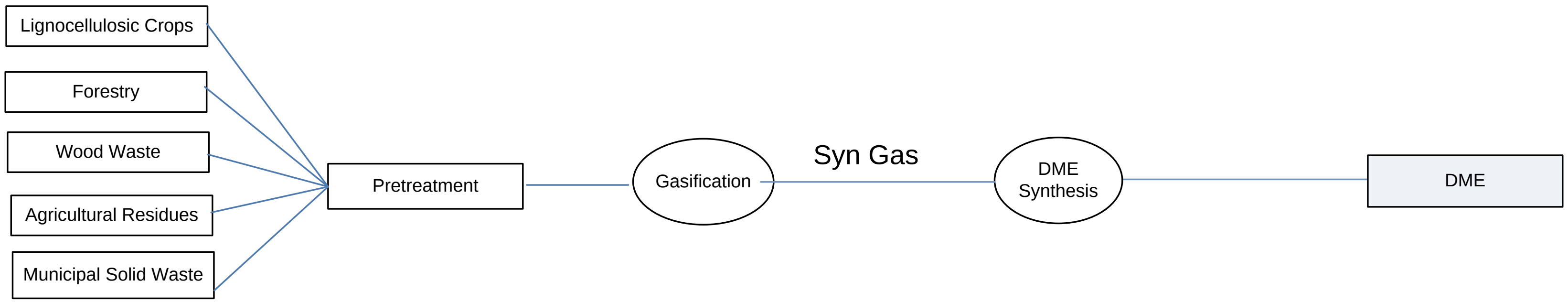



Lignocellulosic Crops
Forestry
Wood waste
Agricultural Residues
Pretreatment
Pyrolysis
Gasification Oil
Syn Gas
FT synthesis
Kerosene
Algae
Pretreatment
Transesterification And Hydrogenation of Algae
Kerosene

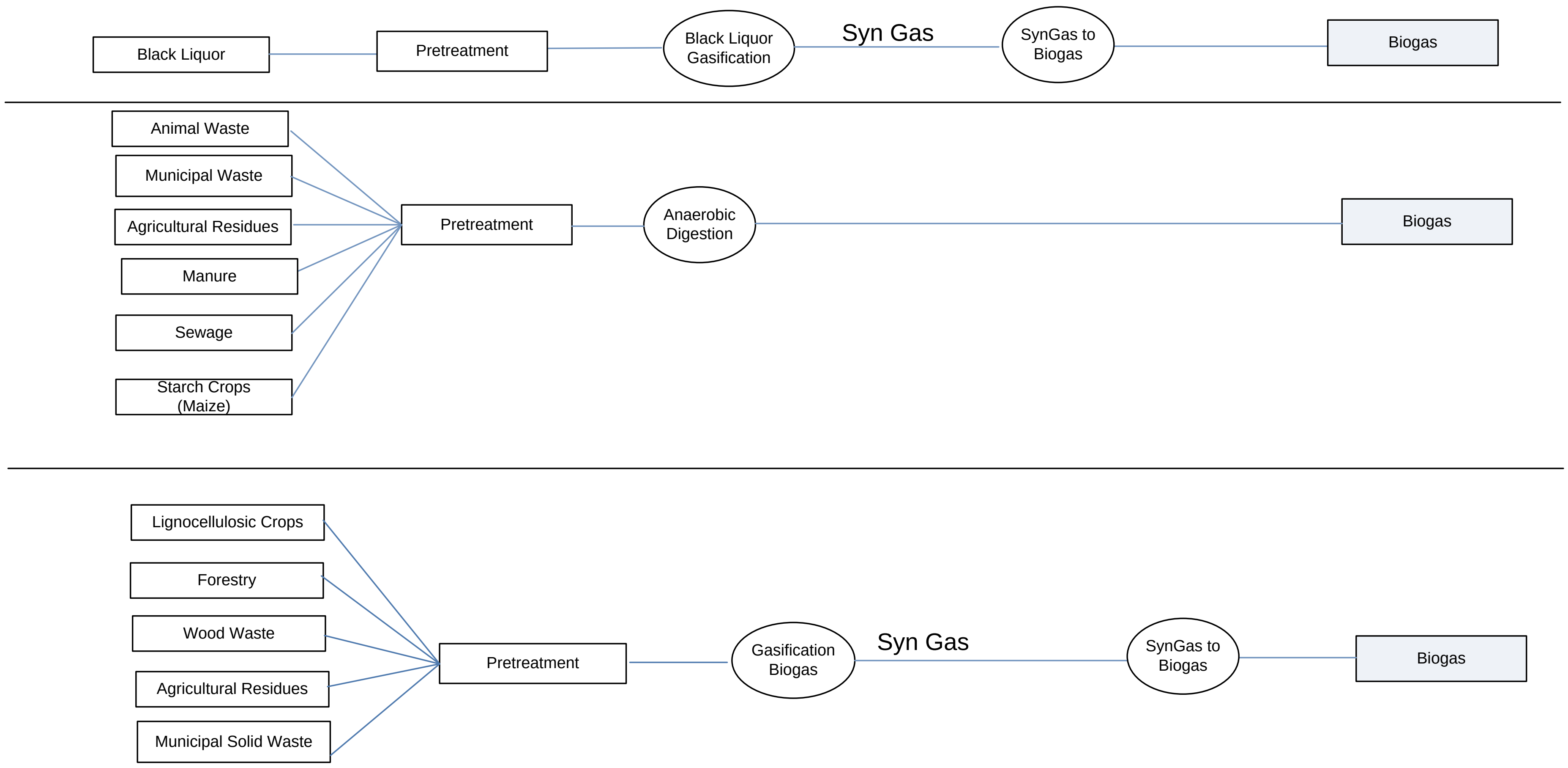
7.1.6 Biomethanol production chain

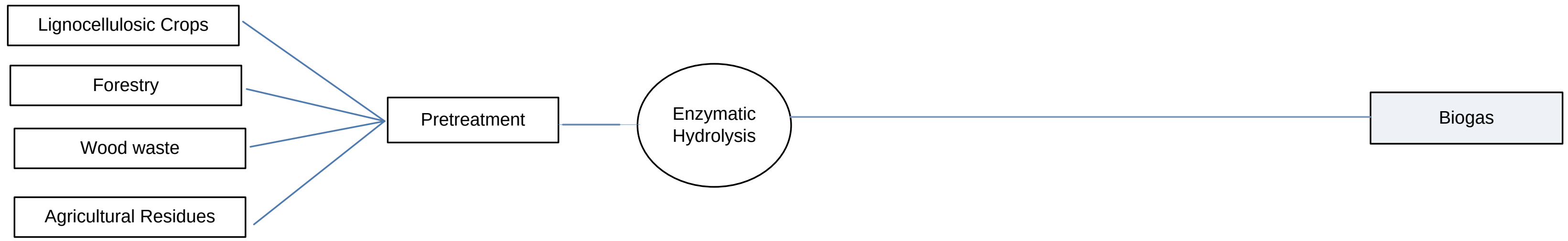


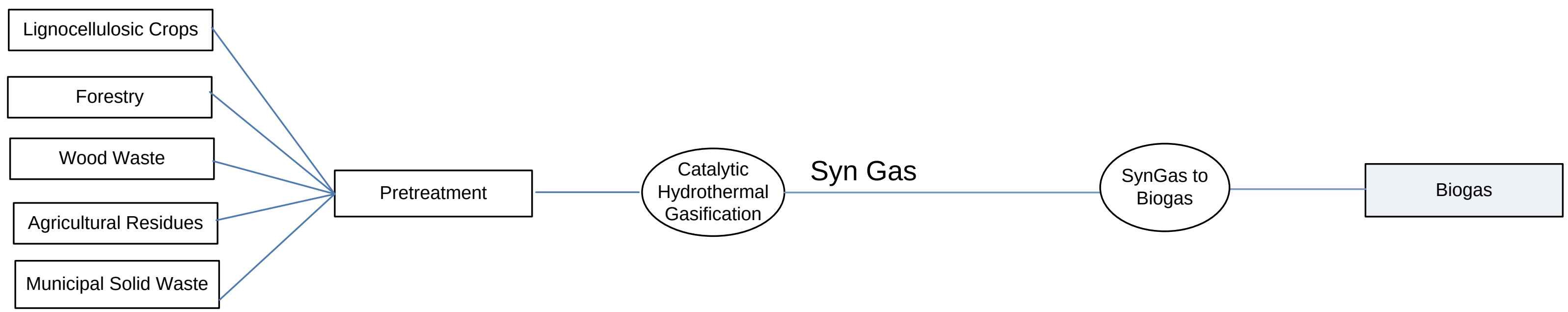
7.1.7 BioDME production chain

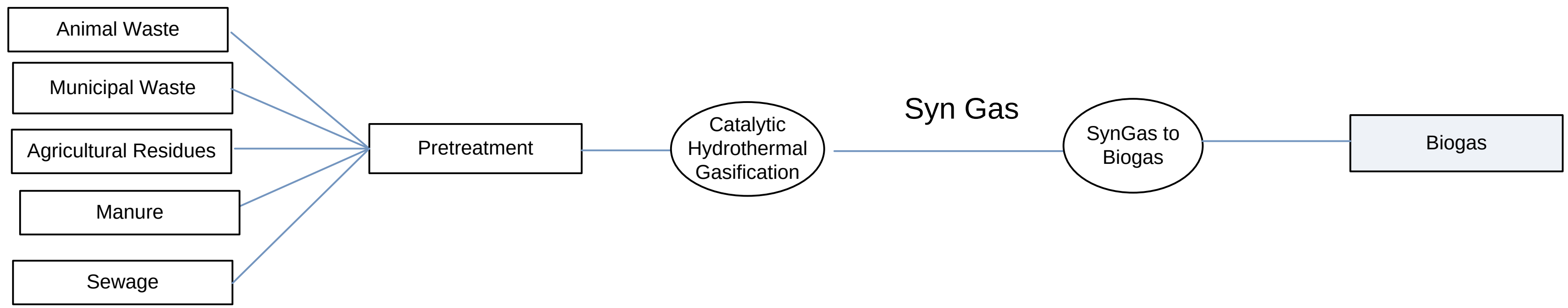


7.1.8 Biogas production chains

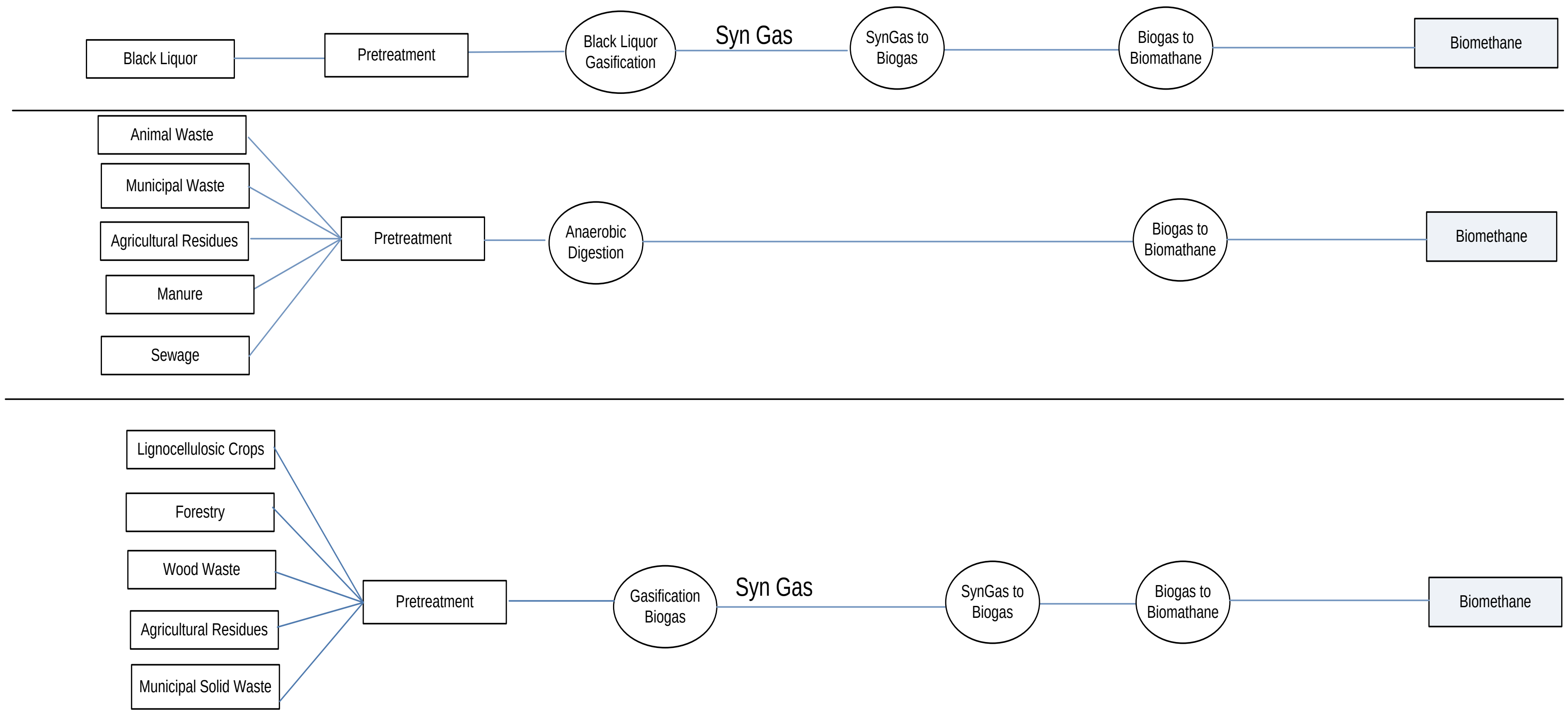


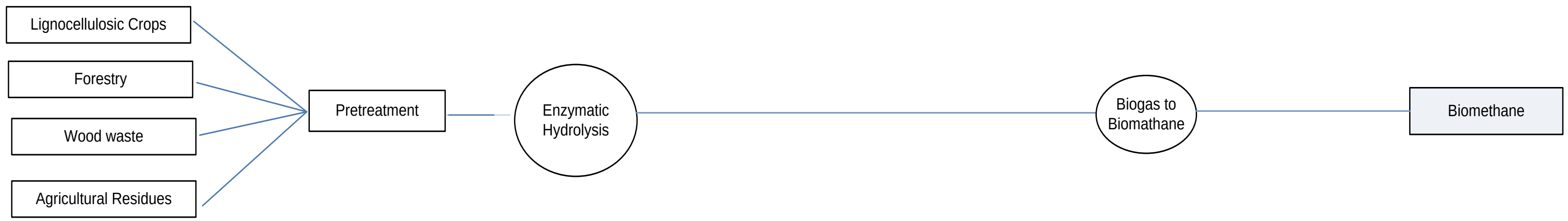

Lignocellulosic Crops
Forestry
Wood waste
Agricultural Residues
Pretreatment
Enzymatic Hydrolysis
Biogas

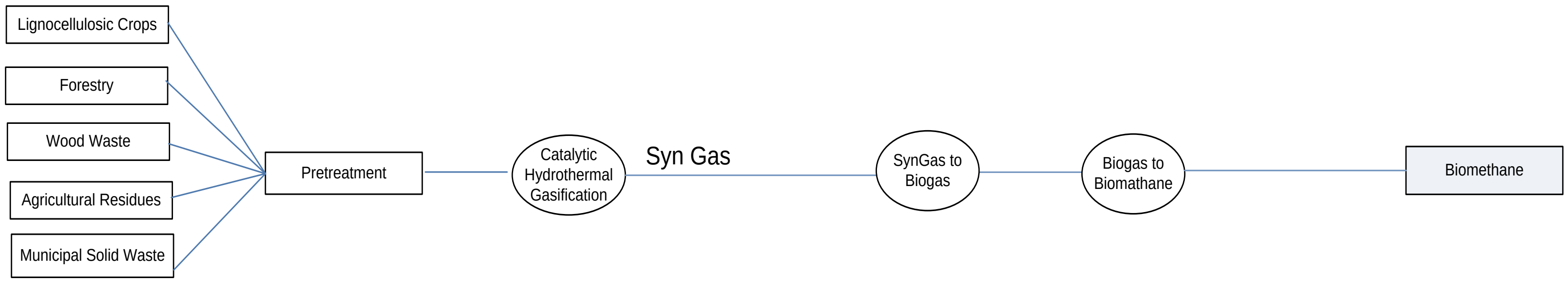

Lignocellulosic Crops
Forestry
Wood Waste
Agricultural Residues
Municipal Solid Waste
Pretreatment
Catalytic Hydrothermal Gasification
Syn Gas
SynGas to Biogas
Biogas

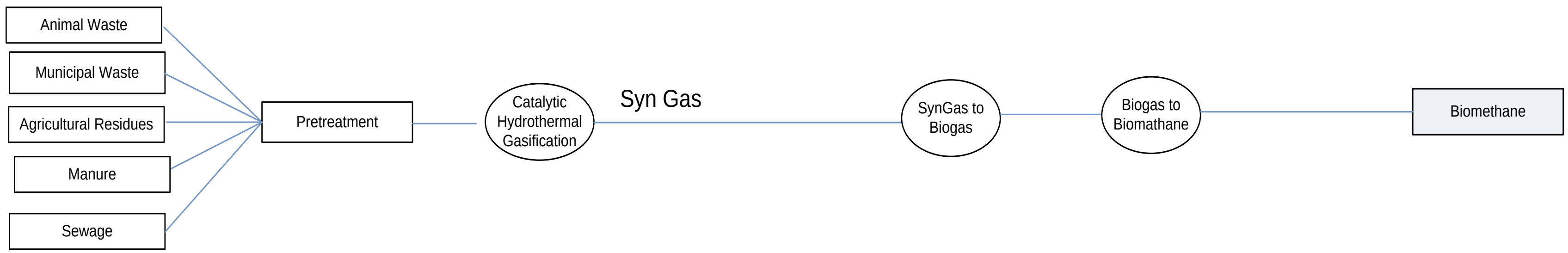

Animal Waste
Municipal Waste
Agricultural Residues
Manure
Sewage
Pretreatment
Catalytic Hydrothermal Gasification
Syn Gas
SynGas to Biogas
Biogas

7.1.9 Biomethane production chains

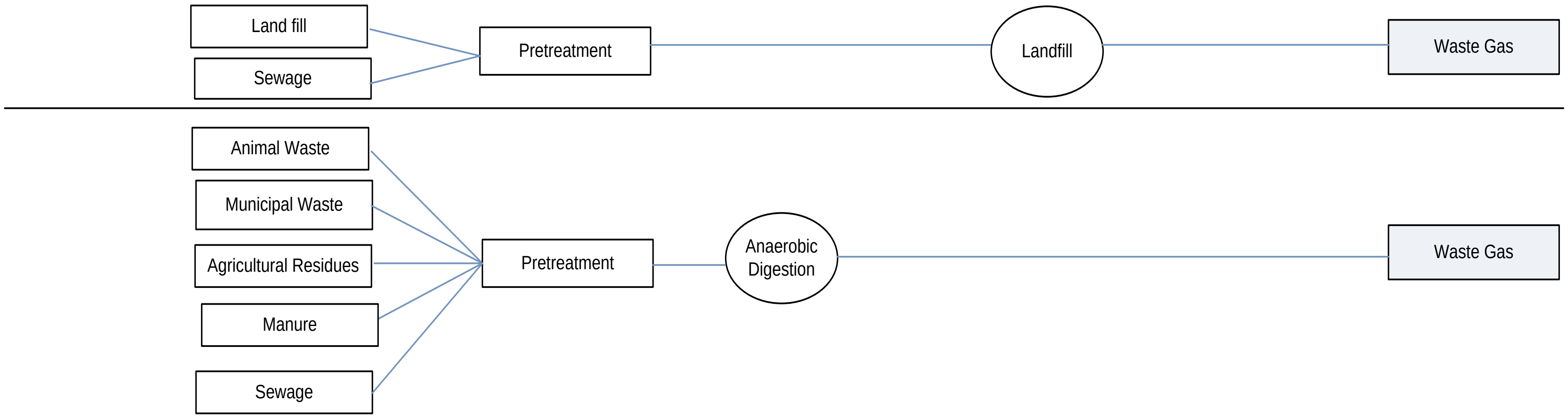



Lignocellulosic Crops
Forestry
Wood waste
Agricultural Residues
Pretreatment
Enzymatic Hydrolysis
Biogas to Biomathane
Biomethane

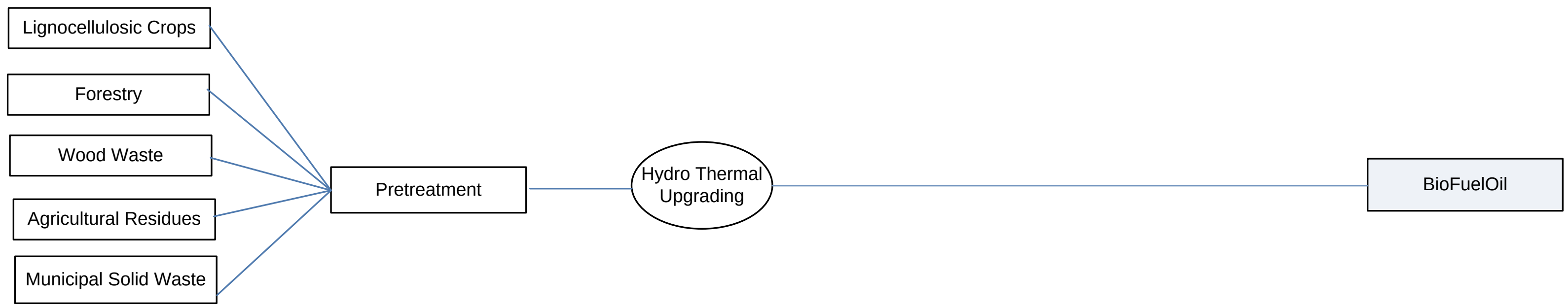

Lignocellulosic Crops
Forestry
Wood Waste
Agricultural Residues
Municipal Solid Waste
Pretreatment
Catalytic Hydrothermal Gasification
Syn Gas
SynGas to Biogas
Biogas to Biomathane
Biomethane

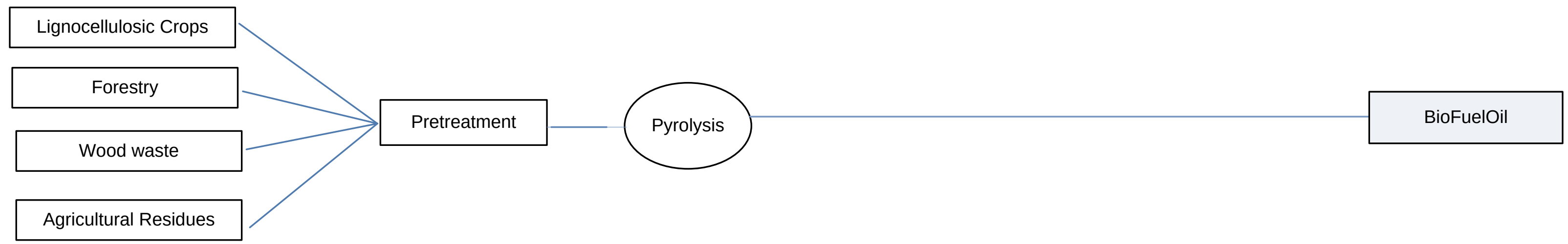

Animal Waste
Municipal Waste
Agricultural Residues
Manure
Sewage
Pretreatment
Catalytic Hydrothermal Gasification
Syn Gas
SynGas to Biogas
Biogas to Biomathane
Biomethane

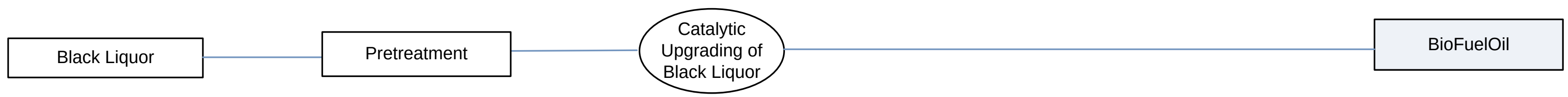
7.1.10 Waste gas production chains



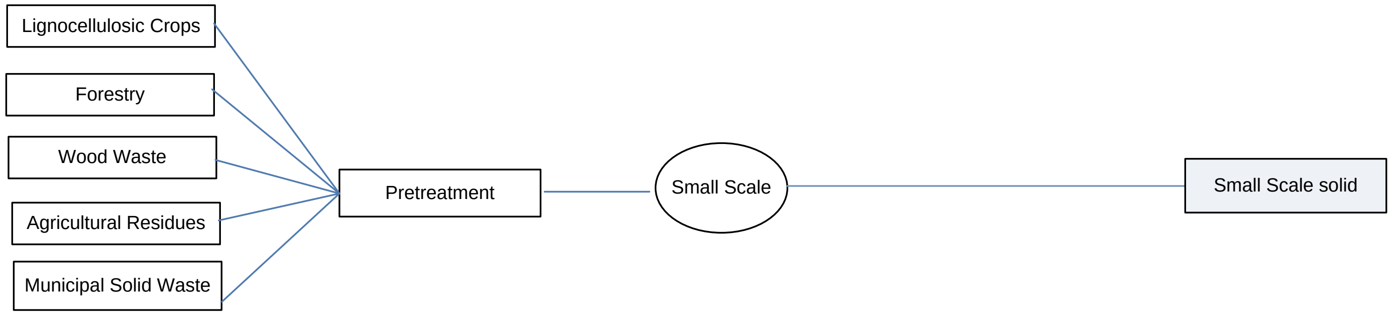
7.1.11 Bio Heavy Fuel Oil production chains

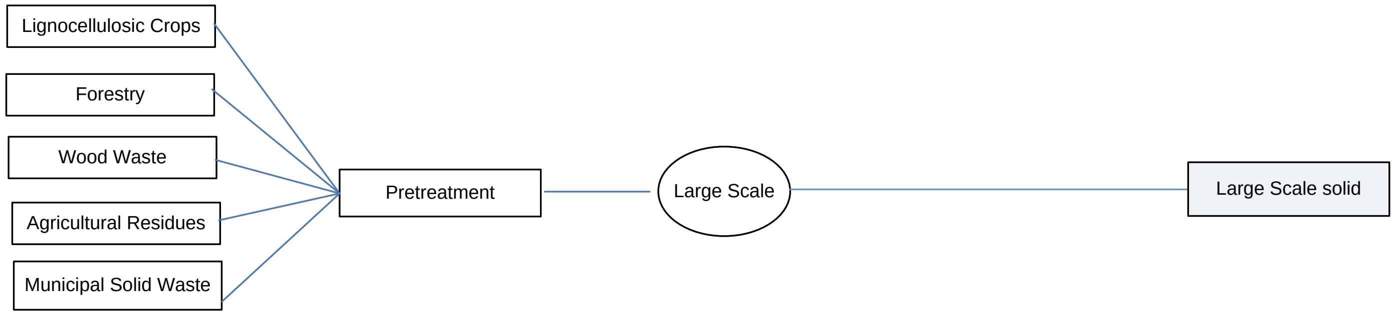




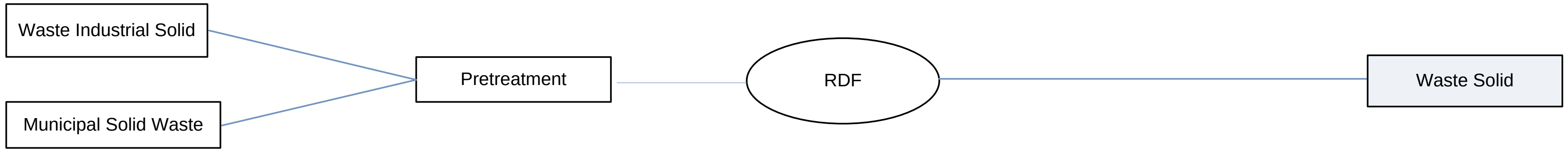


7.1.12 Solid Biomass production chains





7.1.13 Waste Solid production chain



7.1.14 Biohydrogen production chain