Biomass for the Circular Economy

Everything you wanted to know about biomass but were afraid to ask

Johan van Groenestijn, Paulien Harmsen, Harriëtte Bos

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Foreword

In the social debate ‘biomass’ equates to ‘wood pellets’. A debate that has a tendency to turn into an exchange of ‘oh yes it is, oh no isn't’ at that. This is doing a grave injustice to biomass. There is more to it than that, far more than wood pellets. But how much more? And what are the available streams? Where do they come from? Do we ourselves have enough (from Dutch soil)? And how can we use biomass for both Chemicals and Energy?

‘TKI-BBE’ stands for Top Consortium for Knowledge and Innovation in the Bio-based economy (part of the circular economy). ‘K’ and ‘I’ stand for Knowledge and Innovation, a world in which facts play an important role, hence the reason for this booklet.

We have compiled this booklet with the aim of providing an overview and, where possible, guidelines for policy and entrepreneurship. It offers an overview of the types of biomass and biomass availability on the scale of the Netherlands, Europe and the world, and the available technologies for converting biomass into a range of useful products.

But before you turn the page: what do you think is the largest CO_2-absorbing crop in the Netherlands?

Kees de Gooijer
Chief inspiration Officer TKI-BBE

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1 Introduction

The Netherlands and most other countries want to reduce the use of carbon-based fossil fuels, such as petroleum, coal and natural gas. The two most important reasons are the challenges of climate change and the finiteness of reserves of these raw materials. The use of fossil fuels and plastics made from fossil raw materials changes the climate because the carbon dioxide released after burning or after biodegradation accumulates in the atmosphere and intensifies the greenhouse effect. An atmosphere with an increased level of carbon dioxide traps heat better and increases the temperature of the atmosphere, just like a greenhouse gas. Since the dawn of the industrial revolution in 1750, the concentration of carbon dioxide has risen by 48%[1] and many climatologists assume that this is the primary cause of the rise in the earth's temperature. They believe that the global rise in temperature will lead to rising sea levels and to more extreme weather (storms, drought and flooding).

There also are concerns about the use of other raw materials extracted from the earth, such as phosphate, potassium and metals. The dispersion of the material into the environment and the finiteness of reserves similarly pose a problem. Metals are largely reused but potassium and phosphate, like fossil fuel, are generally used just once. The common denominator is the extraction of raw material from the earth, followed by the one-off use and subsequent deposit at a location where the material can no longer enter the cycle. If this is illustrative of a linear economy, then a circular economy is the solution. This is an economic and industrial system in which no finite reserves of raw materials are depleted and residual materials are completely reused in the system. A circular economy could potentially be maintained for centuries and therefore is more sustainable than a linear economy. While a completely circular economy is not possible, efforts aimed at minimising the use of raw materials with finite reserves and limiting discharges into the environment can be pursued.

The extraction of fossil raw materials can be curbed in various ways by, for instance, by using renewable raw materials (biomass), renewable energy (sun, wind and geothermal heat) and reusing materials used before. This will create closed cycles of carbon and other elements, and those cycles will moreover have a short circulation time. For example, wood harvested from a willow plantation can be used as fuel for a power station. Carbon dioxide is released during combustion and discharged into the atmosphere. However, in the willow plantation within four years the same quantity of atmospheric carbon dioxide is absorbed and stored in wood, waiting on the next harvest. This is a far shorter cycle than the current carbon cycle linked to the consumption of fossil fuels. It has taken tens of millions of years to convert the carbon dioxide stored inside plants, that sank to the bottom of swamps, and gradually turned into coal in the quantities present today. Vice versa, it will take nature tens of millions of years to replenish from carbon dioxide the coal and oil reserves we have consumed over the past 200 years, provided there are suitable swamps. Contrary to coal, the use of willow wood for the energy supply is climate-neutral.

Figure 1. Rapeseed has traditionally been an important oil crop in northwest Europe.

Cyclical processes operate only if they are continuously fed with energy, that should preferably be generated by the sun: biomass, photovoltaic electricity and wind energy are various forms of solar energy. Geothermal energy and tidal energy (the gravitational interaction between the earth and the moon) are also sustainable sources. Nuclear energy is a different story: it produces no net carbon dioxide emissions, but depending on the raw material used, depletes reserves and produces potentially hazardous residue streams. Another example of the reduction of carbon dioxide emissions, but not the depletion of reserves, is the artificial storage of carbon dioxide in soil. This can be regarded as a temporary remedy for combating climate change. It prevents carbon dioxide from being discharged into the atmosphere, but if this carbon dioxide is produced from fossil sources, depletion of these resources cannot be prevented.

Transitioning from a linear to a circular economy requires a social transition coupled with scientific/technological, socioeconomic and institutional innovations. Though this ambition is evident in the current policy, given the enormity of the challenge and the numerous vested interests at play, it is a highly complex process.

Biomass is indispensable for achieving a circular economy. It can be used as a raw material for the production of energy, transport fuels, chemicals, materials, food and animal feed. The bioeconomy is an economy in which plant material, such as crops and residue streams from the agriculture and food industries, are used for food and non-food applications. Wood and material derived from other forms of life (animals and micro-organisms) are also used in the bioeconomy. The bioeconomy already existed before 1750 and has never disappeared completely. Examples are leather, silk, cotton, linseed oil, jute, wool and glue and the use of wood as a source of energy, building material and raw material for paper production. However, the variety of products, and the quantity of energy we use today as a result of utilising petroleum, coal and natural gas has risen significantly. If we want to transition to a bioeconomy 2.0 based on the new guiding principle, that alone will require a considerable effort in terms of organising the required quantities of sustainable biomass. In addition, it will require a major effort to achieve economically feasible conversions for a wide array of products.

There are many technological possibilities. New bio-based products and the corresponding production processes are continuously being developed and launched on the market. This development and implementation are the result of the concerted efforts of businesses, public authorities and knowledge institutions. However, there also is a social and economic reality. Bio-based energy, chemicals and materials are often more expensive than the fossil alternative and considerable efforts (and indeed money) will need to be dedicated to developing cost-efficient production. Furthermore, it requires an effort on the part of consumers to use energy and products that are different. Consequently, there is a palpable tension between the scientific and technological reality and the socioeconomic reality. This booklet aims to shed light on the possibilities based on the scientific and technological reality. Our vision draws on the experiences and findings amassed from working on the bioeconomy for thirty years.

2 Biomass

2.1 What is biomass?

The substance living and dead organisms are composed of is biomass. The type of organism is not limited to plants; animals and lower forms of life (micro-organisms) are also composed of biomass.

For the purpose of utilising biomass in the bioeconomy, it is important to know what substances biomass consists of. The biomass available on earth largely consists of plant material, the components of which are shown in Table 1.

Table 1. The main components of plants and their function.

Component	**Function**
Carbohydrates • Cellulose • Hemicellulose • Pectin • Hydrocolloides	Part of cell walls (rigidity and compartimentisation)
• Starch • Sucrose	Reserve substances
Lignin, cork	Part of cell walls
Protein	Biocatalysts (enzymes), reserve substance
Fat, oil	Reserve substances
High-added value ingredients • Pigments • Vitamins • Terpenes • Alkaloids • Phenols • Aromatic and flavouring substances	Antioxidants, protective agents, cofactors of enzymes, good or bad flavour
Minerals	Osmotic pressure on cells, rigidity, enzyme cofactors
Water	Reaction environment, transport mechanism and rigidity

The ratio between the components listed in Table 1 differs for each plant category. Tree wood and older grass stalks mainly consist of lignocellulose, a rigid complex consisting of cellulose, hemicellulose and lignin. Green parts, such as foliage and young grass, have a relatively high protein content and hardly any lignin. Underground parts, such as tubers, bulbs and roots, contain a lot of starch and sugar, the reserves for the following growing season. Seeds contain a lot of reserve substances, such as starch (grain, rice) and oil (nuts), because these substances need to supply the energy and building materials to help a seedling grow. Seaweeds contain special carbohydrates in the cell wall and as a reserve substance (alginate, carrageenan, agar, mannitol), whereas microalgae are far richer in oil. Seaweeds and plants that grow in a salty environment are rich in minerals. Grasses and certain types of algae often contain silicic acid, a mineral that provides rigidity. Plants can prevent damage by releasing toxic substances or substances with an unpleasant flavour or smell. Fruit, on the other hand, should be eaten and contain ingredients with a more pleasant sensation.

Figure 2. Brown seaweed (Ascophyllum nodosum) also known as knotted wrack (photograph: Paulien Harmsen).

The organic substances stated in Table 1 (everything except water and minerals) all contain energy. When they are burned and form carbon dioxide and water, the energy is released as heat. To illustrate this: the energy released from burning one kilogram of starch or a kilogram of cellulose can bring 47 litres of water to the boil. Moreover, one kilogram of starch can supply one person with two days of energy.

2.2 Products made from biomass

Although the classification of biomass types could in principle follow the taxonomic route (plant and animal kingdom classification), in this booklet we have used a classification which focuses on the use of biomass within the human production system. We have followed the value creation route: from the fresh plant to residual products after consumer use. Such a classification for biomass that is or will be relevant in the bioeconomy is presented in Table 2. Apart from the primary product, biomass produces various byproducts which are also suitable for use in the bioeconomy. Table 3 contains a breakdown of primary and byproducts for illustrative purposes.

Table 2. Classification of biomass types specifying current products and byproducts.

Biomass type	**Primary products**	**Important secondary products (primary and secondary residue streams)**
Forestry trees	Wood, cork, resin, latex	Foliage, sawdust, bark
Landscape management plants, trees and grass	Wood, aquatic plants, roadside plants	Pruning waste
Crops		
• Grain	Grain kernels, starch	Straw, bran, chaff
• Oil crops	Beans, nuts, oil	High-protein leftover pulp, pruning waste (wood)
• Sugar beet	Sugar	Sugar beet pulp, molasses, sugar beet crowns, sugar beet leaves
• Potatoes	Potatoes, starch	Potato pulp
• Oil palm	Palm oil	Variety of large quantities of residue streams
• Fruit and vegetables	Fruit and vegetables	Stalks, foliage, fruit and vegetable waste
• Meadow grass	Grass, hay	
Microalgae, seaweeds	Oil, protein, hydrocolloids	Cell wall residues
Residue streams after consumer and animal use (tertiary residue streams)	Organic waste, old paper, manure, waste fat, waste cooking oil, swill, discarded textiles and sewage sludge	

Table 3. Quantitative breakdown of products and byproducts from major biomass sources.

Biomass type	**Primary product with mass share (DM)**	**Byproduct with mass share (DM)**
Sugar beet[2]	Beet 77%	Foliage 23%
Winter wheat[2]	Grain kernels 55%	Straw 45%
Ware potatoes[2]	Potatoes 76%	Foliage 24%
Soybeans[3]	Oil 20%	Leftover pulp 71% Hulls 6% Loss 3%
Tree[4,5]	Round timber 70%	Bark, foliage, twigs 30%

The use of trees aptly illustrates the wide range of applications. Around 75% of a tree consists of the trunk, branches and bark, the root accounts for 20% and the leaves/needles account for 5% (based on dry matter or DM).[4] Round timber is produced from the trunk and branches, the usable fraction (without bark). The bark usually accounts for between 10% and 20% of the wet weight of the trunk and branches.[6] In Canada, after felling a tree, 70% is used as round timber. Round timber is a felled tree trunk with or without bark, with the side branches and crown wood removed. Bark

Figure 3. Various products are made from round timber.

chippings are used for gardens and landscape management, whereas the side branches and crown wood are used as fuel for power stations. If the branches are from trees standing in poor soil, these branches are often left in the forest to nourish the soil with minerals. Round timber is used for the following purposes:[5]

- 29% sawn timber
- 42% paper and pulp
- 14% wood sheets
- 8% fuel for power stations (no pellets)
- 3% wood pellet fuel
- 4% other products

2.3 Production of biomass

Plants take up space, and in essence land and water areas, because they need sunlight for their energy supply. Although this is a general principle, it turns out that various plant species use the energy supplied with a varying yield for the production of biomass. Production ranges from a few to tens of tons of biomass dry matter per hectare per year (Table 4).

Table 4. Main crop and forest yields per hectare per year in the Netherlands.

Biomass type	**Yield (ton DM / ha / year)**
Sugar beet[2]	15.7
Winter wheat[2]	7.4
Silage maize[2]	14.4
Meadow grass[2]	11.5
Ware potatoes (clay soil)[2]	9.6
Actual harvest forest production [7,8,]	1.8

2.4 New biomass sources

Seaweed

Seaweed is a fast-growing crop that grows in the sea. There are three different primary groups based on the presence of pigments (brown, red and green), each of which also contain many different species. Where each species grows depends on the location and parameters such as temperature, light, salinity and nutrients. Seaweed is capable of bioremediation, it can purify water by absorbing nutrients and heavy metals. The combination of seaweed cultivation and aquaculture (Integrated Multi-Trophic Aquaculture, IMTA) is promising while seaweed cultivation for phosphate sequestration could also be an interesting prospect. Water quality (including pollutants) therefore largely determines the options for applying the seaweed.

Global availability currently amounts to around 30 metric tons of wet biomass. The current industry is based mainly on cultivated seaweed from Asia (primarily China). Wild seaweed harvested on a small scale or washed ashore is also processed. Many new activities are currently being undertaken with a view to setting up seaweed farms in Europe (Norway, Ireland, Scotland, Denmark, the Netherlands and Belgium) to boost seaweed production. There is a lack of seaweed and most of it is obtained from Asia. The research questions relate to yield/ha and how to harvest and process it directly into a stable intermediate product.

In terms of composition, seaweed is rich in carbohydrates, minerals and salts but contains fewer proteins. Its composition varies widely not only per species but also per season. Seaweed is an interesting biomass in view of its composition. Seaweed contains substances with special characteristics (including hydrocolloids) which are not found in land plants. The current uses of seaweed range from food, raw material for the hydrocolloid industry (alginate, carrageenan and agar) for applications in food, personal care, technical applications, supplements for food and animal feed to fertiliser or as biostimulant for plants.

Microalgae

The cultivation of microalgae could significantly contribute to enhancing the sustainability of society. Microalgae can be used not only for the environmentally friendly production of countless raw materials but also as waste processors. They thrive on waste streams, such as carbon dioxide from flue gases, residual water from agro-industrial businesses and even diluted manure. They convert waste into usable raw materials. Microalgae recycle the nutrients that would otherwise be washed away and close the nutrient cycle with cleaner water as a bonus.

Algal cells contain so many beneficial substances that they are increasingly being cultivated for that specific purpose. Many species of algae can contain a substantial percentage of high added-value oils, partly consisting of omega-3 and omega-6 fatty acids, which can be used as a raw material for dietary supplements. The well-known omega-3 fatty acids in fish originate from microalgae. At present, dozens of agricultural crops are grown containing oil or starchlike substances from which fuel and other products can be produced. What makes algae unique is that they contain a wide variety of other beneficial components in addition to raw material for energy. More than 15,000 new chemical compounds have been discovered in algae in recent years. Besides fatty acids, algae cells can also contain carotenes (pigments ranging from yellow to red) and other pigments, antioxidants, proteins and starch. These components can be used as raw material for numerous products by the chemical and food industries. As a result, the list of products made from algae is growing steadily.

In addition to high-added value algae products for niche markets, such as algae powder for the dietary supplements industry and algae extracts to control golf course mould, interest is growing not only in bulk products, such as raw materials for bioplastics, biofuels, but also in algae protein for food applications.[9]

Figure 4. Algae cultivation is the focus of substantial research, including at Wageningen University & Research.

3 Current use of biomass

3.1 Introduction

This chapter describes how much biomass is used in the Netherlands, its applications and how that quantity compares to the use of fossil raw materials.

3.2 Use of energy carriers in the Netherlands

Fossil raw materials are mainly used for chemicals, energy and transport fuels whereas biomass is mainly used in animal feed and in human foods. Energy predominates when it comes to the use of raw materials. The quantity of fossil energy carriers in the Netherlands amounted to 2,864 PJ in 2017 (Table 5). The share of renewable energy among all energy carriers used in the Netherlands is rising each year.[10] In 2017, renewable energy accounted for 5.8% (182 PJ), of which 68% was from biomass (124 PJ).[10] The other 32% (58 PJ) was supplied by other sources including wind and solar energy. Compared to other European countries, 5.8% is relatively low and the prospects of achieving the Dutch target of 14% by 2020 seem remote. The percentage of renewable energy is still low for the following reasons:

- The limited availability of affordable renewable energy sources
- The time and effort involved in the transition
- The interests of oil and gas companies in the Netherlands[11,12]
- Dutch regulations and procedures

Fossil raw materials in the Netherlands

The Netherlands is essentially a transit/refining country for fossil raw materials. The transit of fossil raw materials is even around three times higher than domestic use, a third of which is reserved for the production of electricity. The remaining two-thirds are used for the production of transport fuels, chemicals and as domestic fuel. The main fuels used for electricity production in the Netherlands in 2016[10] were:

- 14.3 billion m^3 of natural gas (454 PJ)
- 12,084 kton of coal (305 PJ)

Table 5. Consumption of energy carriers in the Netherlands, for domestic use, not for commercial purposes, in 2017.[10,13]

Type of energy carrier	PJ	%	kton
Natural gas	1,294	41%	34,000
Petroleum raw materials and products	1,187	38%	27,400
Coal and other carbon-based products	383	12%	15,100
Renewable energy (including biomass, wind, sun)	182	6%	
Other (including nuclear energy)	91	3%	
TOTAL	3,137	100%	76,500

Petajoules and kilotons

Large quantities of energy are commonly expressed in petajoule (PJ or 10^{15} J). To given you an idea, one PJ is the quantity of electrical energy produced by the Hemweg-8 Power Station in Amsterdam within three weeks.

Fossil raw materials and biomass contain energy. The quantities are specified in the table below. The net heat of combustion (calorific value) is the energy released during combustion to form carbon dioxide and steam. The gross heat of combustion is the net heat of combustion plus the extra heat produced by the condensation of steam.

Fuel	Net calorific value (MJ/kg)	Gross calorific value (MJ/kg)
Natural gas[14]	38.1	42.1
Crude oil[15]	43.4	45.7
Coal[15]	25.3	26.7
Wood pellets (spruce)[16]	17.2	18.7

More energy can be generated from natural gas per kilo of carbon than from coal, which is why a gas-fired power station emits less carbon dioxide than a coal-fired power station.

3.3 Use, imports and exports of biomass for energy applications in the Netherlands

In 2017, waste incineration plants and boilers accounted for a large share of the biomass-based energy supply to businesses. The various applications of these forms of energy are presented in Table 6. It shows primary consumption: the initial measurable form of energy generated from biomass, i.e. the petajoules in biodiesel, biogasoline, biogas and firewood and the energy in the biogenic (organic) portion of waste and in the biomass for boilers and power stations. It should be noted that the amount of petajoules contained in the electricity produced and in the usable heat (not shown) is lower than that of the original biomass because boilers and power stations have a certain efficiency. Efficiency also depends on the fuel and the technology used. For example, the efficiency from the production of electricity and the usable heat from biogas in a combined heat and power plant (CHP) plant is higher than that of a coal-fired power station.

Table 6. Use (primary consumption) of biomass as an energy source in various applications in the Netherlands in 2017.[10]

Application	**PJ**	**Breakdown**	**PJ**
Waste incineration plants	41.9		
Biomass boilers for businesses	26.8	For electricity For heat only	16.7 10.1
Households	19.5	Open fireplaces Inbuilt fireplaces Stand-alone Charcoal	2.5 2.8 13.9 0.3
Liquid transport fuels	13.7	Biogasoline* Biodiesel	5.4 8.3
Biogas	13.4	From refuse tips Sewage treatment plants Co-fermentation of manure Other	0.6 2.4 4.8 5.6
Co-firing and auxiliary firing in power stations	4,9**		

** Bioethanol, free or included in ETBE (an antiknock agent).*

*** In 2017, very little biomass was used as co-firing in power stations due to the limited Renewable Energy Production Incentive Scheme (SDE). This also accounts for the relatively low level of wood pellet imports (see Table 7).*

The types of biomass products and organic residue streams used for energy supply are shown in table 7. The biomass used for energy generation in the Netherlands is sourced partly domestically and partly from abroad. The Netherlands even is an export country for biomass-based energy applications.

Table 7. Imports, extraction, exports and consumption of energy carriers from biomass and organic residue streams in the Netherlands in 2017.[10]

	NL in (PJ)			**NL from (PJ)**		
Energy carrier	Imports	Extraction	Total	Exports	Consumption	Total
Biogas	0	14	14	0	13	13
Solid and liquid biomass (products) (e.g. wood pellets and bioethanol)	13	128	141	68	68	136
Biogenic fraction of household waste (what is incinerated in the WIP)	11	33	44	1	42	43
Total	24	175	**199**	69	123	**192**

The balance does not close completely due to changes in stocks and statistical effects.

3.4 Dutch biomass imports and exports

The Netherlands is a small country with both a high population density and a high livestock density. Moreover, it borders the sea and is situated at the estuary of major rivers, making the Netherlands a major importer and exporter of goods. This also applies to biomass. An overview of biomass imports and exports is shown in Table 8. It shows that 71% of the biomass products are imported from Europe and that 83% of the biomass products are exported to a European destination. Most of the exports are products and semi-finished products rather than the original biomass itself.

Based on the data, biomass consumption in the Netherlands is estimated to be 43,000 kton DM per year (= 50,000-32,000+25,000), which is far higher than the quantity produced domestically in the Netherlands (25,000 kton DM). Imports exceed domestic production. The high import volume is used to supplement domestic needs and for export purposes. The strong link with international trade is characteristic of the Dutch agricultural and bioeconomy.

Table 8. Dutch imports and exports of biomass and biomass products from/to Europe and the world in 2016 (CBS).[10]

Biomass	**World (kton wet)**	**Europe (kton wet)**	**The Netherlands (kton wet)**
Imported by the Netherlands			
Raw biomass	31,585	20,752	
Semi-finished product	15,989	13,756	
Finished product	31,170	21,066	
Total	**78,744**	**55,574 (71%)**	
*Estimated total dry matter (kton)**	*50,000*		
Exported by the Netherlands			
Raw biomass	22,599	20,730	
Semi-finished product	16,173	11,517	
Finished product	33,057	27,274	
Total	**71,829**	**59,521 (83%)**	
*Estimated total dry matter (kton)**	*32,000*		
Production in the Netherlands			
Total biomass and biomass products**			**41,141**
*Estimated total dry matter (kton)**			*25,000*

** The dry matter content of animal feed crops is 85% according to CBS figures.*

*** Primary biomass only, no meat, limited number of residues.*

A further breakdown of Table 8 is shown in Table 9 and in Figure 5. In 2015, the EU accounted for 60% of the value (in euros) of imported agricultural goods.[17] Grain specifically accounted for around 50% with oilseeds accounting for around 30%. The European share of soy imports is far smaller. According to the CBS Background Report Soy Barameter,[19] this amounted to 4% in 2011. Soy is mostly imported from North and South America. In 2017, all palm oil was non-European. Almost all the palm oil imported in the Netherlands was sourced from six countries: Indonesia (31%), Malaysia (20%), Papua New Guinea (14%), Colombia (10%), Honduras and Guatemala (both 9%).[20] By contrast, some agricultural goods are sourced primarily from Europe. One such example is fruit which, in terms of value, is the largest item in the imported agricultural goods category. In 2015, Europe accounted for over 80% of (the value of) these imported goods .[17]

Similarly, wood and derivative wood products are primarily imported from Europe: 76% (tonnage) of the wood and wood products was sourced from Europe in 2014.[21] These products were mainly paper, pulp, sawn softwood and chipboard. North America supplies 8% of Dutch wood imports (2014).[22] Wood pellets accounted for half of that percentage. In 2013 and 2014, an additional 570 kton and 167 kton of wood pellets (DM) were imported.[10] Due to the abolition of the subsidy for co-firing and auxiliary firing, virtually no wood pellets were imported in 2015-2017. The Netherlands primarily imports non-European biomass and biomass products that are unavailable or cannot be produced in Europe.

Table 9. Dutch imports and exports of the main categories of biomass and biomass products, see also Figure 5.[3,17]

Biomass products	**Imports (kton DM/year)**	**%**	**Exports (kton DM/year)**	**%**	**Δ (kton)**
Grains	12,174	32.5	2,222	10.9	9,952
Oil crops plus leftover pulp	12,914	34.4	7,429	36.5	5,485
Food crops (fruit, vegetables, etc.)	1,877	5.0	2,541	12.5	-664
Animal feed crops and grass	33	0.1	4	0.0	29
Palm oil	2,880	7.7	1,400 (approx.)	6.9	1,480
Wood and derivative wood products	5,090	13.6	3,353	16.5	1,737
Fish and other aquatic organisms	196	0.5	268	1.3	-72
Live animals, meat and meat products	2,323	6.2	3,129	15.4	-806
TOTAL	37,487	100	20,346	100	17,141

3.5 Uses of biomass in the Netherlands

Biomass is primarily used as animal feed in the Netherlands. It is also used for the energy supply, in human food, materials (paper, plastics, wood products) and chemicals. Organic residue streams, such as waste paper, organic waste and manure, are now used in paper production and as soil improvement agents (compost). Figure 6 contains a matrix showing the main streams of domestic biomass and organic residues and their application in the Netherlands. Imports and exports have been added to the matrix in Figure 7.

Around 25,000 kton (DM) of biomass is currently harvested in the Netherlands annually. The largest stream is grass (11,530 kton), which is used almost entirely as animal feed. The second stream consists of grains and silage maize, which jointly account for 5,510

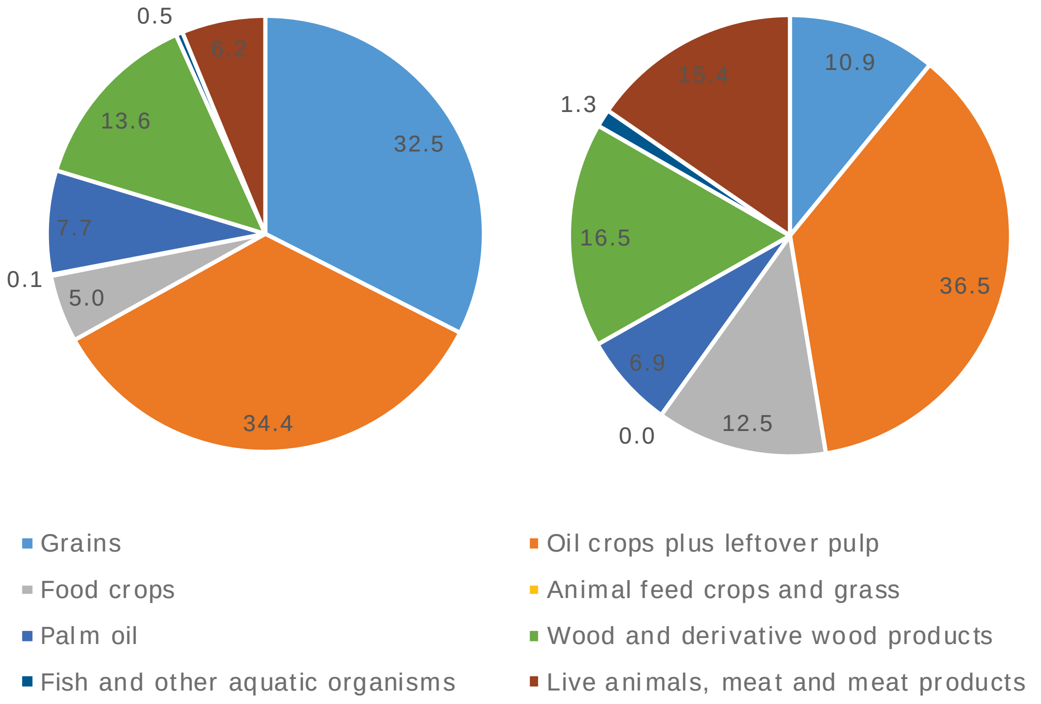
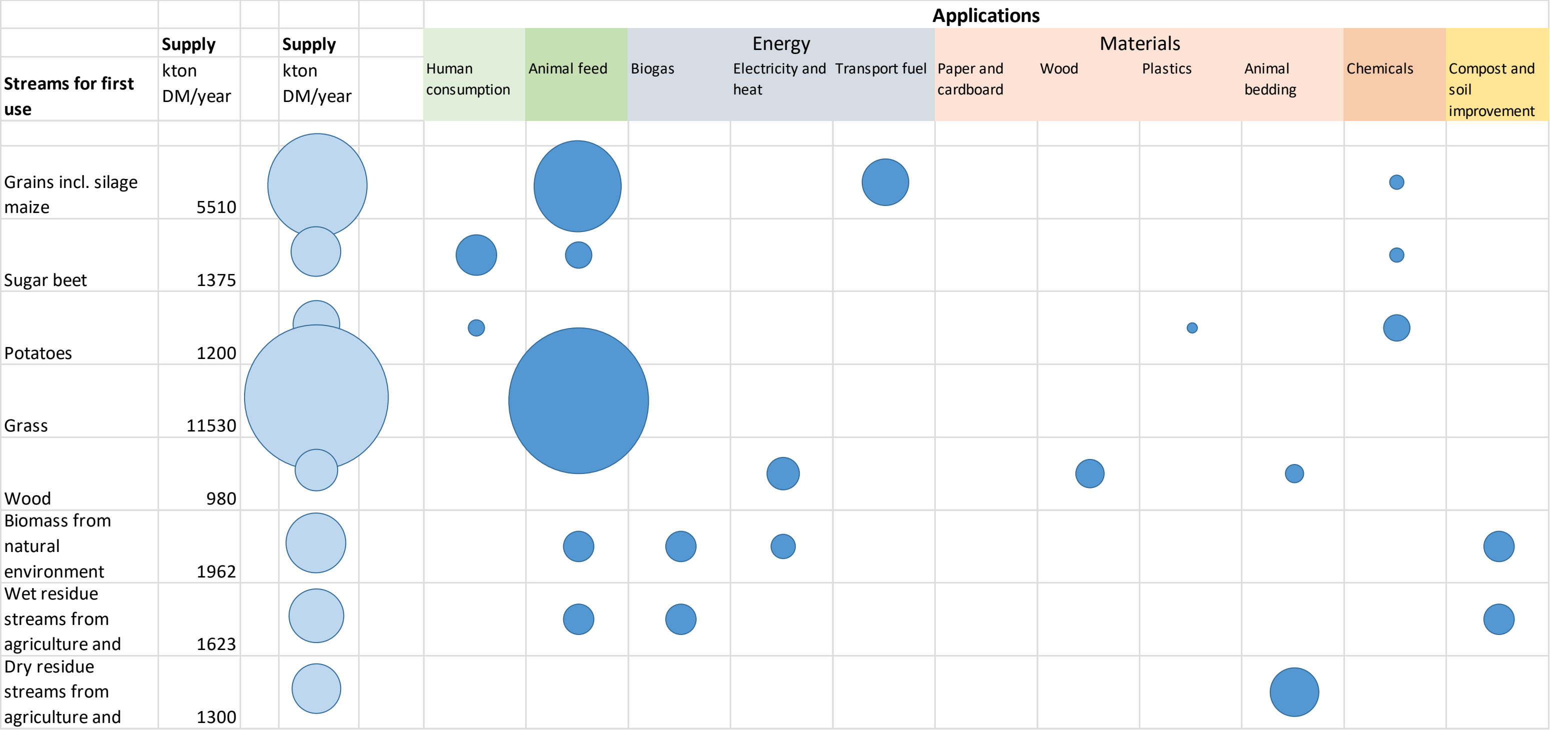


Figure 5. Imports (left) and exports (right) of biomass streams to and from the Netherlands.

kton DM per year, of which 4,200 kton is used in animal feed and 1,200 kton for the production of bioethanol.[23,24]

After use, organic residue streams arise, such as manure (5,730 kton DM per year), most of which is used as a soil improver, and a few per cent is used as a raw material for biogas production.[10] The annual 3,609 kton of wastepaper (DM) is largely used to produce cardboard.[25]

The main biomass streams, both imports, exports and domestic production, are shown in Figure 7. It also shows the main applications of those streams. In 2016, the Netherlands imported 50,000 kton of biomass (dry weight)(see Table 8). The imported biomass referred to in Figure 7 represents 35,500 kton DM. Twenty-nine per cent of the imported biomass (14,500 kton DM) has not yet been specified and includes processed foods, dairy, household waste, ornamental plants, textiles (a few hundred kton), leather goods and cocoa. Besides use as animal feed, exports constitute the second most important use of biomass. These exports are partly transit goods and partly products produced in the Netherlands.



Streams for first use	Supply kton DM/year	Supply kton DM/year	Applications										
					Energy			Materials					
			Human consumption	Animal feed	Biogas	Electricity and heat	Transport fuel	Paper and cardboard	Wood	Plastics	Animal bedding	Chemicals	Compost and soil improvement
Grains incl. silage maize	5510	●		●			●					●	
Sugar beet	1375	●	●	●								●	
Potatoes	1200	●	●							●		●	
Grass	11530	●		●									
Wood	980	●				●			●		●		
Biomass from natural environment	1962	●		●	●	●							●
Wet residue streams from agriculture and	1623	●		●	●								●
Dry residue streams from agriculture and	1300	●									●		

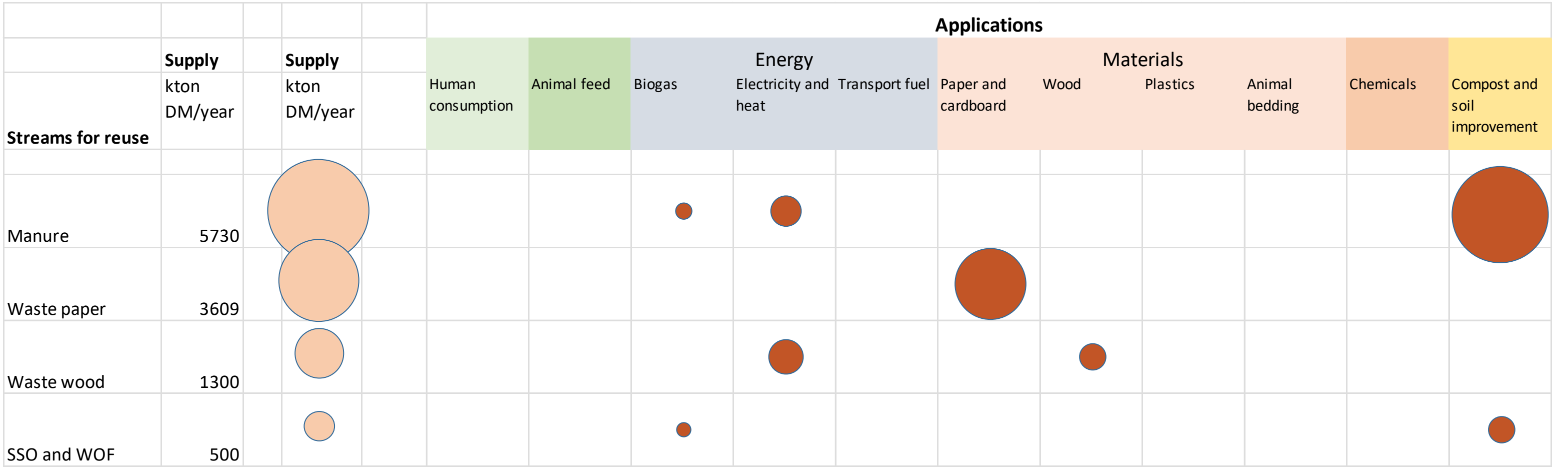
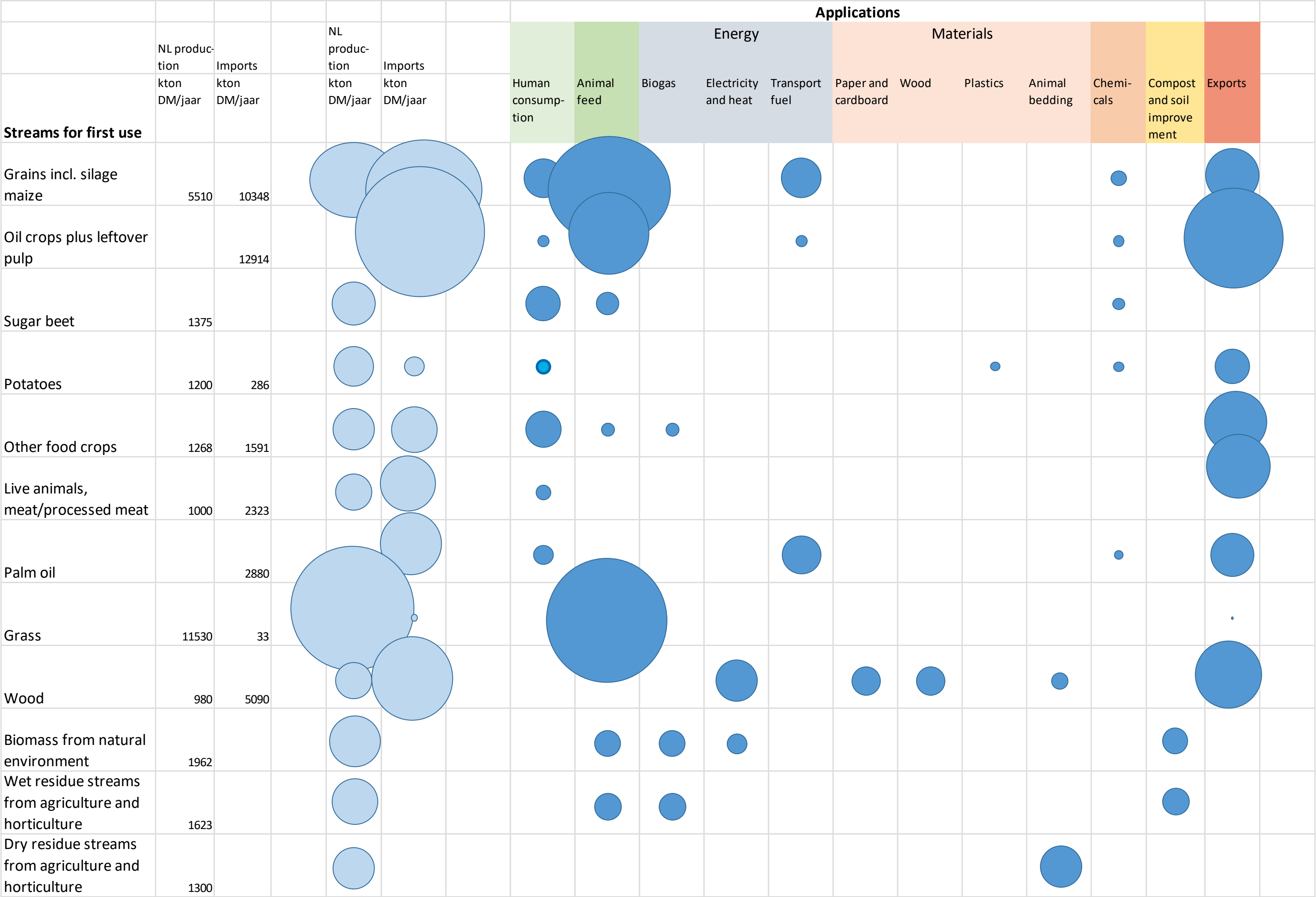


Figure 6. The main *__domestically produced__* *biomass streams and their main applications.*[17,18] *The streams are specified on the left together with the annual tonnage of dry matter. The matrix shows use in the Netherlands. The size of the discs correlates with tonnage. Residue streams are produced as a result of such use, which are shown bottom left. A new application has been allocated to these streams under one of the matrix categories.*



							Applications											
									Energy			Materials						
Streams for first use	NL production kton DM/jaar	Imports kton DM/jaar		NL production kton DM/jaar	Imports kton DM/jaar		Human consumption	Animal feed	Biogas	Electricity and heat	Transport fuel	Paper and cardboard	Wood	Plastics	Animal bedding	Chemicals	Compost and soil improvement	Exports
Grains incl. silage maize	5510	10348		●	●		●	●			●					●		●
Oil crops plus leftover pulp		12914			●		●	●			●					●		●
Sugar beet	1375			●			●	●								●		
Potatoes	1200	286		●	●		●							●		●		●
Other food crops	1268	1591		●	●		●	●	●									●
Live animals, meat/processed meat	1000	2323		●	●		●											●
Palm oil		2880			●		●				●					●		●
Grass	11530	33		●	●			●										●
Wood	980	5090		●	●					●		●	●		●			●
Biomass from natural environment	1962			●				●	●	●							●	
Wet residue streams from agriculture and horticulture	1623			●				●	●								●	
Dry residue streams from agriculture and horticulture	1300			●											●			

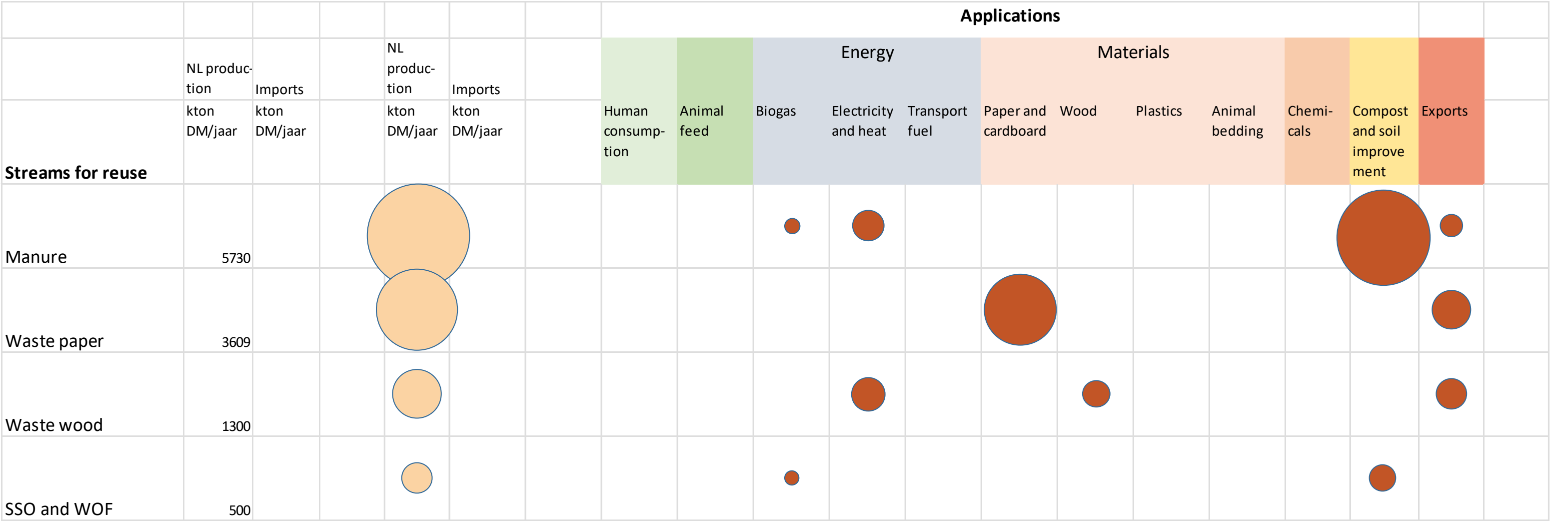


Figure 7. The main <u>imported, exported and domestically produced</u> biomass streams and their main applications.[17] *The specified streams are shown on the left together with the annual tonnage of dry matter. The matrix shows use in the Netherlands plus exports. The size of the discs correlates with tonnage. Residue streams are produced as a result of such use, which are shown bottom left. A new application has been allocated to these streams under one of the matrix categories.*

Figure 8. The Netherlands is an important transit country for various goods, including biomass.

Figure 6 shows domestic production of the various types of biomass and what they are used for. The estimated size of the Dutch bioeconomy can be derived from this figure. In 2016, the share of biomass in energy, chemicals, paper and plastics applications, excluding export products, but including raw materials from the Netherlands and abroad, totalled over 10,000 kton DM/year. If food and animal feed are included, that figure is far higher. So, what is total biomass consumption in the Netherlands? Based on the aggregated data in Table 8, we had already estimated the total annual consumption of biomass products at 43,000 kton DM per year. Based on the underlying figures in Figure 6 (not visible), an estimate can also be made of consumption, including animal feed and human food, but excluding recycle streams and exports. We also arrive at 43,000 kton DM per year, of which animal feed accounts for around 30,000 kton and human food for over 3,000 kton.

3.6 Conclusions

The total annual consumption of biomass and biomass products, including food and animal feed, but excluding recycle streams, is around 43,000 kton DM. Around 30,000 kton of that amount is used for animal feed and 3,000 for human food. The size of the Dutch bioeconomy (energy, plastics, paper and chemicals) is around 10,000 kton biomass DM per year.

In comparison, the Netherlands uses around 76,500 kton of fossil carbon-based sources annually, primarily for the energy supply. The transit of these fossil sources even is triple that amount. The Dutch carbon economy therefore revolves around fossil sources, animal feed and transit goods. The new bioeconomy, mainly the applications of biomass in energy, chemical and plastics, is still small.

Figure 9. Imported soybeans are currently an important source of animal feed.

4 Biomass demand for the bioeconomy

4.1 Introduction

Fossil raw materials, especially coal, petroleum and natural gas play an important role in our society. Coal is chiefly used to generate electricity and heat, petroleum is primarily used to make transport fuels, chemicals and plastics, and natural gas is used for electricity and heat, and for the production of ammonia (for production of fertilisers). The energy and fuel sector is by far the largest user of fossil raw materials with a demand around ten times higher than that for chemicals and materials.

It will take considerable time and effort to replace these fossil raw materials completely. In its Energy Roadmap 2050, the EU proposes meeting at least 55% of energy demand using renewable sources, 32% using fossil sources, but with carbon storage, and the remainder using nuclear energy.[26] This is one of the many scenarios for the replacement of fossil raw materials. Businesses, knowledge institutions, public authorities, sector associations and NGOs have developed a range of scenarios, often with the years 2030 and 2050 as the time horizon. The scenarios differ in terms of the extent to which fossil sources should be replaced (all or only a part) and the role biomass should play (in addition to solar or wind energy, for instance). Scenarios in which a limited role is allocated to biomass are often dictated by uncertainty about the availability of sufficient

Figure 10. Wood chippings are a raw material for multiple processes.

Figure 11. High expectations for seaweed.

sustainable biomass in the future. That future is difficult to predict, because how will the demand for energy, chemicals and materials develop if not only the population size increases, but also energy efficiency and the recycling of materials? Various scenarios are also geared towards this development. In these scenarios both the replacement of fossil sources and the more efficient use of energy play a role. Considerable efficiency gains can be made particularly by insulating houses.

In this chapter the various replacement scenarios have initially been bypassed by estimating how much biomass would be needed to replace the current consumption of fossil raw materials completely (Section 4.2). The complete replacement of fossil raw materials by biomass is purely a thinking exercise because it is not realistic. Based on selected growth and replacement scenarios, how large demand could be in the year 2050 is subsequently estimated (Section 4.3). This is followed by estimating how much biomass can be made available in the Netherlands, Europe and worldwide in 2050[*] (Section 4.4). Section 4.5 explains why the mobilisation of biomass is so important. This chapter concludes with a total overview of the scenarios discussed.

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[*] *The Netherlands import biomass and the availability of biomass cannot be seen in isolation from the needs and plans of Europe and the rest of the world. If the rest of the world also wants to minimise the use of fossil raw materials, this will have consequences for the Netherlands. This chapter therefore includes European and global demand for biomass.*

Methodology for converting PJ to Mton of biomass

Energy applications

The energy contained in fossil raw materials and biomass is expressed in PJ. Spruce wood pellets, our model biomass which is used for the calculations in this chapter, contain 18.79 MJ/kg dry matter (DM), or 18.79 PJ/Mton.[16] This is the net calorific value or lower heating value. In this booklet a conversion factor of 18.79 PJ/Mton biomass is used to convert PJ into biomass for <u>energy</u> applications.

Non-energy applications

There also is a connection between weight and energy content for fossil fuels. It is useful to express weight in MTOE (million tons of oil equivalent) first. This involves converting all quantities, including gas and coal, into tons of oil with the same energy content. The energy content is 42 PJ/MTOE.[27]

The replacement of fossil raw materials by biomass in the chemical industry should be approached prudently. A significant part of the petrochemical industry is dedicated to the production of plastics, of which polyethylene and polypropylene account for a major share (around half). If all of these plastics and chemicals have to be made from biomass, the weight of the biomass required (dry matter) will be higher than the product weight. This is caused by differences in the nature of the product and raw material (products contain fewer oxygen atoms than the raw material) and by limited conversion efficiencies. However, two efficiency improvements can be achieved:

- If we succeed in allocating chemicals and plastics that contain a larger percentage of oxygen, such as polyesters, a larger area of application at the expense of the low-oxygen chemicals, less biomass will be needed to produce the same quantity of chemicals.[28]
- If the raw material more closely resembles the product, losses will be smaller and biomass will be used more efficiently.

According to Bos and Sanders,[29] these efficiency improvements can reduce the biomass needed (dry matter) by 40%. Biorefining processes ultimately produce residue streams which, although unsuitable for extracting products, still contain energy. These residue streams can be utilised to supply energy to the biorefining processes. With all these efficiency improvements, 1 Mton of basic chemicals can be produced from 2.2 Mton DM biomass. This is the quantity contained in the products. In addition, biomass is still needed for the energy required to convert those building blocks into chemical products.

In this booklet a conversion factor of 42PJ/MTOE is used to convert PJ into biomass for <u>non-energy</u> applications multiplied by the factor 2.2 stated above to arrive at Mton biomass.

4.2 Scenario 1: Replacement of fossil raw materials by biomass only, based on current use

4.2.1 The Netherlands

Chapter 3 states that the Netherlands used 2,864 PJ of fossil raw materials in 2017, of which 585 PJ was used for non-energy applications. In addition, 123 PJ of biomass was used to supply energy and 10 PJ of biomass was used for chemicals and plastics. These figures are shown in Table 10 and converted into Mton biomass. Based on the calculation rules presented earlier, an additional 152 ±20 Mton DM biomass is estimated to be needed for the complete replacement of fossil raw materials. This represents the demand for the 2017 consumption level. The biomass used for paper, wood products, animal feed and human consumption amounts to 34 Mton and is not included in this calculation.

Table 10. Use of raw materials (fossil and renewable) in the Netherlands (2017 data) and the calculated quantity of biomass needed to replace all fossil raw materials.

Raw material	**Quantity of mass equivalents (MTOE)**	**Quantity of energy (PJ)**	**Quantity of biomass (Mton)**	**Share (%)**
Fossil				
Non-energy application	14	585	31 ±4	18.6
Energy application	54	2,279	121 ±16	72.6
Total	*68*	*2,864*	*152*	*91.3*
Renewable				
Biofuels and chemicals	3.2	133	7.1	4.2
Other		49		
Total	*4.3*	*182*	*7.1*	*5.8*
Nuclear and other sources	*2.2*	*91*		*2.9*
Total	***74.5***	***3,137***	***159 ±20***	***100***

4.2.2 EU

The use of fossil raw materials in the EU for 2016 is summarised in Table 11. Compared to the Netherlands, the EU uses a lower percentage (of the demand for raw materials for energy, chemicals and materials) for fossil raw materials. This has always been the case because there are more possibilities for using hydropower and biomass in many EU countries. In order to replace all fossil raw material by biomass, an additional quantity of 2,898 Mton DM biomass will be needed annually for a consumption level equivalent to 2016.

Table 11. Use of raw materials (fossil and renewable) in Europe (EU 28, 2016 data) and the calculated quantity of biomass needed to replace all fossil raw material [30] (estimates/extrapolations based on Bos & Sanders).[29]

Raw material	**Quantity of mass equivalents (MTOE)***	**Quantity of energy PJ***	**Quantity of biomass (Mton)**	**Share in the Netherlands %**	**Share in EU28 %**
Fossil					
Non-energy application	85 ±30	3,570 ±1,300	187 ±68		
Energy application	1,213	50,946	2,711 ±350		
Total	*1,300 ±30*	*54,600 ±1,300*	*2,898*	*91.3%*	*75.2%*
Renewable					
Biofuels and chemicals	83	3,486	186 ±24	4.2%	4.8%
Other		5,376			
Total	*211*	*8,862*		*5.8%*	*12.2%*
Nuclear and other sources	*217*	*9,114*		*2.9%*	*12.6%*
Total	***1,728 ±30***	***75,576 ±1,300***	***3,084 ±400***	***100%***	***100%***

**EU28*

4.2.3 World

Table 12 contains an overview of the quantity of fossil raw materials and the quantity of other raw materials and energy sources used worldwide in 2016.

Table 12. Use of raw materials (fossil and renewable) worldwide (2016 data)[31,32] *and the calculated quantity of biomass needed to replace all fossil raw materials.*

Raw material	**Quantity of mass equivalents (MTOE)**	**Quantity of energy (PJ)**	**Quantity of biomass (Mton)**	**Share in the Netherlands %**	**Share in the world %**
Fossil					
Non-energy application	870	37,000	1,938 ±250		
Energy application	10,373	436,000	23,203 ±3,000		
Total	*11,243*	*472,000*	*25,141*	*91.3%*	*81.7%*
Renewable					
Biofuels and chemicals	1,349	67,000	3,566 ±465	4.2%	9.8%
Other		14,000			
Total	*1,926*	*81,000*		*5.8%*	*13.4%*
Nuclear and other sources	*669*	*28,000*		*2.9%*	*4.9%*
Total	***13,761****	***578,000***	***28,707 ±3,700***	***100%***	***100%***

**World energy consumption amounted to 9,555 MTOE, which is lower than the total quantity of raw materials stated in this table.*[32] *The limited yields of power stations and boilers, the energy companies' own energy consumption and losses account for the difference.*

If all fossil raw materials are to be replaced by biomass, the world would need an additional 25,141 Mton DM biomass annually. In comparison, current use amounts to around 22,000 Mton per year (see Figure 28). That quantity applies to the consumption level for the year 2016. Such a large-scale replacement of fossil raw materials by biomass is unrealistic. A more nuanced picture is set out in the next chapter.

4.3 Scenario 2: Expected biomass demand in 2050 for the complete replacement of fossil raw materials by a mix of renewable sources

4.3.1 Trends

Given that predictions are difficult to make, the scenarios for economic growth and the extent to which a sustainable and circular economy can be created vary. This section presents scenarios in which biomass plays a major role and then looks at the extent to which the huge demand for biomass can be covered by biomass availability.
The following trends should be taken into account:

- Agriculturalists argue that it is hardly, if at all, necessary to expand the agricultural area in the world in the future in order to continue to feed the world, even if the population increases. This will be achieved by improving agricultural efficiency and by combating food wastage. More nutrients (manure or chemical fertiliser) will therefore be needed, which could push up energy demand.
- The demand for materials and chemicals will increasingly be accommodated through recycling, which will reduce the need for virgin raw materials (unless an economic growth spurt negates this effect).
- Renewable energy will not only consist of biomass, but also of solar and wind energy. The distribution between the various sources depends on technological developments, including energy storage.
- Energy savings programmes (such as insulation in buildings), technological improvements (vehicle energy consumption, power station efficiency, heat pumps) and lifestyle changes (flying and driving less) can have a considerable impact on energy consumption.
- The share of electricity in energy will rise.
- The chemical industry is expected to be partly electrified (hydrogen as raw material, produced by electrolysis with CO_2 as the second raw material).
- The population and the economy will grow.
- Meat consumption per inhabitant is rising in developing countries but decreasing in developed countries.

4.3.2 The Netherlands

In 2050, the Netherlands will also need a considerable amount of biomass for chemicals and energy. The Royal Association of the Dutch Chemical Industry (VNCI) presented a plan outlining how the Dutch chemical industry can achieve the 80-95% reduction in greenhouse gas emissions in 2050, in line with the Paris Climate Agreement.[33] The plan takes the further reuse and recycling of materials into account. It describes a number of possible scenarios, one of which allocates a key role to biomass. The VNCI scenario assumes that biomass will be used for the production of traditional chemicals, such as C_2 and C_3 compounds, methanol and BTX. Potential efficiency improvements arising from opting for other basic chemicals have not been included. In this scenario the Dutch chemical industry is estimated to require 700 PJ (37 Mton DM) biomass as a raw material and energy source.

A 2018 study by De Gooijer[34] provides an estimate of how much biomass the Netherlands needs in 2050 for the production of energy. Biomass will have to supply a large share of energy. The share of wind energy will be limited due to the vast surface area required to accommodate wind farms. Moreover, the use of solar and wind energy will be limited by fluctuating production (seasons, day/night, windlessness) and the lack of affordable energy storage systems. The quantity of energy needed by the Netherlands in the year 2050 for energy generation, including mobility and bunkering (seagoing vessels and aircraft), excluding the share of chemical raw materials, is estimated to be 4,266 ±2,300 PJ. De Gooijer proposes sourcing 2,200 ±1.200 PJ from biomass, which amounts to 117 ±64 Mton DM. The wide margin is attributable to various scenarios focusing on savings and consumption growth. In this scenario, 25% of the Dutch part of the North Sea is occupied by wind turbines that collectively generate 1,346 PJ and the yield produced by solar energy is estimated to be 470 PJ and 250 PJ is provided by other renewable forms of energy.

If the two studies are aggregated (the chemical sector energy demand should not be double counted; is around 320 PJ), the Netherlands needs 137 ±64 Mton DM biomass in the year 2050. However, if significant energy savings are made, there even is a possibility that we may scarcely need biomass to supply energy, although it will still be needed by the chemical industry.

4.3.3 EU

According to the Energy Roadmap 2050,[26] the EU will need 71,400 ±3,000 PJ of energy in 2050. This estimate takes a scenario of policy measures adopted in 2012 into account. A portion of the energy will be supplied from sources other than biomass. In 2016, the other sources accounted for 14,490 PJ. If the remainder is to be provided by biomass and we add the estimated biomass demand for the European chemical industry (120 Mton), the EU28 will need 3,150 ±200 Mton DM biomass in 2050. This is an extremely biomass-oriented scenario. The growth of the wind and solar energy sector will reduce biomass demand. Also, if larger energy savings are made (compared to the measures conceived in 2012), less biomass will be needed.

4.3.4 World

According to the UN Food and Agriculture Organization (FAO), the world's population is estimated to reach 9.8 billion by 2050.[35] Global food consumption will rise from 1,482 Mton DM in 2011 to 2,059 Mton in 2050.[36] The production of the most important basic chemicals will rise by a factor of 2.4, based on a forecast annual growth rate of 2.5%.[37] If growth is lower or higher, this factor will also be lower or higher. If this factor also applies to all non-energy applications of fossil sources, the demand for fossil raw materials for the chemical industry is expected to be 87,690 PJ in 2050. The quantity of biomass required in 2050 to replace that amount, including the efficiency improvements described earlier, will be 4.600 ±400 Mton DM.

Table 13: Compilation of the data from the studies described.

Source	**Raw material demand (PJ)**	**Biomass demand (Mton)**	**Comments**
VNCI (2018)	700	37 (converted)	For chemical industry NL (raw material and energy source) in 2050
De Gooijer (2018)	2,200 ±1200, of which 1,346 wind, 470 solar, other 250	117 ±64 (converted)	For energy (incl. mobility and bunkering) NL in 2050
	4,646	137 ±64 (converted)	Energy and chemicals NL in 2050
EU (2012)	71,400 ±3,000	3800 (converted)	For energy EU in 2050
	14,490	771 (converted)	Energy EU actual (not being biomass) in 2016
		3150 ±200 (converted)	Energy and chemicals EU in 2050
FAO (2016)		1,482	Food for world actual in 2011
		2,059	Food for world in 2050
Bos and Broeze (2019)	87,690	4,600 ±400	Chemicals for world in 2050
Shell, IEA, Exxon	800,000 ±400,000		Total global energy demand in 2050

More energy will also be needed. Bos and Broeze[37] have used an average figure based on various widely diverging estimates from Shell, IEA and Exxon Mobil, among others, for the total amount of energy needed in 2050. It amounts to 800,000 PJ, or more accurately expressed: 800,000 ±400,000 PJ. Currently, 9% of global energy demand is covered by sources other than fossil sources and biomass.

Table 13 contains a compilation of the estimates derived from the studies described.

4.4 Biomass availability

4.4.1 The Netherlands

In a 2009 report, Koppejan et al. estimated the availability of Dutch biomass for electricity and heat in 2020.[38] They worked out four varying but realistic scenarios, based on studies by CPB (Netherlands Bureau for Economic Policy Analysis), geared towards various social developments. These scenarios differed according to the extent to which markets would be open or closed and the level of importance of sustainability. The assumption was that the emphasis on sustainability would be linked to lower economic growth. The study focused on biomass that can be released for an energy application, separate from the existing applications in animal feed, human consumption and materials, for instance. The biomass had to be suitable for use as raw material for fermentation and combustion, etc. Liquid biofuels were not included.

In the actual situation in 2009, 125 PJ of biomass was available that could in principle be used for energy generation, but only 40% (50 PJ) of which was actually used for that purpose. The authors' expectation for 2020 was that 15 ±1.,5 Mton DM biomass (282 PJ) could be released for energy generation. Major contributions would be made by solid manure, old/processed wood and the remaining fraction of household waste. Although energy crops cultivation is included in the study, it does not play a major role in any of the scenarios, whereas aquatic biomass plays a minor role. From a 2019 perspective, this is a reasonably accurate scenario.

The largest quantities of biomass can be released in a scenario where there is a strong willingness to opt for sustainability. The openness of the global market has a slight positive effect on the aggregate of all the available biomass, plus a modest effect on the type of biomass used. As this study focused on biomass suitable for electricity and heating, the total quantity of available biomass will be larger. In 2016, over 6 Mton DM biomass was used for energy, of which domestic biomass accounted for 4.5 Mton. This is lower than the 15 Mton stated, which means there is still room for expansion. The quantity of domestic biomass used in 2016 was higher than the 50 PJ actually used in 2009. A more recent study was conducted by Schulze et al.[39] It also focuses on the freely available biomass potential for the energy sector, excluding imports, but with horizons of 2023 and 2035. The findings corroborate the estimates made above.

4.4.2 EU

In 2012, Ros et al.[40] made an estimate of the biomass potential in the EU27 for applications in bioenergy and in biobased chemicals. This again relates to the quantities of energy contained in biomass and biomass that could realistically be released and, on top of that, in an environmentally friendly manner. The estimate relates to the year 2030 and amounts to 12,000 ±2,000 PJ, of which 6,000 PJ is from agriculture and horticulture, 1,800 PJ from forestry and 4,000 PJ from waste. This would equate to 640 ±100 Mton DM of biomass.

In 2010, Elbersen et al.[41] estimated that 362 Mton DM biomass would be available in the EU in 2030 in the form of byproducts from agriculture and forestry and that it would be possible to cultivate an additional 184 Mton DM.

4.4.3 World

The 2015 SCOPE Report[42] states that 10,000 Mtons (wet/fresh weight) of energy crops, agricultural residue streams and forestry residues were available in 2015 (actual production), which probably equates to around 100,000 PJ/y. The report states that an additional 50-200 million hectares of land area should be made available for energy cultivation for the year 2050. Does this exist? The world has a land area of 13 billion

Figure 12. Oil palm is a high-yielding source of oil and residue streams, but there are major concerns about the sustainability of the cultivation.

hectares, of which 1.5 billion hectares is used for agricultural and horticultural purposes. The additional 50-200 million hectares could be realised in Sub-Saharan Africa and South America. The crops grown on these cultivation zones can produce 150,000 ±50,000 PJ/y biomass. The report proposes using 40-50 million ha for conventional biofuels (from starch crops and palm oil) and the remainder for the cultivation of lignocellulose crops. There is even more potential for 2050, according to the report. By making more efficient use of grassland (for livestock farming), an additional land area could be created for energy cultivation (potential 215,000 ±75,000 PJ/y) and the use of dry and marginal parcels of land could yield another 80,000 PJ/y. The total potential for 2050 could be 550,000 ±200,000 PJ/y.

The SCOPE Report is a solid and complete piece of work, with 779 pages and 137 authors from 24 countries. However, there are more studies. Estimates have been made in various other studies, varying from under 100,000 PJ/y if only residues are included to 1,500,000 PJ/y for extreme scenarios. Dornburg et al.[43] provided an overview of these studies in 2010 and maintain the availability of biomass at an average 350,000 ±150,000 PJ/y with residues as the basis and, on top of that, the use of forestry wood not yet used for wood products plus cultivation on new land that is released, for example, as a result of optimising agricultural efficiency on existing agricultural land. A quantity of 350,000 PJ equates to 18,600 Mton DM biomass.

It remains uncertain whether that quantity can actually be made available. The Intergovernmental Panel on Climate Change (IPCC) can live with a slightly lower availability. The IPCC published a report on global warming containing scenarios to limit the temperature rise to 1.5°C. In one of the scenarios a relatively large quantity of biomass is used in the year 2050. It is a scenario marked by a relatively high level of economic growth and food consumption. The world will need 700,000 PJ (of primary) energy, of which 291,000 PJ will be produced by biomass. The remaining energy will be sourced from the sun, wind, atomic nuclei and fossil sources. Carbon capture and storage is also used to reduce carbon dioxide emissions (see Chapter 6).[44] That IPCC scenario takes use of over 15,000 Mton DM/y biomass into account.

The quantity of sustainable biomass that is predicted to be available in 2050 depends on the widely diverging assumptions made in the numerous studies. Moreover, the focus is on potential availability. Everything depends on the actions undertaken to actually mobilise biomass and establishing the appropriate policy. We have provisionally used the figures deemed realistic by the IPCC: 15,000 Mton DM/y biomass, or 282,000 PJ.

Figure 13. Miscanthus is a biomass crop with a high yield.

4.5 Biomass mobilisation is crucial

In addition to the potential availability of biomass, the mobilisation of biomass is another important consideration. Many agricultural and forestry residue and waste streams currently remain unutilised because they are left on the land, or are incinerated in the open air. If biomass owners are encouraged to release and make biomass available, large quantities can still be mobilised. Farmers can even start taking the expected sales of residues into account by adapting their work methods, thereby maximising the quantity of biomass that can be made available for the bioeconomy. The best way of meeting sales expectations is to ensure that large quantities of marketable uniform semi-finished products (commodities) are launched on the market. These biomass commodities must carry sustainability certification, be transportable over large distances and available for purchase by multiple customers in multiple sectors. Examples are wood pellets or pyrolysis oil, or pellets made from washed, mineral-free bagasse. The minerals can be returned to the local plantations and the compact pellets can be shipped and purchased by energy companies and biorefineries. Pyrolysis oil or cleaned, torrified biomass (see Chapter 5) can be allocated a role as a commodity. The energy sector will lead the way in purchasing these commodities and in the wake of this development biorefineries will have the opportunity to take up this offer with supply security.

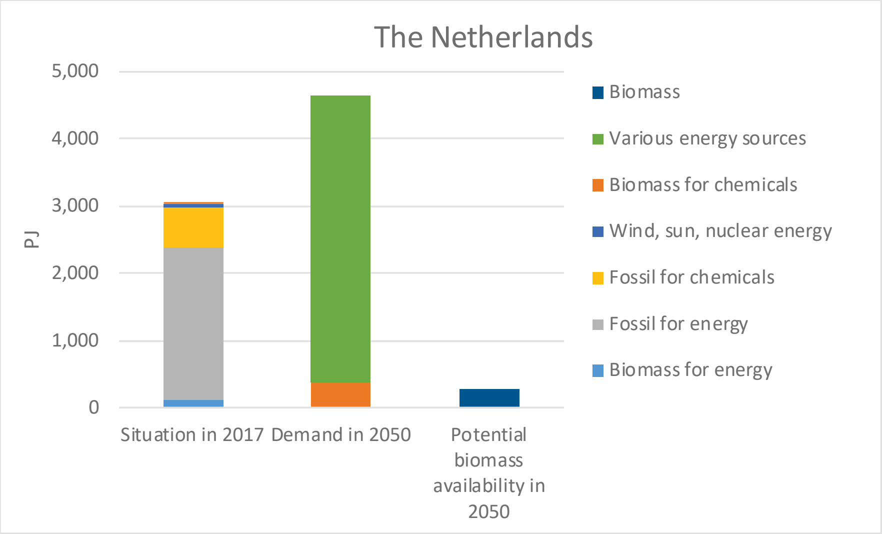

Figure 14. Raw materials for energy supply and chemicals for the Netherlands in 2017 (actual) and 2050 (estimate).

The presence of large quantities of internationally marketable biomass commodities offers certainty to both biomass owners and biomass users. Certainty is required in order to mobilise biomass streams.

4.6 Biomass demand versus availability

If the Netherlands replaced all fossil fuel raw materials with biomass today, more biomass would be needed than the quantities required in 2050, according to various scenarios. This is because increasing efficiency in many areas and the increasing use of other renewable energy sources in the Netherlands is taken into account for 2050. Figure 14 provides a comparison of the quantity of raw materials for energy and chemicals in 2017 with demand and availability in 2050. It is evident from this figure that other renewable sources must be developed.

The 2016 data for Europe (Table 11) and the 2050 estimates (Table 13) are very similar. Again, Europe will need to do its utmost to achieve this. While the economy grows, the demand for raw materials needs to level off considerably.

This is not yet evident on a global scale. Due to population growth and the rise in prosperity, a considerable quantity of raw material would still seem to be needed in 2050. Figure 15 shows that the whole world could source part of the demand for raw materials for chemicals, materials and energy from biomass in 2050. To that end, it is

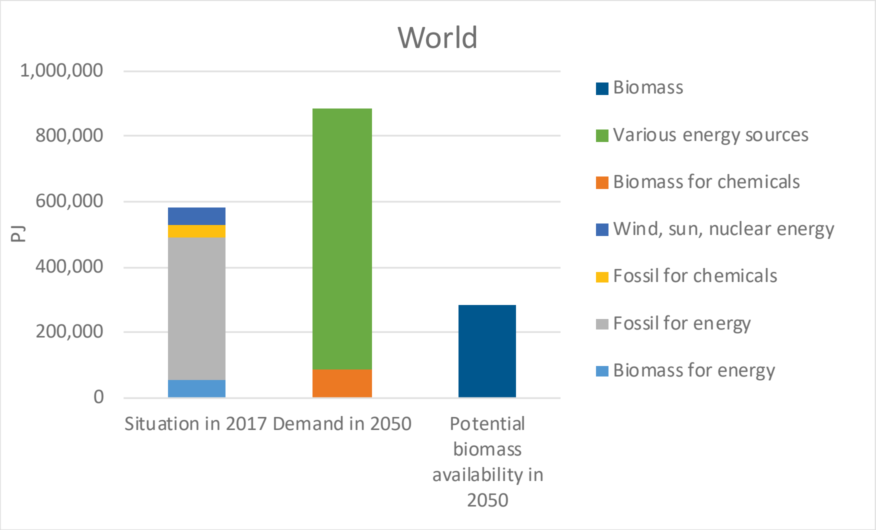

Figure 15. Raw materials for energy supply and chemicals for the world in 2017 (actual) and 2050 (estimate).

essential to develop new agricultural and biorefining techniques and to use marginal land. Around two-thirds of the energy will need to be produced from other renewable sources. If two-thirds can be successfully produced using wind, the sun and hydropower, sufficient biomass could potentially be made available on a global scale. This offers the Netherlands the argument and the scope to import biomass. These imports will be one order of magnitude larger that the biomass that can be released domestically for energy and chemicals, and roughly double the current biomass imports (including grains, oil crops and wood). Biomass will largely be imported from outside the EU because the EU will be similarly faced with a shortage of biomass. The Netherlands could therefore also play a major role as a biomass transit country. The biomass import flow could in that case potentially be larger than current fossil fuel imports.

5 Processing technologies for biomass

5.1 Introduction

Biomass needs to be processed in order to use it for chemicals, energy and materials. A range of conversion and separation technologies are available for this purpose, as well as mechanical processing (such as size reduction). The conversion technologies can be divided into the following processes:

- Biological processes in which micro-organisms or enzymes convert biomass components into other components.
- Thermochemical processes in which biomass is broken down into usable substances under a high temperature.
- Chemical processes in which biomass components are converted into other components using a catalyst and/or by reacting with an added reagent.

This chapter describes the most important proven conversion processes and briefly discusses mechanical processing and separation processes. Technologies that are still largely in the development stage are described in Chapter 6.

5.2 Mechanical processing

Raw biomass usually needs to be reduced in size before further processing. It can be cut and ground for this purpose. For some processes, the biomass even needs to be pumpable, which means that it needs to be considerably reduced in size and dispersed in a liquid. Pressing is another mechanical process and separates juice or oil from solid substance.

Mechanical processes are often used when producing materials incorporating biomass. An example is extrusion in which biomass components, mainly fibres, are mixed with a (bio)plastic to produce composites. Melting, casting, frothing, emulsifying, dispersing, pelleting, mixing and formulating are also used to create usable products.

5.3 Biological conversion processes

5.3.1 Fermentation processes

Principle

Fermentation is a process in which micro-organisms (bacteria, yeasts, moulds) are used to convert organic material into alcohol, acids or hydrogen, for instance. Although fermentation is sometimes defined as conversion under oxygen-free conditions (anaerobic), the definition is often broadened to include processes that need oxygen (aerobic). The processes used in the chemical and energy sectors are often carried out in a stirred reactor vessel (fermenter) with a liquid that usually contains carbohydrates, but sometimes organic acids as well. The substrate and the fermenter need to be sterilised regularly in order to work with one type of micro-organism in the form of a pure culture.

Suitable raw materials

The most important raw material, called substrate in fermentation science, consists of fermentable sugars: monosaccharides (such as glucose) and disaccharides (such as sucrose, or sugar crystalline). Cane sugar, beet sugar and molasses are suitable raw materials as are starch, cellulose or lignocellulose from which these fermentable sugars can be produced. A wide range of biomass types can therefore be used, including wheat, corn, straw, grass, leaves and wood, as long as the material contains a substantial quantity of carbohydrates. As it is economically beneficial to achieve high product concentrations in a fermentation process, the raw material may not be diluted too much with water. The raw material should preferably contain more than 25% of dry matter, which means that fruit, juices and wastewater are less suitable. Raw materials with high carbohydrate content are the most frequently used. Other types of raw materials, such as organic acids, proteins, amino acids, alcohols, fats and glycerol, can also be used in fermentation processes, which enlarges the eligible categories of biomass. Completely different products can also usually be created from these raw materials.

Products

Important products in the energy carrier category are ethanol, butanol, isobutanol (all three are liquid transport fuels) and hydrogen gas. In the chemical category lactic acid, a building block for the bioplastic polylactic acid, is important as well as polyhydroxyalkanoate (PHA), a bioplastic which accumulates in the form of granules in bacteria cells. The trend suggests that the fermentation products succinic acid, itaconic acid and other dicarboxylic acids are becoming increasingly important due to their suitability for the production of bioplastics. Apart from an application in energy and chemicals, fermentation is a process that is known for its use in the production of beer, wine, bread, baker's yeast, citric acid, antibiotics, enzymes and amino acids.

Experience

The Netherlands has three large fermentation plants that produce ethanol from starch. The plant in Rotterdam, one of the world's largest plants, has a production capacity of 480,000 m^3 ethanol/y. A plant that produces lactic acid is located in Gorinchem.

A typical plant that produces ethanol from corn or wheat starch can produce 100,000 tons of ethanol per year from 200,000 tons of starch. The facility needs around 2,500 m^3 of fermentation space, often distributed across 150-200-m^3 units.

Figure 16. Bioethanol plant located at the Maasvlakte, Port of Rotterdam.

Economy

The production of ethanol from corn or wheat is marginally viable. The production costs approximate the selling price of ethanol (€550/ton).[48] Lactic acid production from starch is viable as well. The production of second-generation ethanol or lactic acid (from residue streams such as corn straw and sugar beet bagasse) regrettably is economically still not feasible due to the high costs of making the lignocellulose accessible and enzymatic hydrolysis. Consequently, the production process still needs to be optimised. The trend is primarily geared towards anaerobic fermentation processes, because they are more cost efficient than aerobic fermentation processes. An expensive aeration system is not required for anaerobic processes and the product yield is high. In aerobic processes a large part of the substrate is oxidised to form carbon dioxide and converted into the cell mass of micro-organisms: both have a limited value and moreover undesirable loss of carbon occurs. During the fermentation of starch into ethanol, in practice 89% of the energy value in sugar is converted into ethanol energy. However, the final yield is slightly lower due to the distillation process and other factors. During distillation less than 1%

of ethanol is lost. The energy for the two-stage distillation process amounts to around 18% of the energy contained in the ethanol.

5.3.2 Anaerobic digestion

Principle

Anaerobic digestion is a biological process in which micro-organisms break down organic material under oxygen-free conditions. This usually refers to methane fermentation in which the final product is biogas, a mixture of methane and carbon dioxide. Anaerobic digestion therefore is a form of fermentation. The process takes place in stirred and heated reactors, often with a volume of more than 1,000 m^3, and the conversion of solid organic substances into biogas usually takes one month.

Suitable raw materials

Raw materials suitable for anaerobic digestion are vegetable, fruit and garden waste (SSO, Source Separated Organics), manure, sludge from sewage treatment plants, residue streams from the food industry, swill (mainly kitchen waste and food scraps) and industrial wastewater with high concentrations of organic substances. Manure is often processed together with corn, grass or another co-substrate during a co-fermentation process to obtain a higher biogas yield with the same reactor volume.

Products

Biogas is the primary product and can be further upgraded to a quality similar to that of natural gas. Purified biogas is called green gas and can be injected into the natural gas grid. It can also be liquefied (Bio-LNG) and used as transport fuel. An alternative is the use of biogas in a combined heat and power plant (CHP) for the production of electricity and heat.

The byproduct of anaerobic digestion is digestate that still contains unfermented organic material, water and minerals (including phosphate and ammonia). In SSO digestion, the digestate is composted and in manure digestion the digestate is usually used to fertilise agricultural land.

Experience

There are almost one hundred sludge digesters in the Netherlands, a few SSO digesters (operated among others by Attero, De Meerlanden, Laarakker and Orgaworld), dozens of manure digesters on farms, dozens of all-purpose digesters, dozens of wastewater digesters and a few swill and residue stream digesters from food businesses.[46] A typical SSO digester with a volume of over 2,000 m^3 processes 35,000 tons of SSO annually

Figure 17. A manure digester on a farm.

and consequently produces 4.2 million m^3 of biogas.[46] Around 50% of the gross calorific value of the SSO is converted into biogas.

Economy

Anaerobic digestion businesses usually charge €25 per ton SSO (personal communication from Orgaworld) or per ton of manure.[47] In this case, the biomass therefore has a negative value. However, the market value of the biogas produced is usually lower than the production costs, due to which digestion is only economically viable with a supplementary government subsidy. In 2017, 14 PJ (600 m^3) biogas was extracted and 1,294 PJ natural gas was consumed (see Chapter 3) in the Netherlands.

5.3.3 Composting

Principle

Composting is a microbiological process in which organic material is oxidised and broken down into compost, in a set-up where air passes through a heap (pile, mound) of porous, solid material. Although composting can occur spontaneously in the field (for example

Figure 18. The composting process.

in mown verge grass), the process referred to here is controlled composting. It is often carried out with forced ventilation (through a ventilator) in a container, hall or in the open air. As composting is a kind of biological combustion process, heat is emitted which can also be harvested. The heat also causes water to evaporate and the material becomes drier, and many pathogens and seeds of weeds are exterminated due to the high temperature (70°C). The process takes a few weeks.

Suitable raw materials

Suitable raw materials are SSO, pruning and mowing material (grass, foliage), straw, dry manure types and the thick fraction of digestate from various types of digesters. The material must be damp but solid and porous, which excludes liquids and slurry.

Products

Compost is the most important product. It is the material that has not been converted during the composting process, for example minerals and organic material that is difficult to break down, such as certain fractions of lignocellulose (pieces of wood) and humic acids produced during the process. Compost can be used as a soil improver and certain types of compost can be used as a growth substrate for mushroom cultivation. A second product is heat but it is only harvested by a minority of composting businesses (such as Upcycling Gemert). Some businesses have even allocated a new use to the condensed water produced by the evaporation.

Experience

The Netherlands has around 60 large composting plants.[49] A typical capacity is 40,000 tons of processed biomass per year, from which 16,000 tons of compost can be produced. With a two-week composting period and six weeks for further maturation, around 4,000-5,000 m^3 of material is always present on the premises of a composting plant.

Economy

Compost is worth €18 per ton[50,51] but the yield is insufficient to cover the costs of the composting company. The supplier offering the biomass for composting is therefore required to pay a contribution. For example, €25 per ton is charged for SSO.

5.3.4 Other biological conversion processes

Enzymes (derived from organisms) can be used to convert substances into other substances. The enzymes act as catalysts. An example is the conversion of starch into glucose using the enzyme amylase. Consequently, the largest area of application of enzymes is the hydrolysis of natural biopolymers such as cellulose and protein.

Ensilage and Bokashi are processes in which solid material (grass, food scraps) is fermented under oxygen-free conditions, for the purpose of producing organic acids that acidify the raw material to eliminate any further biological activity. This method preserves the raw material so that it can be stored for months.

Vermiculture is the process of composting solid biomass using worms. A kind of compost is produced when worms eat the biomass in an environment with sufficient oxygen.

5.4 Thermochemical conversion processes

5.4.1 Combustion

Principle

During combustion the biomass reacts with an oxygen surplus, and carbon dioxide, water and ash are primarily produced. Heat is released in this process. Biomass combustion can be used in power stations in which heat is used to produce steam that drives a steam turbine. There are power stations in which mixtures of coal and biomass can be burned, but depending on the technology installed, biomass can also be used on its own. Biomass is also additionally used in boilers in which steam, hot water or only heat are produced for purposes other than the production of electricity. Households use biomass for fireplaces and barbecues. Waste is also incinerated and the energy produced is captured as usable heat. This process takes place in waste incineration plants (WIP).

Suitable raw materials

The most suitable biomass for combustion contains hardly any water and minerals. Coal-fired power stations want to use biomass pellets with a low mineral content as biomass for co-firing, such as wood pellets. This application will ensure that a significant share of sustainable biomass is accessible for use in the Netherlands and that the investments already made in industrial infrastructure are effectively utilised. The accessible biomass potential can be used in the medium term (when the infrastructure has been written off, and other sustainable energy sources have been sufficiently implemented) for alternative, high added-value applications in the bioeconomy.

In the Netherlands green waste, chicken manure and the remaining fraction of household waste is incinerated, after the removal of metals, glass and paper. The remaining fraction partly consists of biomass and partly of fossil-based flammable plastics. Furthermore, straw, lignin, paper slurry and cocoa shells are suitable for incineration. Apart from wood pellets, pellets made from straw-like biomass can also be used. However, at present the co-firing of non-woody biomass is subject to a maximum permitted level, set by the government. In the Netherlands most of the sludge from wastewater treatment plants is incinerated, but it does not produce any net energy because of its high moisture content (65-75%).

Products

Heat is the primary product of combustion and it can be used in various ways. Ash, which has a high mineral content, is also produced. Chicken manure incineration ash produces a high added-value fertiliser while the ash from co-fired power stations (consisting of a mixture of biomass and coal) is used in low-value added applications such as cement, concrete and road construction. Fly ash from waste incineration plants is used as an asphalt filler and bottom ash is used as embankment material in road construction. Research is currently being conducted into the extraction of specific minerals (phosphate) from ash. Flue gases form another ‘product’ and flue-gas scrubbing must be carried out before allowing these gases to be discharged into the atmosphere.

Experience

The Netherlands has 12 waste incineration plants, a few large power stations in which biomass can be co-fired with coal and more than one hundred smaller biomass incineration plants. The typical capacity of a waste incineration plant is 500-1,000 kton of residual waste per year. Large power stations produce roughly 800 MW_e from 3,000 kton coal/biomass per year. The smaller biomass incineration plants are often operated

by small and medium-sized enterprises (SMEs) and use a few hundred to thousands of tons of biomass per year. These plants produce energy for these enterprises.
A heat producing company, Warmtebedrijf Ede, supplies heat to 20,000 homes via a district heating system in Ede (the Netherlands). The heat can replace natural gas and is generated by three plants in which local pruning wood is incinerated. Each plant processes 30 to 90 tons of pruning wood per day and can produce 9 MW of heat.[52]

Figure 19. Biomass is co-fired in several coal-fired power stations.

Economy
The energy efficiency level of waste incineration plants is 25-30% (electricity and heat).[53,54] However, the operating costs of the businesses running these plants are higher than the energy yield and the yield of the separated waste streams. These businesses are therefore primarily waste treatment companies that charge a fee for the waste supplied. The electricity yield of coal-fired/biomass power stations ranges from 38% (older plants) to 46% (newer plants).[55] Coal is cheaper than wood pellets (factor 3-4 on an energy basis), making the production of electricity and heat from biomass more expensive. This is currently compensated in the Netherlands under the SDE+ subsidy scheme.

5.4.2 Gasification

Principle

During gasification biomass is usually converted into heating or synthesis gas at high temperatures (more than 600°C) in an oxygen-deprived environment. The gas mainly contains hydrogen, carbon dioxide and methane. It also contains pollutants related to the fuel type. These pollutants, for example hydrochloric acid, ammonia and hydrogen sulfide, occur in a reduced form and can be washed out relatively easily. Moreover, the carbon monoxide can be converted into carbon dioxide using a chemical process, producing even more hydrogen. The carbon dioxide produced can subsequently be separated through adsorption processes. Consequently, gasification is especially suitable for combining biomass conversion with the capture of carbon dioxide, which could potentially result in negative carbon dioxide emissions (see BECCS in Section 6.6).

Suitable raw materials

Gasification is suitable for relatively dry biomass streams (>85 % dry matter), often woody biomass. This could also be demolition wood, and chicken manure, as experience has shown.

Products

Although the above heating gas/syngas is the primary product, it needs to go through other conversion processes in order to make it into a usable product. Heating gas can be used as fuel for gas engines and gas turbines for electricity and heat generation. Syngas (hydrogen and carbon monoxide) can be used to synthesise chemicals. The most common process is methanization, in which hydrogen gas and carbon monoxide are converted into gas with a high methane content. The gas produced is called Synthetic Natural Gas (SNG), which can be injected into the natural gas grid after purification. All the material that is not converted into gas ends up in a remaining fraction called biochar, which has properties similar to activated carbon, and can be used as a soil enricher or as a fuel for heating the gasifier. The primary product can also be directly used, after purification, in the production of heat and electricity. Syngas can additionally be used to synthesise methanol, ethanol and dimethyl ether. The Fischer-Tropsch process (see Section 6.4.2) can be used to convert the gas into liquid hydrocarbons (usually alkanes). Methanol and ethanol can also be produced by variants of this process.

Experience

Wood gasification has been used for the production of gas for street lighting (gas lighting) since 1870 and in the 1930s motorcars were equipped with a wood gasifier.

The technology faded into the background after the 1940s. Hundreds of small wood gasifiers are now being used in Europe, for example, in hotels and for district heating. The capacity is limited to a few tens of kW. Only two large-scale wood gasifiers are currently operating in the Netherlands. In 1999, a wood gasifier with a demolition wood (B wood) processing capacity of 150,000 tons per year was built at the Amercentrale, a coal-fired power station in Geertruidenberg. The gases were used as fuel for the power station.[56] However, its operations were discontinued. Delfzijl used to have a plant that converted glycerol, a residue stream from biodiesel plants, into gas and then into methanol. From a chemical perspective, glycerol is an excellent raw material and could perhaps be better utilised for chemical or biological conversion into chemicals. Furthermore, a Dutch business has supplied a number of chicken manure gasifiers (capacity around 1MW) to customers in the Netherlands and abroad.

Economy

Although Smekens et al. (2017)[57] observed that there are few practical examples of biomass gasification in the Netherlands (or elsewhere), they have based their economic assessment on a typical scale of 11 million m^3 green gas/year (over 10 MW). The investment costs of these types of large plants range from €7 to €30 million for gasification, gas scrubbing and gas upgrading. This makes it difficult to implement while having to compete with cheap fossil sources. The energy efficiency of biomass to green gas is 65%.[57] If the gas produced is used in a gas engine, the electrical efficiency is expected to be 29% (green gas to electricity) and the energy efficiency (electricity plus heat) 76%. The electrical efficiency can be increased to 36% through interventions but this will adversely affect total energy efficiency, which will decline to 58%.[58] This implies that the efficiency levels approximate those of anaerobic digestion with gas upgrading.

5.4.3 Pyrolysis

Principle

In pyrolysis the biomass disintegrates under a high temperature in an oxygen-free environment. Although the production of charcoal (carbonisation) and torrefaction (see Section 5.4.4) are also slow forms of pyrolysis, the process referred to here is rapid pyrolysis at 500°C, during which around 70% of the biomass is converted into an oil and the remainder into biochar and gas. Rapid pyrolysis does justice to its name because the process takes no more than two seconds. The process is usually carried out in a fluidised bed reactor and does not need to operate under pressure.

Suitable raw materials

While pyrolysis can be carried out with a wide range of biomass types, the products, and in turn the raw materials, must meet certain requirements. From an economic perspective, residue streams such as agricultural waste, pruning wood and verge grass are ideal. However, the high mineral content in these types of biomass makes the pyrolysis oil unsuitable for use as fuel, but it could perhaps be used in the future as a source for the extraction of chemicals. The biomass may not contain too much water (less than 10%). Dried wood, dried manure, bagasse, rice husks, straw, palm oil residues, olive residues and dried sludge have been tested or specified. Tropical raw materials should preferably be pyrolysed in the country of origin, and the oil (with a high energy density) subsequently transported efficiently by sea to its destination.

Figure 20. Verge grass can be used in a pyrolysis process.

Products

The primary product of rapid pyrolysis is pyrolysis oil, a mixture of hundreds of components containing aromatic compounds (such as phenol), sugar derivatives, organic acids (such as acetic acid), and other substances. Like petroleum, pyrolysis oil can be used as fuel and as a source for a naphtha-cracking process in which chemicals can be extracted. A disadvantage is the high oxygen content which limits the quantity that can be added to a cracker unit. The oil has a far higher density than the original biomass, which is more convenient for storage and transport purposes. The gas byproduct is usually used to supply energy to the pyrolysis reactor and the biochar is used as a soil enricher.

Experience

The Netherlands only has a number of pilot plants and one large-scale pyrolysis plant, the world's first on a commercial scale. The latter plant, delivered by BTG Biomass Technology Group, produces 20,000 m^3 of oil per year which Friesland Campina uses as fuel for the production of steam and electricity.[59] Finland recently purchased four pyrolysis reactors and the complete plant will be built in the Netherlands.[60] Demonstration plants are located in the USA and Canada. Research is currently being conducted into a more controlled pyrolysis process, for example using catalysts or hydrogen additives, aiming at producing larger quantities of certain products.

Economy

According to www.ecp-biomass.eu,[61] the products of a typical pyrolysis plant in which relatively dry wood is used as input are:

- Pyrolysis oils: 0.55 GJ per GJ input
- Heat: 0.21 GJ per GJ input
- Electricity: 0.004 MWh per GJ input

The heat is used to dry the biomass. If the biomass input is very wet (>60% moisture), additional energy will be needed to dry it. The investment costs of the pyrolysis plant, excluding pre-processing and post-processing, amount to €200-300/MW$_{th}$.[61]

5.4.4 Torrefaction

Principle

Torrefaction (roasting) similarly involves breaking down biomass at a high temperature in an oxygen-free environment. However, the temperature used is only 200-400°C. During this process the biomass is dried and converted into solid substances, while gases are also produced. The gases are used to supply energy for the process. The process can be carried out in various reactors, such as rotating drums or band driers.

Suitable raw materials

In principle, torrefaction can be applied to many biomass types, but considerable experience has been gained primarily with wood and woody biomass.

Products

The primary product is biocoal (black pellets), which is drier than the original raw material (wood), has a higher density, a seven times higher energy density, is more water-resistant and can withstand biodegradation. The material is more coallike, which has considerable advantages over wood in terms of retention, storage and transportation. The material is suitable for gasification and co-firing in coal-fired power stations.

Experience and economy

A decade ago, a few large torrefaction plants operated in the Netherlands with production capacities of 60,000 and 90,000 tons of biocarbon per year, for use in large power stations. These operations were rendered unviable in the Netherlands due to the abolition of subsidies. Dutch knowledge and expertise are now employed to set up torrefaction plants in countries with large quantities of biomass (such as Estonia), while domestic use of the technology remains small-scale (businesses and households).

5.5 Chemical conversion processes

In chemical processes substances are converted into other substances, by reacting either with themselves or with another substance (reagent or reactant). Sometimes a catalyst is been added, a substance that increases the rate of chemical reactions without

Figure 21. Polylactic acid (PLA) is a frequently used bioplastic.

being consumed in the process. There are numerous of types of chemical reactions. A number of important chemical processes are briefly introduced in this section.

In the Netherlands many vegetable oils and animal fats are used to produce various substances. Vegetable oil consists of triglycerides, a reaction product between glycerol and fatty acids.

Soap is an example of a product made from vegetable oil. Soap production from vegetable oil is a centuries old process. Another example is the production of biodiesel. Although vegetable oil can be directly used as transport fuel, modifications need to be made to the engine. For this reason, the oil is usually converted into methyl esters of the fatty acids present. The resulting product is called biodiesel and its properties are similar to those of diesel. The production of fatty acid methyl esters from vegetable oil is a transesterification using methanol as a reactant. Along with the methyl esters, glycerol is produced as a residual product.

A route frequently used for the production of bioplastics involves producing the required monomers from biomass (with various processes), followed by polymerisation of the monomers into a polymer (long chain). This is the way in which biopolyesters like polylactic acid are produced, and also for instance biopolyethylene, which is identical in structure as fossil polyethylene.

Chemistry also plays a role in the production of substances and products from cellulose, such as carboxymethyl cellulose, viscose and cellophane.

Pulping is an important activity carried out in various countries. Wood and other lignocellulosic materials are pulped for the paper industry: almost all biomass is dissolved with chemicals except cellulose and part of the hemicellulose.[†] The cellulose fibres are the main raw material used in the production of paper and cardboard. Pulping operations were carried out in the Netherlands in the past but are now virtually non-existent.

As a considerable amount of biomass consists of lignocellulose, many processes have been developed in the past 20 years to make the cellulose, hemicellulose and lignin more accessible to enzymes or chemical catalysts. This is referred to as pretreatment, which is similar to the pulp process for paper and cardboard. It can be achieved in various ways. Primarily the hemicellulose can be partly hydrolysed at a high temperature

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[†] *See also the publication on Lignin in this series.*

Figure 22. Wood is pulped with chemicals for paper production.

(150-170°C) or using steam explosion, with or without an acid, to make the three polymers, cellulose, hemicellulose and lignin more accessible. Sodium hydroxide or organic solvents can be used to dissolve lignin and certain fungi can be used to break it down.

Another important chemical conversion that has disappeared from the Netherlands is leather tanning. Molecules of the protein collagen are crosslinked with a tanning agent, such as trivalent chromium, in the leather tanning process. This creates a strong complex that cannot easily be broken down biologically or otherwise.

5.6 Separation techniques

In addition to conversion and mechanical processing, separation is an important process for the conversion of biomass into components for use in chemicals, energy and materials. Certain target components often need to be extracted from a solution containing compounds, and be further purified. An example is the distillation of ethanol from a fermentation liquid. The separation of solid substances and liquids, such as pressing oil from seeds, extracting substances from biomass, such as lignin from wood, and separating particles of solid substance (sieving) is also regularly used in production processes.

Separation techniques are used in many sectors, including the chemical, food technology, waste treatment and water purification sectors, and are by no means unique to the processing of biomass.

6 New technologies

6.1 Introduction

In order to achieve a sizeable, technically and economically feasible bioeconomy, new technologies will need to be developed. New agricultural technologies are required in order to produce more biomass on the planet. Research is being conducted into improved land management, fertilisation and cultivation methods. One of the most significant developments is the improvement of photosynthesis in plants so that they can use light more efficiently and hence grow faster and achieve a higher yield. Various teams across the globe are working on bringing this to fruition. In addition, technologies capable of processing and converting biomass into products still require considerable improvement. The economic viability of many of the technologies presented in Chapter 5 is still poor, partly due to the low price of fossil fuels, and a considerable amount of research focuses on further developing and optimising them. In addition, new variants of these technologies are being developed and even entirely new directions are being pursued. An example of a new direction is the electrification of the chemical industry. New biomass-based products are also continuously being developed. These products sometimes have properties similar to those of known products based on fossil raw materials, but may also have completely new properties. Another route vigorously being pursued is the production of chemicals from biomass that are exactly the same as chemicals made from fossil raw materials, known as ‘drop-in’ chemicals, such as bioethanol and the bioethylene produced from it. The advantage of this route is that a market for these products exists.

This chapter further examines new developments, primarily in the Netherlands, in biological, thermochemical and chemical conversion and carbon dioxide capture, storage and utilisation.

6.2 New biological conversion processes

Notable Dutch research projects, in terms of new processes with biological conversions, include the production of medium-chain fatty acids (for example caproic acid) from acetic acid. In a process developed by Wageningen University and Research (WUR), organic residue streams are first biologically converted into organic acids and the organic acids are subsequently reacted with ethanol, to produce caproic acid in a second biological process.[62] A demonstration plant that can produce 1,000 tons of caproic acid per year started operations in Amsterdam. Caproic acid can be used as a crop protection agent, feed additive and for other purposes.

Reverdia (fully transferred to Roquette effective 1 April 2019) has developed a yeast-based fermentation process for the production of succinic acid.[63] The advantage of using yeast is that the process can be carried out with a low pH value so that little or no alkali is needed as an additive. An Italian plant produces 10,000 tons of succinic acid annually. This a relatively new development but is already operating on a large scale.

Figure 23. Cornstarch can form the basis for the production of chemicals such as succinc acid. The protein in the corn can be used in food.

An inescapable trend is the use of gases such as fermentation substrate, for example mixtures of hydrogen gas, carbon monoxide and carbon dioxide, which can in principle be produced from biomass. Significant progress has been made with mixtures of hydrogen gas and carbon monoxide for the biological production of ethanol.[64] Lanzatech operates a number of pilot plants in China that can produce 300 tons of ethanol per year.[65] Although these plants use gas from blast furnaces, in principle, gas from the gasification of biomass can also be used. Other alcohols and organic acids can also be produced from hydrogen gas and carbon monoxide.

Biomass can be used to produce biogas containing methane. Biogas is usually used as an energy source. However, methane can also be used as a substrate for the microbiological production of various chemicals. More experience is being gained in this area. Decades ago methane was used for the production of single-cell protein on an industrial scale, but the research now being carried out focuses on chemicals, such as lactic acid, the building block for the bioplastic polylactic acid. It is still on a laboratory scale,[66] as is the bacterial conversion of carbon dioxide into lactic acid. The economic replacement of the conventional production of lactic acid by fermentation will, however, be a challenge.

The production of polyhydroxyalkanoate (PHA) is still too costly. To resolve this issue, research is being conducted into more cost-efficient processes, cheaper substrates and more valuable forms of PHA, for example with long-chain alkanoates.[67,68] The production of PHA from methane is also being explored.[69]

One of the greatest wishes of the bioeconomy is to replace the plastic polyethylene terephthalate (PET), known from softdrink bottles and textile fibres, which is currently produced from fossil raw materials. A prime candidate is polyethylene furandicarboxylate (PEF). Corbion has a biological process for producing furandicarboxylate from furan, a sugar degradation product.[70] Avantium has developed a chemical route (see Section 6.4.1) for the production of furandicarboxylate from sugar.

In addition to using new substrates and facilitating ‘new biological conversions’, innovations are taking place in the genetic modification of the relevant micro-organisms. The aim of genetic modification is to let the organism do what we want it to do. Genetic modifications can be carried out more precisely with new techniques such as CRISPR-CAS.

6.3 New thermochemical processes

One of the innovations various research institutions and businesses are working on is the gasification of biomass in supercritical water. The biomass must be dry enough in the conventional gasification process, which restricts its area of application. However, it is now clear that this is not case if the process is carried out above the critical point of water. The critical point is a term used in the field of thermodynamics. It is a combination of one specific temperature value, pressure, composition and optionally other thermal dynamic variables, that cause a substance or mixture to display special behaviour. The critical point of water is 218 bar and 374°C.[71] If the pressure and/or temperature are higher, the process is carried out in the supercritical area. The properties of water change around the critical point so that biomass with a moisture content between 70-90% can still be processed. Under supercritical conditions there no longer is any difference between liquid and gas. Consequently, there is no need to evaporate the water. In this process almost all of the biomass can be converted into hydrogen gas, methane, carbon monoxide and carbon dioxide. On top of that, the byproduct tar is no longer produced. Although the high pressure may seem costly, a compressor is no longer needed for the downstream processes either. One of the problems is the precipitation of minerals under these conditions, which can cause blockages. The process is only being tested in the laboratory and in pilot plants. The Aa and Maas Water Authority has such a pilot plant for the gasification of sewage sludge.[72]

6.4 New chemical conversion processes

6.4.1 Carbohydrates as raw material

In order to produce the bio-based plastic PEF referred to earlier, Avantium has developed a process for producing furandicarboxylate from glucose in a series of chemical steps. As this process was recently proven on a pilot-plant scale, the company plans to launch the large-scale production of furandicarboxylate within a few years.[73]

In the Netherlands, considerable attention is also being devoted to finding an alternative for aromatics, which are now produced from petroleum, usually as a byproduct of the oil refining process. Due to the shrinking petroleum-refining capacity arising from the switch to natural gas (from Qatar and other countries) and shale gas, a shortage of aromatics is looming. At the same time, there is a wish to produce aromatics sustainably in the form of bioaromatics, for example. Under the BIORIZON programme, technologies are being developed for the conversion of carbohydrates and lignin from biomass into bioaromatics.[74] Lignin is one of the largest sources of aromatic compounds on the planet. Research is also be carried out on the application of sugars from food industry residue streams, for instance from sugar beet pulp (Pulp2Value).[75]

6.4.2 Gases as raw material

Another promising development is the Fischer-Tropsch process which uses bio-based raw materials. A mixture of carbon monoxide and hydrogen gas can be converted in the presence of a catalyst into a liquid fuel consisting of hydrocarbons. In practice, the gas mixture, also known as syngas (synthesis gas), is usually extracted from coal (CTL: coal-to-liquids) or natural gas (GTL: gas-to-liquids). Large-scale Fischer-Tropsch facilities are located in South Africa, Qatar and Malaysia. The bio-based alternative is BTL (biomass-to-liquids), in which the Fischer-Tropsch process or other processes that produce methanol or ethanol are applied. No commercial BTL facilities exist at present, only pilot plants. However, in Germany a fairly large demonstration project was carried out, in which a facility operated with a capacity of 15,000 tons of fuel per year.

The electrification of the chemical industry is a new trend in biomass utilisation. Electricity produced from renewable sources (biomass, wind, sun) can be used to carry out electrochemical conversions: converting a substance into another substance using electric power. On top of that, the raw materials can be derived from biomass or from another renewable source. Nowadays, there is a strong focus on basic compounds such as methane, water, oxygen, nitrogen and carbon dioxide. For example, an electrochemical process can be used to produce methanol from methane. An alternative has been developed for the production of formic acid, for which fossil sources are currently used. This alternative converts carbon dioxide into formic acid with renewable electricity. These types of conversions are currently being researched on a laboratory scale, including under the Dutch VoltaChem programme.[76] Various research programmes are also engaged in the development of artificial photosynthesis.[‡]

6.4.3 Lignin as raw material

Large quantities of lignin are released during the paper pulping process and are expected to rise sharply when lignocellulose biorefineries enter the arena. To date, lignin is largely used as fuel, while lignosulfonates are used as a binder or plasticiser in concrete. The small quantities of lignin released from the soda pulping of straw are used in glue. The R&D activities, focusing on the development of processes that use lignin as raw material for the production of chemicals and materials, are now rapidly expanding. In the new processes, lignin is used in such a way that it is broken down into monomers or modified, making use of the polymer structure.

An example is the use of lignin to replace bitumen in asphalt. Lignin has binding properties similar to the fossil-based bitumen, the sticky, tar-like substance in asphalt.

Figure 24. Lignin is a source of aromatic compounds (photograph: WFBR).

[‡] *See also the Dutch publication on Artificial Photosynthesis in this series.*

The research has now progressed to the stage where mixtures of lignin and asphalt have been used to build trial sections of road and a cycle track.[77]

An example of modification in which the polymer structure is retained is the manufacture of lignin-based carbon fibres. These fibres are suitable for use in high added-value composites. Activated carbon can also be produced from lignin. Research is being conducted into modifying lignin by coupling functional groups to it (carboxymethyl ring, amine ring), which changes its properties.

Figure 25. A cycle track with lignin asphalt was opened at the Wageningen University Campus in 2017 (photograph: Marte Hofsteenge).

Most of the research focuses on lignin depolymerisation, in other words producing smaller molecules (monomers), often with an aromatic character. Pyrolysis, for instance, can be used to cut up polymer chains (see Chapter 5). A considerable amount of research focuses on controlling degradation by selecting the right catalyst.[78] Lignin molecules can also be broken up using acid or lye at a high temperature under pressure. This often produces molecules that still contain oxygen, which is undesirable for certain applications, such as stable high added-value liquid fuels and applications that need a lower boiling point. Research has shown that the oxygen can be removed by allowing the products to react with hydrogen in the presence of a metal catalyst.[78] By contrast, a large amount of oxygen is required for some applications, for example if organic acids have to be produced. Lignin can then be polymerised and oxidised with ozone or hydrogen peroxide in the presence of a metal oxide. All these processes have been tested on a laboratory scale.[78] The greatest challenge posed by this development is that always a mixture of monomers is formed, which is caused by the heterogeneous composition of lignin. Numerous research activities focus on finding catalysts that allow certain products in the mixture to become dominant. The opportunities for this

Example of a cascade

Meerlanden: the green energy factory

Dutch waste treatment company Meerlanden processes vegetable, fruit and garden waste (SSO, Source Separated Organics) into a range of products. Anaerobic digestion and composting play a key role in the treatment process. This produces useful products such as citrus oil, green gas and compost. Other products are heat which is used in greenhouse horticulture, brine for de-icing roads and water to clean streets (road sweepers). There are plans to start using the carbon dioxide, which is extracted as a concentrated gas, in greenhouse horticulture. A flow chart of the cascade including the quantities processed and produced in 2017 is shown below.[46]

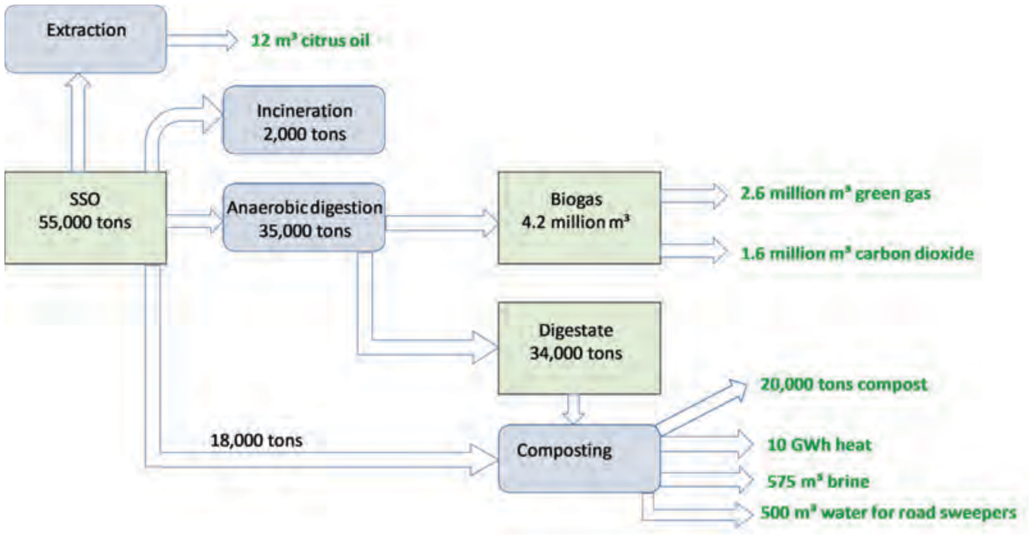


Figure 26. Example of a cascade for Dutch waste treatment business Meerlanden.

polymerisation route lie primarily in the production of aircraft fuel and the replacement of phenol, for instance in phenol formaldehyde resins. [78]

6.5 Biorefining and cascades

Multiple products can be made from any type of biomass. The set of processing operations should therefore be organised in such a manner that these products can be extracted cost efficiently. This is referred to as biorefining: the sustainable processing of biomass into a range of marketable products and energy. Biorefining is similar to the processes we have known from the oil industry for more than a century: oil refining, in which crude oil is partly separated into lighter and heavier fractions, but also conversions are performed (cracking). An example of biorefining is the extraction of native protein from vegetable processors' residue streams. The protein extracted represents a high value, yet only a small mass share of those vegetables. The residue can be digested to produce biogas. However, not all vegetable components are thoroughly digested. The digestate can be thickened and composted to produce a third product: compost. Potatoes can also be refined. Avebe extracts not only starch from potatoes but also Solanic, a protein with gel properties suitable for replacing animal proteins in certain foods.

A specific order is often used when extracting products from biomass: the product with the highest value is extracted first and then products with a lower value. This is a form of cascading. In the best cascades, the biomass is fully utilised (see also Figures 26 and 27).

6.6 Capture, storage and utilisation of carbon dioxide

One of the reasons why we want to use biomass instead of fossil sources, is to reduce emissions from the long-term cycle of carbon dioxide (see also Chapter 1). Although the utilisation of biomass as an energy source generates carbon dioxide emissions, the same quantity of carbon dioxide was removed from the atmosphere in the preceding years by plants, and will be removed from the atmosphere once again in the coming years by the renewed growth of plant material. This creates a short cycle of a few years, with low net carbon dioxide emissions. These net carbon dioxide emissions could even become negative, if the carbon dioxide produced in biomass-fired power stations and biorefineries is not discharged into the atmosphere, but captured and stored underground. The technique for capturing and storing carbon dioxide (CCS) is known primarily from experiments with flue gases from coal-fired power stations. These gases contain 10-15% carbon dioxide.[80] In CCS, the carbon dioxide from flue gases is captured by gas scrubbers using amine solutions, subsequently released in concentrated form and transported to a location where it is stored underground in a stable geological formation.

Example of a biorefinery

Borregaard: wood products

Borregaard, a Norwegian company, has a biorefinery in Sarpsborg. This plant, which has been operating for over half a century, uses wood as raw material. Sulphite pulping is central to the production process. The following primary products are produced from 1,000 kg DM spruce chippings:[79]

- 400 kg cellulose for clothing, paint, construction material and cosmetics
- 400 kg lignosulfonate for concrete (additive), animal feed and pigments
- 50 kg ethanol for medicines, car care products and fuel
- 3 kg vanillin for food, perfume and medicines

In addition, the residue streams are converted into energy carriers. A simplified flow chart of the production process is shown below.

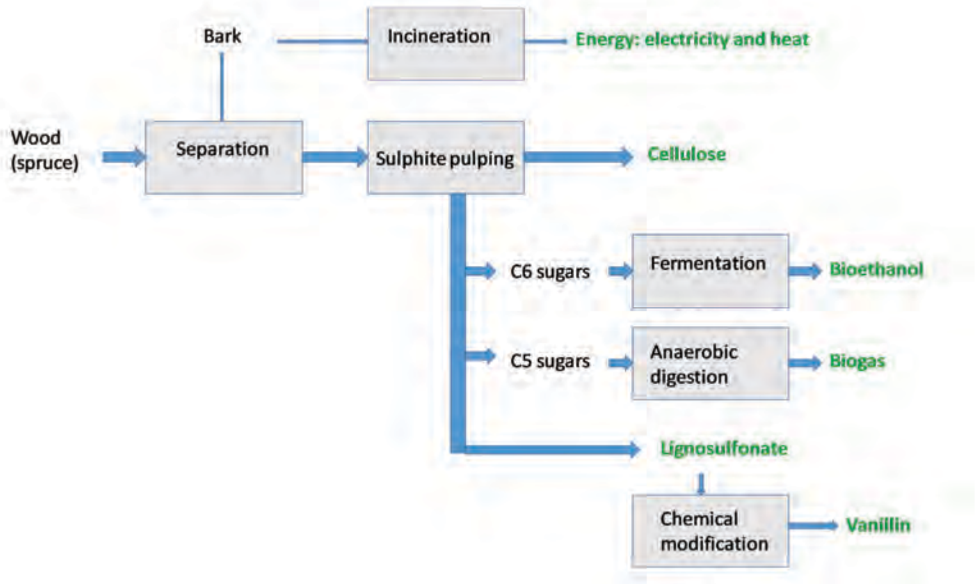


Figure 27. Example of a wood-based biorefinery.

The first demonstrations of CCS were carried out in Norway as far back as 1996. In 2018, 23 large-scale CCS facilities operated worldwide or were under construction, collectively accounting for 40 Mton carbon dioxide storage per year.[81] This represents 0.1% of global carbon dioxide emissions. However, this method still poses two major problems: costs and safety. Capturing carbon dioxide from flue gas from coal-fired power stations consumes more than 20% of the energy produced by these power stations. Experiments are being conducted with more efficient absorption agents. There also are safety concerns about carbon dioxide seeping through the ground from the underground storage facility. Improvement of the technology and more experience are therefore required. CCS is anything but a fully-fledged technology.

If you apply CCS to facilities that convert biomass into energy (and carbon dioxide), what you get is bio-energy with carbon capture and storage or BECCS.[82] Six large-scale BECCS facilities are currently operating worldwide, all of which are bioethanol plants and household waste incineration plants. The major advantage of BECCS for bioethanol plants is that the carbon dioxide has a concentration of nearly 100%, which saves on CCS energy consumption. The largest project being carried out since 2017 is at a bioethanol plant in Illinois, where one million tons of carbon dioxide is stored underground in sandstone.[83] In the Netherlands, a pipeline is currently being built for carbon dioxide from various sources for injection into depleted North Sea gas fields. It has a capacity of 2.5 Mton of carbon dioxide per year.[83] BECCS also seems be suitable for biomass-fired power stations. A pilot plant project for the capture of carbon dioxide has been operating at the biomass-fired power station in Drax, England, since February 2019.[84] However, it is a technology that comes with a considerable price tag.

Instead of storing carbon dioxide it can also be put to use. This is known as CCU (carbon capture and utilisation) and its uses include:

- Converting it into fuel, for example using algae or solar fuel technologies. Solar fuels, basic organic substances, can be produced from carbon dioxide and water with the aid of sunlight, using chemical technology.
- Converting it into chemicals and materials such as methanol, polycarbonates, acetic acid and urea.
- Converting it into calcium carbonate or magnesium carbonate which is used as construction material.
- Using it for optimising oil extraction in oil fields: injecting carbon dioxide into the field sets the oil in motion.
- Using it in greenhouse horticulture for faster plant growth.

The techniques stated under the first three points of the list are still in the development stage. More experience has been gained with the use of carbon dioxide from biorefineries for greenhouse horticulture. A bioethanol plant in the vicinity of Rotterdam supplies 100 kton carbon dioxide annually to greenhouse horticultural businesses, whereas a waste incineration plant in Duiven extracts 50 ton carbon dioxide each year from flue gas that is also used in greenhouse horticulture.[83]

For the sake of completeness, it should be noted that research is additionally being conducted into the direct capture of carbon dioxide from the air (outside air). One method that can be used for this purpose is absorption in caustic soda. After absorption, the lye is heated releasing the carbon dioxide in concentrated form, which can then be stored. Another method that works is adsorption on the surface of amine-based particles. After heating under a vacuum the carbon dioxide is released in concentrated form. Separation with membranes is a third method, and a completely different approach is the reaction of carbon dioxide with magnesium from stone with a high magnesium silicate content (such as olivine). It is then sequestered as a mineral. All these methods are still in their infancy and have high energy consumption levels (higher than CCS from flue gases), caused by the low concentration of airborne carbon dioxide (0.04%).

The carbon dioxide concentration in the atmosphere can also be affected by changes in land use. The Intergovernmental Panel on Climate Change (IPCC) has written several articles on this topic and calls the effect LULUCF (land use, land-use change and forestry). The transformation of forests into agricultural land, for instance, causes net carbon dioxide emissions.

7 How the application depends on the type of biomass

7.1 Introduction

Chapter 4 provides an overview of the current availability of biomass, and describes a replacement scenario in which all fossil raw materials are replaced by renewable raw materials, including biomass. Given that there are limits to the production and release of sustainable biomass for the bioeconomy, it is important that biomass is used in areas where there are no good alternatives for the production of all the products we need. This chapter presents a qualitative picture of the most efficient and logical use of biomass in the bioeconomy, for the applications in human consumption, animal feed, energy, materials, chemicals, compost and soil improvement. For reference purposes, figure 28 provides an overview of the current worldwide use of biomass and fossil raw materials in the various applications.

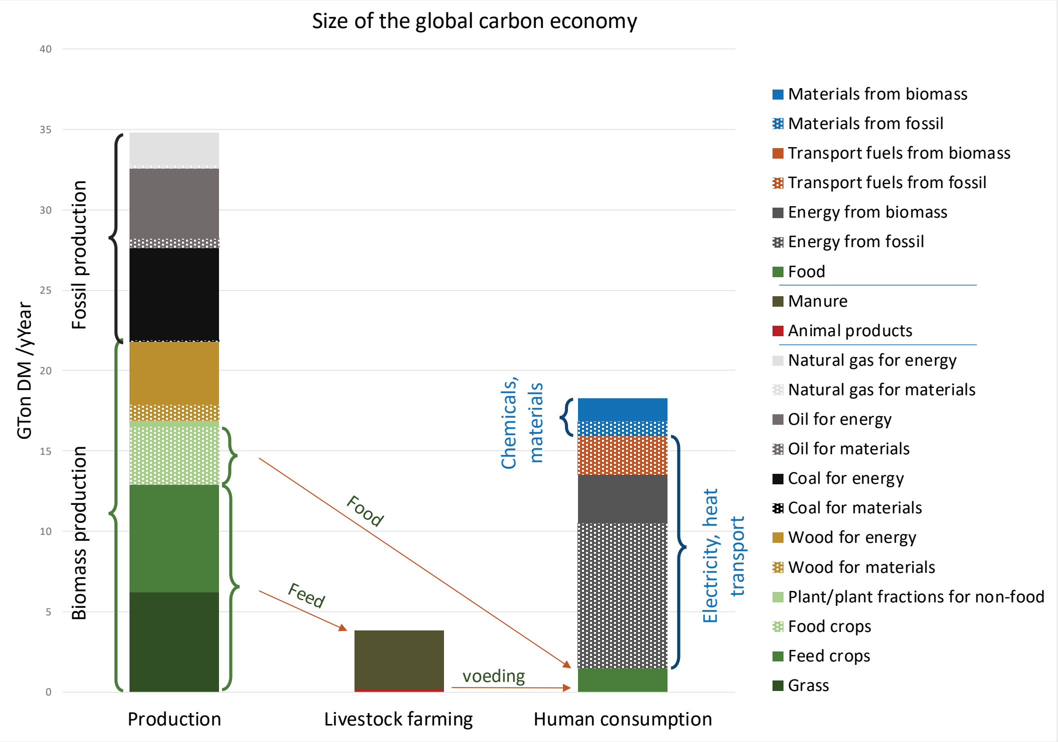


Figure 28. Current worldwide production volume of biomass and fossil raw materials and application of these raw materials.

7.2 Biomass properties in relation to suitable applications

7.2.1 Biomass properties are the determining factor

The application and transportability of biomass depends on its physical and chemical properties and legal status. The following sections provide more information on these aspects. Figure 29 contains an overview of the relevant properties of various types of biomass and biomass products. Figure 30 links a suitable application and or type of processing to those properties.

7.2.2 Moisture content

Wet biomass is unsuitable for thermochemical processes, such as pyrolysis and gasification, because of the extra energy needed to heat the water.[85] The permissible limit for gasification is a moisture content of around 15%.[86] Incineration, for example in power stations, also is less efficient when the biomass is wet. If raw materials have to be transported or stored for weeks, wet biomass is unsuitable on account of the storage costs and durability. However, wet biomass is suitable for anaerobic digestion and as raw material for fermentation processes or ensilage.

Examples of wet biomass are grass, vegetable, fruit and garden waste (SSO), manure, foliage, sugar beet, potatoes, vegetable and fruit residue streams, algae, aquatic plants and sludge from sewage treatment plants. Dry raw materials are wood, sawdust, vegetable oil, straw, seeds, waste paper, sugar and grains.

7.2.3 Density

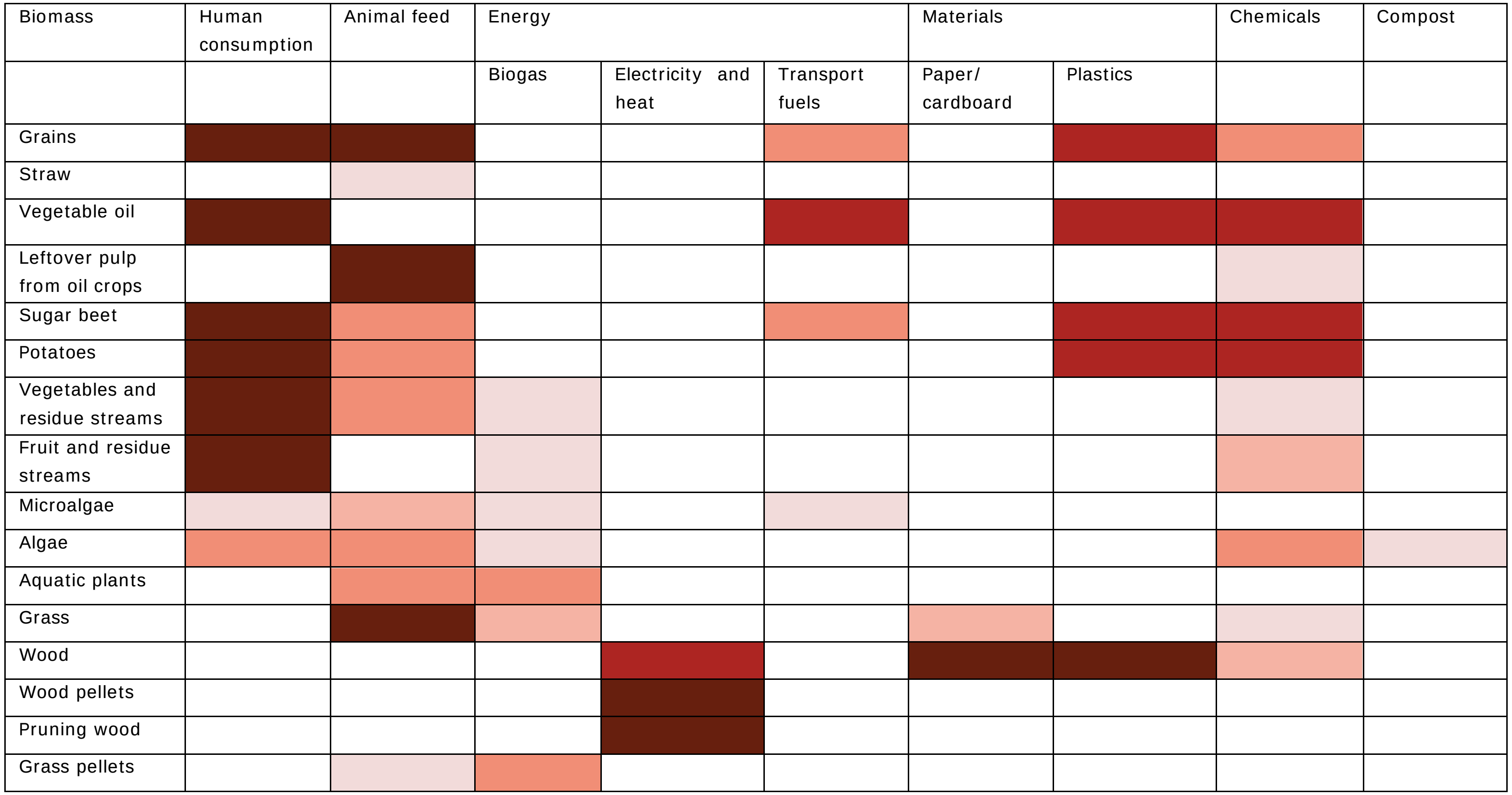
If a low moisture content can be combined with a high density (ton/m^3), this is favourable for transportation, imports and exports, and handling in general. High densities are achieved with wood pellets, grass or straw, wood, torrified biomass, vegetable oil, sugar and grain. These densities are also achieved with derivative products such as pyrolysis oil, methanol, ethanol, butanol and liquid methane. Loose straw and bagasse are less favourable.

7.2.4 Carbohydrate content

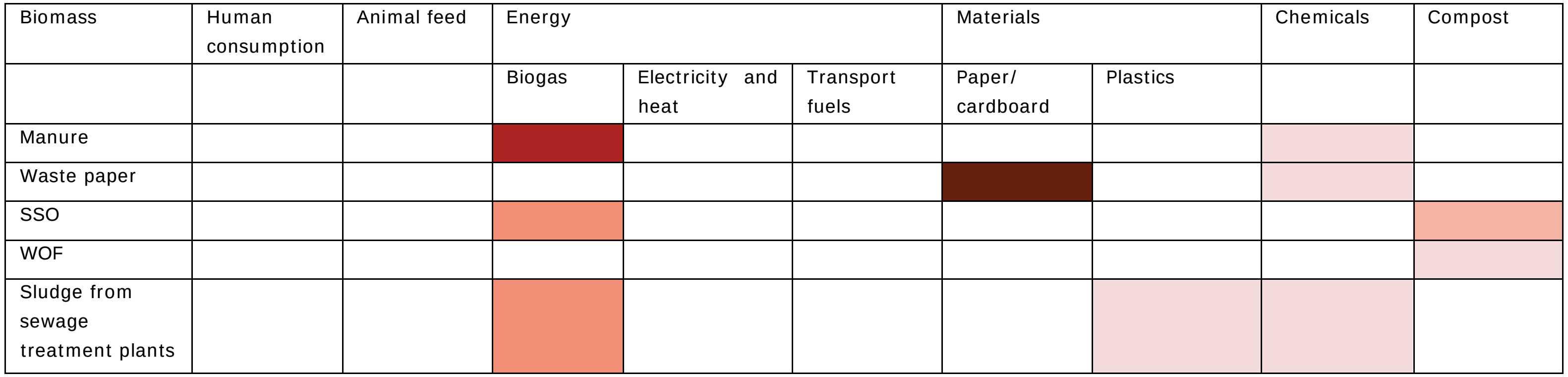
Carbohydrate-rich raw materials, such as grains and sugar beet, form an important basis of our diet. They also are important raw materials for the chemical industry that can be used to produce the chemical building blocks for materials or transport fuels, by means of chemical conversion or fermentation.[87] Sugar and grain are good raw materials for the fermentation industry. They can, for instance, be used for the production of ethanol, lactic acid (building block for PLA), butanol, succinic acid (for the production of PBS, a biodegradable bioplastic with properties similar to those of PP), amino acids and various other organic acids.

Biomass	High moisture content	High-density DM	High carbo-hydrate	High protein content	Fibres	High oil content	High mineral content	Waste status
Grains		🟩	🟩	🟩				
Straw					🟩		🟩	
Vegetable oil						🟩		
Leftover pulp from oil crops				🟩				
Sugar beet	🟩		🟩				🟩	
Potatoes	🟩		🟩	🟩				
Vegetables and residue streams	🟩		🟩					
Fruit and residue streams	🟩		🟩					
Microalgae	🟩			🟩		🟩		
Seaweed	🟩		🟩				🟩	
Aquatic plants	🟩			🟩				
Grass	🟩			🟩	🟩		🟩	
Wood		🟩			🟩			
Wood pellets		🟩			🟩			
Pruning wood		🟩			🟩			
Grass pellets		🟩			🟩		🟩	
Straw pellets		🟩			🟩		🟩	
Torrified biomass		🟩						
Foliage	🟩							
Manure	🟩						🟩	
Waste paper								🟩
SSO	🟩					🟩	🟩	🟩
WOF	🟩					🟩	🟩	🟩
Sludge from sewage treatment plants	🟩			🟩		🟩	🟩	🟩

Figure 29. Properties of the various biomass raw materials.



Biomass	Human consumption	Animal feed	Energy			Materials		Chemicals	Compost
			Biogas	Electricity and heat	Transport fuels	Paper/ cardboard	Plastics		
Grains	█	█			▒		▓	▒	
Straw		▫							
Vegetable oil	█				▓		▓	▓	
Leftover pulp from oil crops		█						▫	
Sugar beet	█	▒			▒		▓	▓	
Potatoes	█	▒					▓	▓	
Vegetables and residue streams	█	▒	▫					▫	
Fruit and residue streams	█		▫					░	
Microalgae	▫	░	▫		▫				
Algae	▒	▒	▫					▒	▫
Aquatic plants		▒	▒						
Grass		█	░			░		▫	
Wood				▓		█	█	░	
Wood pellets				█					
Pruning wood				█					
Grass pellets		▫	▒						



Biomass	Human consumption	Animal feed	Energy			Materials		Chemicals	Compost
			Biogas	Electricity and heat	Transport fuels	Paper/ cardboard	Plastics		
Manure			▓					░	
Waste paper						█		░	
SSO			▒						▒
WOF									░
Sludge from sewage treatment plants			▒				░	░	

Figure 30. Suitable applications and types of processing for biomass types and biomass products in the future; white is unsuitable, dark is extremely suitable. Construction wood and animal bedding are not included.

The use of grain and sugar outside the food market is controversial, but new sustainability studies have shown that there is no advantage in using second-generation raw materials (such as lignocellulose) over first-generation raw materials such as grain and sugar beet.[88] Due to the abolition of the EU sugar production quotas in 2017 plus the increase in yields, there currently is a sugar surplus in the EU. In addition, sugar sales for the food market are set to decline. The expectation is that the EU will become a net sugar exporter[88] and that there will be scope for the use of first-generation sugars in the chemical industry.

7.2.5 Protein content

Protein has a disruptive effect in combustion and thermochemical processes due to the NH_3 and NO_x produced, which can corrode materials and have a negative environmental impact. In digestion and fermentation processes the presence of moderate quantities of proteins can be favourable. Protein, however, is beneficial for animal feed. Grass, oilseeds and the derived pulp, nuts, vegetables, microalgae, sludge from sewage treatment plants and grains are high in protein.

7.2.6 Fibres

Wood, grass, straw and stalks consist of cellulose, hemicellulose and lignin fibre structures and can be used in material applications requiring those structures, such as paper, cardboard and building materials. Specific fibre crops such as cotton, flax and hemp contain strong fibres that can be used for textiles and in composites.

7.2.7 Vegetable oil

Vegetable oil primarily is a raw material for human food. It is also used in the chemical industry, for instance for the production of surface active substances, for alkyd paint and for products such as linoleum. Vegetable oil can also be used as transport fuel. The relevant biomass streams are palm oil, oilseeds (soy, sunflower and olive seeds) and waste cooking oil.

7.2.8 Mineral content

In many applications the fraction of minerals in biomass is disruptive, particularly in combustion and thermochemical processes. Biochemical processes, such as digestion, composting and fermentation processes are less sensitive to minerals. Mineral-rich biomass is represented by the wet organic fraction (WOF) of household waste, SSO waste, manure, straw, grass, sugar beet, seaweeds and sludge from sewage treatment plants.

7.2.9 Waste status

Certain types of biomass have the legal status of waste, which means that the type of processing and application of the products are restricted. The reason is that the composition of the biomass cannot be checked and the biomass might be microbiologically or chemically contaminated. Rules also apply to the recycling of meat waste to prevent diseases (BSE) and to SSO waste, WOF, waste paper, supermarket waste, swill and sludge from waste treatment plants. This rules out an application in food or animal feed and many customers are disinclined to use the products in all kinds of materials. Restrictions equally apply to imports and exports. Manure does not qualify as waste but is subject to specific regulations.

7.3 Importing biomass

If biomass needs to be imported into the EU due to insufficient availability (which is highly likely), biomass will have to be transported from areas located at a considerable distance from the Netherlands. In order to limit the transport costs and energy consumption of overseas biomass shipments to less than 10% of the costs and energy content of the biomass, the biomass transported must have a high density. Suitable materials include wood pellets, straw, bagasse or grass, torrified biomass, pyrolysis oil, liquid methane, alcohols (methanol, ethanol, butanol), sugar and grain.

The advantage of upgrading biomass to semi-finished products (pellets, ethanol, methane, oil) at the cultivation site, is that it is easier to return the minerals from there as fertilisers to the plantations. Pellets can therefore be made not only from wood waste but also from straw and grass. The latter two streams are washed first to lower the mineral content. This is a requirement particularly for many thermochemical applications. Such processes should be optimised before they can be economically applied.

7.4 Use of domestic biomass

Chapter 3 states that a beneficial use has often already been designated to the biomass harvested in the Netherlands. However, there still is room to designate a higher value use to part of the biomass or to increase the yield. This is especially the case for the biomass derived from the natural environment and waterways, wet residue streams from agriculture and horticulture, manure and SSO waste. These streams are currently used as soil improvers, sometimes for the energy supply and sometimes as animal feed. However, the share in the energy supply can still be expanded and these biomass streams can even be used to produce chemicals. Multiple R&D and demonstration projects are being carried out in this field in the Netherlands.

7.5 Non-utilisation of biomass is unfavourable

Biomass that could have, but nonetheless has not been released for use in the bioeconomy, makes no contribution to the replacement of fossil fuels. On top of that, various other adverse effects may arise from unutilised biomass. In the best case scenario, easily degradable biomass left at the harvest location will be converted into carbon dioxide and water with oxygen from the air. This essentially comes down to combustion without extracting useful energy for people.[§] Examples are verge grass left on the side of the road and aquatic plants dumped on shores. In a worst-case scenario, under oxygen-free conditions, deeper into the pile of biomass or deep underground (one decimetre), the biomass can start to rot and release methane. The methane is gaseous and is discharged into the atmosphere, which has a serious impact. The greenhouse effect of methane is 25 times higher per kilogram than that of carbon dioxide.[89] Aquatic plants that sink to the bottom of a lake or water course are rapidly converted into methane, which forms methane gas bubbles that travel into the atmosphere. But isn't this just a natural process? No, it’s not, because the Dutch surface water is over-fertilised, causing abnormal quantities of aquatic plants to grow in it. Even fertilising land with manure or injecting it into the soil often produces methane emissions. The preferred route would be to channel these methane emissions into an anaerobic digestion plant that can capture methane. The methane can be utilized as biogas.

Rotting aquatic plants

Five tons of aquatic plants (DM) can easily be produced per hectare of Dutch surface water per year.[90] Utilising these plants for anaerobic digestion will produce a quantity of biogas per hectare that can replace 1.5 tons of natural gas. This will save emissions of as much as 3.6 tons of CO_2-equivalents However, if all these aquatic plants sink to the bottom and rot away, 1.3 tons of methane can be produced, generating emissions of 33 tons of CO_2 equivalents.

[§] *It should be noted that in order to maintain the level of carbon in the soil, part of the less easily degradable biomass, such as the lignocellulosic components, should be left on the land, or other carbon sources should be fed back for this purpose.*

8 Use of biomass in the various applications

8.1 Introduction

As highlighted in the previous chapter, there is a rationale behind the use of biomass in the various applications, that is dictated by the specific properties of the biomass. In this chapter we discuss the most logical use of biomass for the various areas of application.

8.2 Human consumption

Our food is always produced from biomass. The use of biomass for food therefore has the highest emotional value. However, in food production a large quantity of biomass is produced as a residue stream that is unfit for human consumption.[91] These biomass residues are partly used for animal feed, but can often be put to good use as raw material for the bioeconomy. In addition, the residue streams generated by the food processing industry can also be utilised.

8.3 Animal feed

Besides side streams and residue streams from the food industry (scraps, brewers spent grains), crops are used for animal feed (grass, silage maize). Animal feed accounts for a far larger quantity of biomass than the quantity used directly for human food.[92] The production of biomass for animal feed can be reduced by reducing meat consumption, creating more room for the production of other types of biomass for the bioeconomy.

8.4 Energy

Biogas

Wet, low-value biomass streams can be converted (via anaerobic digestion or methane fermentation, see Chapter 5) into biogas containing methane in a biological process. A thermochemical process can be used for dry biomass types (less than 15% moisture content), in which methane gas is also produced (gasification, see Chapter 5). Both types of gas can be upgraded to a product that mainly contains methane. Like natural gas, this gas can be liquefied by cooling (-162°C), which reduces the volume by a factor of 600. This is a routine operation for natural gas stretching back 50 years. In 2017, 29 million tons of liquefied natural gas (LNG) was shipped worldwide from Qatar and other countries. Rotterdam (Maasvlakte) has an LNG terminal where the liquid can be reconverted into gas and added to the natural gas grid.

Biogas can therefore be used as fuel for the production of electricity and heat, or for the production of LNG. Anaerobic digestion can be used to process mainly low-value, wet biomass streams which are unsuitable for other uses into a useful product. The final product is biogas, which is similar in purified form to natural gas, and that can be injected into the natural gas grid and broadly applied. This combination makes anaerobic digestion a valuable technology for the bioeconomy.

Electricity and heat

Dry low-mineral, high-density biomass streams, such as wood, that can be incinerated in the current coal-fired power stations, should preferably be used to produce electricity and heat from biomass. Torrefaction also produces a product (biocoal) that can be used as fuel for power stations. The biocoal produced by torrefaction is water-resistant (which is convenient for transportation and storage) and has a higher energy density than the original biomass. Lastly, biomass pyrolysis can be used to produce pyrolysis oil for electricity and heat generation.

Given that electricity and heat cover a large part of our energy demand (Figure 28), it is essential that, in addition to biomass, other forms of renewable energy such as sun and wind make up part of the total quantity needed, especially if passenger transport switches to electric. Solar panels and solar-powered water heaters in homes make a small contribution in absolute terms to the total demand for electricity and heat, but it is one way consumers can contribute to the transition from fossil fuels to renewables.

Transport fuels

Different types of transport fuels are used for passenger transport, heavy road transport, maritime transport and air transport.

Various types of renewable alternatives are available for passenger transport, such as biogas, hydrogen gas, biodiesel, bioethanol or electricity. Large car makers have meanwhile overwhelmingly decided to transition to electric drive vehicles, and the expectation is that the vehicle fleet will consist of electric vehicles in the future. Electricity is still produced on a large scale by coal-fired power stations (possibly co-fired with biomass) but biomass-free alternatives are also available.

Electricity is unlikely to offer a solution for heavy road transport, maritime transport and air transport, and alternatives are being sought for heavy duty diesel, fuel oil and kerosene. These alternatives, so-called advanced biofuels, will need to have a number of properties including a high energy density and a large radius of action. Biomass is expected to play a role in this.

A daunting technical challenge that lies ahead for the air transport sector is the replacement of kerosene by a renewable energy source. Discouraging flying as a mode of transport by significantly increasing air fares will partly contribute to solving this problem, especially if more environmentally friendly alternatives are available for short-haul flights, such as the train. The expectation is that biomass will continue to be needed for the production of renewable alternatives for kerosene.

8.5 Materials

Biomass is required for the production of paper and cardboard. Woody biomass is mostly used but other biomass types such as herbaceous species are equally suitable as raw material. The production of paper and cardboard could rise in the years ahead, especially if the replacement of plastic packaging by paper-based packaging materialises.

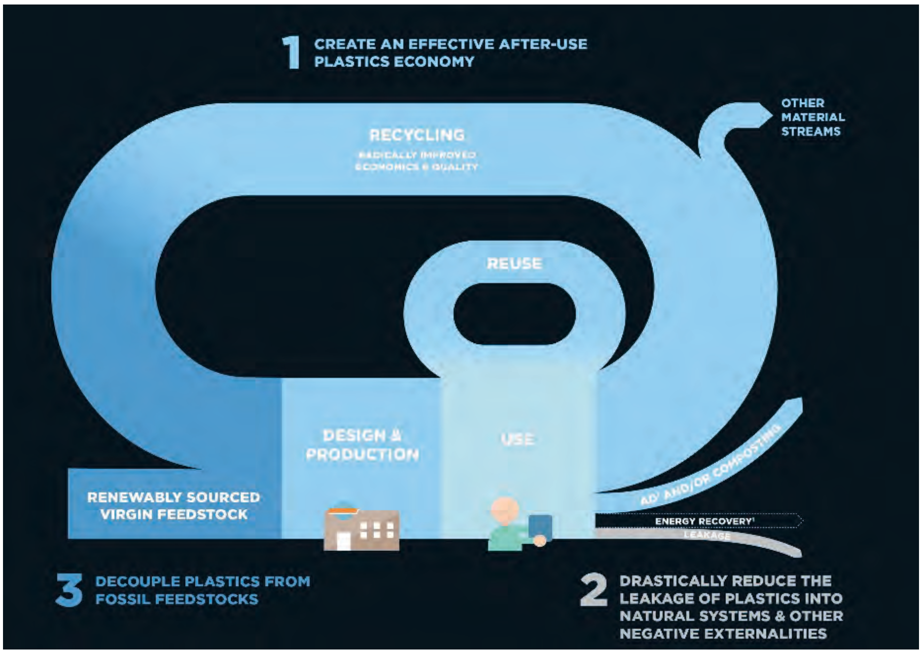


Figure 31. The 'new plastics economy' (Ellen MacArthur Foundation).[93]

Wood is an important raw material for construction material, furniture, floors, stairways, etc. Apart from high added-value wood products, forests produce side streams, such as bark, sawdust and branches that can be put to good use in the bioeconomy.

Although the current contribution of biomass to plastics production is minor, less than 1% of the total,[94] it could increase significantly if the transition of plastics from fossil to renewable raw materials materialises. The Ellen MacArthur Foundation outlines what the new plastics economy could look like (see also Figure 31).[93] The three most important elements of the new plastics economy are:

- All plastics must be circulated as far as possible (recycled) in equivalent applications.
- The leakage of plastics into the environment must be prevented.
- The production of virgin plastics will be uncoupled from fossil raw materials.

Bio-based plastics are an important element in this new model due to the uncoupling of fossil raw materials.

In recent years, more and more fossil raw materials are being used in textile production (mostly in countries outside Europe) whereas textiles were originally produced from natural materials, such as wool, cotton, flax and silk. This is another area where biomass will need to make a greater contribution if the use of fossil raw materials is to be avoided. Flax and hemp could be used as alternative raw materials for cotton fibres. Bamboo and other lignocellulosic streams, including textile recycling streams and residue streams, are increasingly being used as a source of cellulose for the production of viscose. In

Figure 32. Bamboo is a plant that is increasingly being used in textile applications.

addition, bio-based variants of synthetic fibres such as polyactic acid, polyesters and polyamid are being developed.

8.6 Chemicals

The chemical industry has been utilising renewable raw materials (oil, starch, sugar, cellulose) for decades for the production of chemicals and materials. With the emergence of fossil raw materials, many renewable raw materials were replaced by fossil raw materials, and numerous new chemicals and materials (plastics) were created, offering us great convenience. Examples are food packaging material, which considerably extends shelf life, and lightweight packaging, which keeps transport costs low.

At present, 80% of the raw materials for the petrochemical industry are used to produce plastics. Producing these materials from biomass instead of fossil sources will considerably contribute to the development of the bioeconomy. From a technical point of view, it usually is possible to produce chemical building blocks from biomass. Mainly drop-ins, the building blocks chemically identical to their fossil counterparts, are rising markedly because they can be directly used in the existing infrastructure.[87]

Sugars are very suitable for producing chemical building blocks with acid and alcohol functionalities, such as ethanol, butanol, glycols, lactic acid and succinic acid, because the raw material already contains the oxygen atoms needed for these building blocks. The production of lactic acid for polylactic acid (PLA) does not even have a fossil counterpart and is a prime example of a new bio-based material. Chemical building blocks that can be used in many different plastics due to their specific chemical structure are promising and are expected to grow considerably. Polyesters, polymers usually consisting of two chemical building blocks, one with two acid functionalities and one with two alcohol functionalities, are particularly interesting because they have the potential to be made from biomass. This may even trigger a shift in the use of different types of plastics. Polyolefins, such as polyethylene (PE) and polypropylene (PP) in particular, are less efficient to produce from biomass and their market size might decline in favour of bio-based polyesters if use of biomass as a raw material increases.

8.7 Compost and soil improvement

Compost from composting facilities is used as a soil improver, but the mineral fractions from biomass streams can also be used for this purpose. In addition, methane from biogas can be used as raw material for the production of ammonia, an ingredient for chemical fertiliser.

8.8 Conclusions

The Netherlands will need to import a substantial portion of the biomass required in the future, as it does today, and energy is expected to be an important application. These two aspects must be synchronised with each other in the form of energy-dense, dry and low-mineral biomass that will have to be transported across continents. This calls for the conversion of biomass residues from farmers and processors from across the globe into commodities, in other words readily marketable units of uniform semi-finished products, such as pellets.

Figure 33. Sugar beet and sugar beet pulp are a source of various carbohydrates that can be put to good use in the chemical industry.

Dutch biomass can be more effectively utilised and far more biomass can be released. The types of biomass that can be made available in the Netherlands have wide-ranging properties, which means they can be used in various areas of application. Biomass is an extremely important raw material for applications in food, animal feed, materials and chemicals, particularly if use of fossil raw materials for materials and chemicals is to be avoided. Furthermore, it would be logical to use carbohydrates from sugar beet and grains for various applications in the chemical industry.

The efficient and sustainable use of biomass depends on choosing the right combinations of biomass properties, conversions and applications. We hope that this booklet has offered a number of guidelines in this area.

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