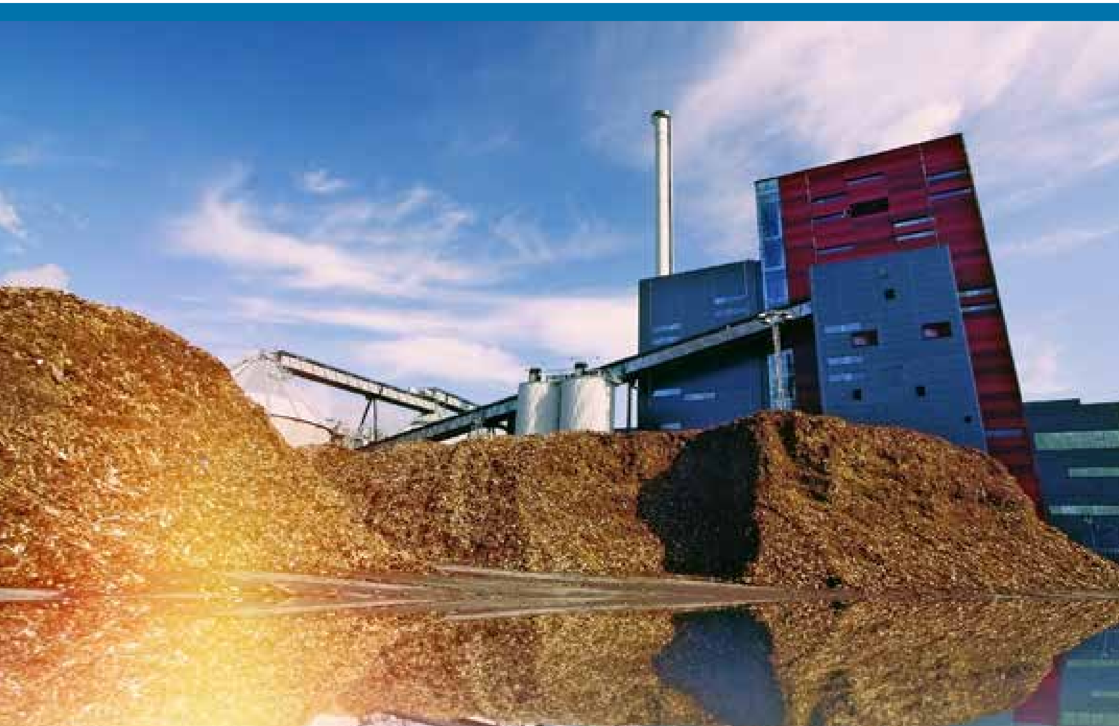
SOLID BIOMASS SUPPLY FOR HEAT AND POWER

TECHNOLOGY BRIEF



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ABBREVIATIONS

BD	bulk density
CAPEX	capital expenditure
CIF-ARA	cost, insurance, freight at Amsterdam-Rotterdam-Antwerp
EBITDA	earnings before interest, tax, depreciation and amortisation
FIT	feed-in tariff
FOB	free on board
FSC	Forest Stewardship Council
GBEP	Global Bioenergy Partnership
GHG	greenhouse gas
GPGO	Green Power Generation Oita Co.
HTC	hydrochemical carbonisation
iLUC	indirect land use change
ISO	International Organization for Standardization
LUC	land use change
max.	maximum
min.	minimum
n/a	not available
OPEX	operational expenditure
PEFC	Programme for the Endorsement of Forest Certification
PKS	palm kernel shells
PRESPL	Punjab Renewable Energy Systems Pvt. Ltd.
SBP	Sustainable Biomass Program
SDE+	Stimulation of Sustainable Energy Production
VLE	village-level entrepreneur

UNITS OF MEASUREMENT

cm^2	square centimetre
GJ	gigajoule
GJNCV	gigajoule net calorific value
GW	gigawatt
ha	hectare
kha	thousand hectares
kg	kilogram
kgDM	kilogram of dry matter
km	kilometre
kt	thousand tonnes
kWh	kilowatt hour
MJ	megajoule
mm	millimetre
Mt	million tonnes
MW	megawatt
MWh	megawatt hour
MWth	megawatt thermal
m^3	cubic metre
PJ	petajoule
toe	tonne of oil equivalent
t	tonne
TWh	terawatt hour
°C	degree Celsius

INSIGHTS FOR POLICY MAKERS

Solid biomass from forests, farms and cities is a major source of energy. Heat and power from solid biomass could provide a fifth of the energy the world consumes in 2050 (IRENA, 2017a). Notably, wood and crop residues must usually be collected from widely dispersed sites to serve district heating systems, power plants, and combined heat and power plants at a cost-effective scale. They must be produced, harvested, transported and stored for use over time, while retaining the technical qualities that allow their conversion to energy. And they must be delivered at a price that will allow the energy produced from them to compete in the marketplace with other energy forms.

This multi-dimensional logistical challenge is successfully met in many places around the globe. Wood pellets for power plants are shipped from Southeast Asia to Japan and from Southwestern Europe to the Netherlands, taking advantage of their high energy density, low moisture content and durability, as well as the low cost of sea transport per tonne-kilometre of cargo. Wood chips and pellets also fuel district heating plants in towns and cities of other European countries, such as Lithuania and Ukraine. Straw and other agricultural residues from production of food crops are being collected to provide heat and power in some villages in India. In all these places, an effective supply chain has been established, with contracts to ensure provision of sufficient feedstock at the required quality and cost.

But large quantities of available residues are not being collected. In Sweden and other countries with large managed forests, just a small share of the tree tops and branches left over from logging operations are collected. In Canada, large amounts of dead wood are abandoned in forests after being felled by storms or left standing in forests after insect infestations. On many farms around the world, crop residues not needed to feed or bed livestock are left in the field or burned to make room for the next planting. Typically, such residues are discarded because the cost of collecting and transporting them is greater than the market value they can fetch. Their enhanced use will therefore require more cost-effective logistical approaches or higher-value-added applications.

Quality standards play a key role in expanding solid biomass markets. Different feedstocks have different physical and chemical characteristics that vary by region and season of the year. Often they start with too low an energy density for practical use or too high a moisture content for practical transport and storage. Standardisation of biomass feedstocks, to ensure quality at point of use, is therefore an important enabler of solid biomass trade in an increasingly globalised market. Feedstock pretreatment, with drying and densification, can help ensure quality standards are met.

Sustainability standards for solid biomass fuels are also likely to play a growing role. The wood pellet trade has generated interest in ensuring that pellets are sourced from the residues of lumber production that displace carbon emissions from fossil fuels without affecting land use, or from short-rotation wood crops that quickly compensate for combustion with carbon uptake. When wood residues are used, enough should be left in the forest to sustain biodiversity. When crop residues are used, enough should be left on the ground to maintain soil carbon and quality.

The wood pellet industry has made considerable progress in developing the logistics infrastructure for global biomass supply, including well-defined supply chains, contract provisions, quality standards and terms of trade. As concerns continue to mount over environmental degradation and climate change, sustainability standards are being developed and adopted to meet these concerns. However, considerable further logistical efforts will be required to harness the full increment of sustainable solid biomass supply for productive application in the heat and power sectors.

INTRODUCTION

This technology brief focuses on the commercial supply of solid lignocellulosic biomass for heat and power. The range of solid biomass sources and applications is wide, but several are prevalent:

- use of biomass residues for cooking and heating
- use of biomass residues in industrial applications for heat and power
- use of biomass pellets and firewood in household heating
- use of biomass chips and pellets in industrial/standalone heat and power applications.

Other prospective uses of solid biomass are as feedstock to produce bio-based materials such as plastics, polymers, liquid biofuels and chemicals in advanced biorefineries. These uses are not widely established yet, but may present important markets in the future.

Running an energy facility on solid biomass fuel presents significant logistical challenges, since large amounts of fuel must be collected from a wide area on a continuous basis. Assuming a notional energy content of 15 gigajoules (GJ) per tonne of solid fuel and continuous plant operation:

- A 1 megawatt (MW) power plant at 40 % efficiency would require 216 GJ or over 14 tonnes of fuel daily.
- A 1 MW heat plant at 80 % efficiency would require 108 GJ or over 7 tonnes of fuel daily.
- A combined heat and power plant with an overall efficiency of 80 %, divided evenly between 1 MW heat and 1 MW power production, would also require 7 tonnes of fuel each day.

Assuming crops annually yield between 5 tonnes of residue per hectare (ha) (such as maize, wheat and rice) and 10 tonnes of residue per ha (such as sugarcane), these daily rates of fuel consumption would require some 260 to 1 050 ha of land for each MW of energy generating capacity. So up to roughly 10 kha could be needed for a 10 MW energy plant and 100 kha for a 100 MW plant.

Not only does biomass have to be grown and collected, it must also be channelled for energy use in a manner that does not compete with alternative uses (e.g. bedding for livestock and material use) and must be:

- transported to energy production facilities while retaining its energy content
- gathered cost-effectively to compete with other heat and power sources
- grown in an environmentally sustainable fashion
- of sufficient quality to be used with confidence and traded freely.

This technology brief explores some of the ways in which these challenges are being met.

FEEDSTOCK SOURCES AND STANDARDS

SOURCES OF SOLID BIOMASS SUPPLY

There are broadly two main sources of lignocellulosic biomass for heat and power applications (IRENA, 2017b):

- **Agricultural biomass** – also referred to as herbaceous biomass.

  Generally, herbaceous biomass resources are either agricultural residues or purpose-grown crops such as grasses. Agricultural residues are biomass that is left over in the field (such as straw, prunings, stalks and leaves) or generated during processing after the portions of the crop used for food production have been extracted (such as husks, shells, kernels and bagasse).

  Agricultural and energy crops are harvested in short harvesting windows; therefore their biomass is collected and treated seasonally. Continuous production of biofuels from agricultural sources thus requires extensive storage for year-round use, which may be challenging as the herbaceous biomass easily rots.

  Herbaceous biomass has higher ash, chlorine, nitrogen and sulphur content and contains more abrasive particles than woody feedstock. It also has a lower ash-fusion temperature, resulting in greater boiler slagging and fouling, faster boiler corrosion and higher emissions of atmospheric pollutants.

- **Forestry biomass** – also referred to as woody biomass.

  Woody biomass includes trees or parts of trees, such as trunks, branches, bark and tops. It contains more lignin than herbaceous feedstock or tree leaves. Lignin is an organic polymer that supports vascular plants, such as trees, structurally acting as a glue. It also reduces their rate of decomposition. Forestry biomass is usually harvested during all seasons, often on demand.

  Most wood species have similar energy content on a mass basis. Softwood has a slightly higher heating value than hardwood, on a mass basis. On a volume basis, hardwood has a higher heating value because it is generally denser. The energy content of wood by weight varies only slightly between timber species, but the density varies significantly.

  Clean stem wood with no bark and no branches usually has an ash content of 0.5–1%. Bark has higher ash content of, typically, 3–5% (dry basis). Woody biomass is known to have less silica than herbaceous biomass. Uncontaminated woody biomass with no additives hardly ever produces clinker under normal combustion conditions.

The main differences between woody and herbaceous biomass are shown in Table 1.

Table 1 – Main differences between woody and herbaceous biomass.

	Woody biomass	Herbaceous biomass	
High lignin content			**Low lignin content**
Low to medium ash content	Forestry products and byproducts	Agricultural residues	**High ash content**
High ash melting temperature			**Low ash melting temperature**
Bulky	Wood processing byproducts		**Very bulky**
Decomposes slowly		Energy crops	**Decomposes quickly**
Continuously harvested	Woody agricultural byproducts		**Seasonally harvested**
Requires no binder to pelletise/briquette			**Requires binder to pelletise/briquette**

Both herbaceous and woody biomass belong to the broader class of lignocellulosic biomass, but their different properties may favour their use in different applications. Lignocellulosic biomass can be obtained as residuals from harvesting and processing, or from dedicated energy crops. Energy crops include commercial forests, short-rotation coppice (such as poplar and willow) and grasses (such as switchgrass and Miscanthus) that are grown for use in the energy sector rather than for food production. Table 2 shows typical parameters of herbaceous and woody lignocellulosic biomass.

Different kinds of woody biomass work best for different applications

Table 2 – Characteristics of agricultural residues and dedicated energy crops

Feedstock	Dry mass yield (tonne/ha/year)	Lower heating value (MJ/kgDM)	Energy produced (GJ/ha)	Water content at harvest (%)	Ash content (%)
Herbaceous biomass					
Straw	2–4	15–18.1*	35–70	14.5	5.0
Herbaceous crops					
Miscanthus	8–32	17.5–18.1	140–560	15.0	3.7
Switchgrass	9–18	16.8–18.6	150–335	15.0	6.0
Giant reed	15–35	16.3–18	245–570	50.0	5.0
Canary grass	6–12	16.3	100–130	13.0	4.0
Woody crops					
Willow	8–15	16.7–18.5	280–315	53.0	2.0
Poplar	9–16	18.7	170–300	49.0	1.5
Black locust	5–10	18.5–19.5	100–200	35.0	n/a
Wood	3–14	18.7	56–262	50.0	1–1.5

* Corn stalks/stover 16.8–18.1 MJ/kgDM; sugarcane bagasse 15–17.9 MJ/kgDM; wheat straw 15.1–17.7 MJ/kgDM.

Notes: kgDM = kilogram of dry matter; MJ = megajoule; n/a = not available.
Sources: AEBIOM (2008), "New dedicated energy crops for solid biofuels"; IRENA (2012), Biomass for Power Generation, www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-BIOMASS.pdf.

QUALITY STANDARDS FOR SOLID BIOMASS FUEL

Solid lignocellulosic biomass covers a very diverse set of materials that can be generally classified according to the following parameters:

Elemental composition – The main constituents of biomass are carbon (C), oxygen (O) and hydrogen (H). As carbon and hydrogen are oxidised in the combustion process, they release energy. Most biomass has a carbon content of around 50% (dry basis), 40% to 45% oxygen and 5% to 7% hydrogen. There are also other chemical elements, although these constitute much lower percentages of the total dry biomass. Nitrogen (N), sulphur (S) and chlorine (Cl) contents are some of the main causes of air pollution from biomass combustion. A higher percentage of these elements generally results in a higher level of air contaminants being released. Minerals, such as silica, are also present in small quantities and together form the ash that remains after combustion.

Chemical composition – A different level of chemical analysis of biomass is more concerned with the presence of chemical compounds such as sugar, starch, oil, protein, cellulose, hemicellulose and lignin. These substances are present in biomass at different levels and determine the potential uses of the biomass. In the case of solid biofuels, the presence of dissolved sugars, starch, oil and protein is expected to be very low. The substances of interest are cellulose, hemicellulose and lignin. That is the reason this class of biomass is often referred to as lignocellulosic biomass.

Moisture – All biomass contains water, typically expressed as percentage moisture content. Moisture is most often undesirable and has a significant negative impact on the value of the biomass for several reasons. Moisture reduces energy content as it adds mass without calorific value, increasing transport costs per unit of energy. It also increases the necessary furnace volume and requires larger exhaust channels, resulting in higher capital costs for combustion plants. Moisture requires energy during combustion to evaporate, reducing plant efficiency (unless the application allows for low-temperature heat recovery), and it can induce corrosion in boilers and combustion equipment. Moist biomass also decomposes faster than dry biomass.

Ash content – Ash content reflects the amount of minerals, such as calcium (Ca), chlorine (Cl), potassium (K), nitrogen (N), sulphur (S) and silicon (Si), contained in the biomass. This forms the residue left after combustion. The ash content of biomass is determined by its chemical composition and by contamination with dirt that often occurs during harvesting, transport and storage. For instance, biomass stored on the ground can pick up dirt, which increases the ash content significantly.

High ash content is undesirable because ash adds weight without adding calorific value. It also can cause equipment damage depending on its melting temperature. The high temperatures in the combustor may melt the ash, giving it a lava-like consistency that sticks to the equipment, causing damage. Another fraction of the ash can also be emitted through the stack as fly ash and often needs to be removed prior to emission of the combustion gases to the atmosphere. Such properties need to be considered in plant design by selecting the appropriate combustion technology, tube materials and/or coating, or mitigated by temperature control of combustion or co-firing with low-fouling fuel. Ash content varies considerably with biomass type, from as low as 0.3 % in clean wood to 4 % in Miscanthus and up to 7 % in some straws.

Density – Density is the measure of mass per volume. The factors that affect biomass density are the chemical composition of the biomass (including moisture) and its inherent structure. Bulk density depends on the method of conditioning biomass for storage and transport, which affects the volume of biomass as purchased or as delivered. Bulk density is an important property that impacts logistics, storage and handling of the biomass, and it can be improved by using techniques that reduce the total volume of the bulk biomass, such as compaction or densification.

Energy content – The calorific or heating value of a fuel indicates the energy available in the fuel per unit mass. The difference in available energy depends on the chemical composition of the biomass, and its moisture and ash content.

Particle size – The distribution of biomass particle size in the biomass fuel can range from macroscopic dimensions, such as in a wood log, to microscopic dimensions, such as the fine particles that result from milling and grinding processes. Some biomass applications are sensitive to particle size and demand tight control for optimal results.

The importance of controlling for these quality parameters has led to the development of quality standards for solid biofuels. To facilitate commerce and trade, commodities should be fungible; with quality standards, buyers and sellers can be assured that one batch of the commodity has the same physical and chemical properties as any other batch in same quality category.

Austria, Germany and Sweden initiated the European standard that was created with EN 14961-2. As Europe dominates the global pellet market, this standard has also been widely accepted outside Europe. The International Organization for Standardization (ISO) has also developed standards for solid biofuels, and released its dedicated wood pellet classification system (ISO 17225-2:2014) to the market in 2014/15. This established distinct technical quality standards for pellets in residential/commercial applications and industrial applications. The standards define wood pellet requirements in terms of moisture, energy density, abrasion resistance, particle size and shape. They have enabled a trade code for wood pellets to be established so that wood pellet trade flows are now covered in official trade statistics (Thraen *et al.*, 2017).

SUSTAINABILITY AND GREENHOUSE GAS EMISSIONS

Production chains for solid biofuels must be selected so that sustainability is ensured and greenhouse gas (GHG) emissions minimised. In the case of liquid biofuels for transport, several countries already include minimum criteria for the GHG emission reductions different biofuel types attain. Requirements for solid biofuels also are likely to be imposed soon, demanding GHG emission reductions (from forest/field to chimney).

Thraen *et al.* (2017) set out key questions relating to the development of sustainability criteria for solid biofuels:

- How should the sustainability criteria applying to agricultural biomass differ from the requirements for forest biomass?
- Should land use change (LUC) and indirect land use change (iLUC) be criteria?
- What level of GHG emissions reduction should be required?
- Should sustainability criteria be applied to generation capacity below 20 MW?
- To what extent should certification schemes (such as FSC, SBP and PEFC)[1] be recognised by national legislation?

The frameworks and guidelines for solid biomass sustainability that have been established in the European Union, Japan and the Republic of Korea are worth examining to help answer these questions.

For instance, the Sustainable Biomass Program (SBP) was established in the European Union in 2013 as a certification scheme for woody biomass, mostly in the form of wood pellets and wood chips, used in industrial, large-scale energy production. SBP's first objective was to develop a framework of standards and processes for voluntary certification, which enables any biomass producer or heat or power generator to demonstrate compliance with sustainability requirements for woody biomass. From 2014 through 2016, over 70 wood pellet producers were certified, including some of the largest worldwide.

The Global Bioenergy Partnership (GBEP) was founded in 2006 and now has more than 70 members with an expanded range of activities in different countries (GBEP, 2018). GBEP brings together public, private and civil society stakeholders in a joint commitment to promote bioenergy for sustainable development. It has developed a set of 24 voluntary sustainability indicators, including environmental, social and economic, to guide assessment of bioenergy options. The indicators have been tested in a number of countries at both regional and national level to evaluate their feasibility and enhance their practicality as a tool for policy making. An implementation guide for their use has also been developed (GBEP, 2018).

In 2015, ISO also released its standard on sustainability criteria for bioenergy, ISO 13065:2015 (ISO, 2018). This could be key to making biomass feedstocks fungible commodities in the marketplace (Thraen *et al.*, 2017).

1 FSC = Forest Stewardship Council; SBP = Sustainable Biomass Program; PEFC = Programme for the Endorsement of Forest Certification.

HARVESTING, TREATMENT AND TRANSPORT

Harvesting and collection are the first steps in any biomass feedstock supply chain. Biomass has traditionally been picked by hand from the field and forests by rural households all over the world to provide fuel for cooking and heating. But large-scale commercial use of lignocellulosic biomass mostly relies on modern, mechanised, industrialised harvesting and transport methods.

Harvesting of crops: Mechanised harvesting of herbaceous crops occurs in a field where harvesting equipment can easily work. Examples include combine harvesters, swathers (windrowers), forage choppers, self-propelled balers and pelletisers. Depending on the crop and local weather conditions, harvesting may be limited to a certain time window or be delayed until after rainy periods. Short-rotation woody crops such as willow and poplar are also typically harvested by agricultural equipment (e.g. modified forage harvesters) in the form of wood chips.

Collection of residues: Agricultural residues such as straw are collected in the course of threshing by a combine harvester. Forestry residues are costlier to collect because of the bulky characteristics of branches, treetops and stumps. Process residues such as husks, shells and sawdust are cheaper to collect as the food and forest industries produce them in relatively large quantities, with similar physical and chemical characteristics, over a wider time window.

The bulk density and moisture content of biomass affect its transport and storage costs. Thus, fresh biomass typically needs to undergo further processing to reduce its moisture content and bulk volume, improving biomass logistics. The challenge in upscaling bioenergy use is not only having access to enough biomass feedstock, but also turning feedstock into high-quality fuel that can be easily handled, stored and transported. Treatment raises costs, so the ideal type and amount of treatment depend on specific supply chain conditions, such as transport distances, the potential need to store biomass for longer periods, dry matter losses along the chain, and final end uses.

Losses of biomass typically occur during harvesting, transport and storage, with physical losses during harvesting and transport (for instance, by falling from a truck), and chemical or biological degradation during storage. Losses can be lowered by improving harvest, transport and storage processes and by reducing the moisture content of biomass and the presence of oxygen at storage sites.

Treatment: Many treatment processes are used to improve feedstock quality, avoid feedstock degradation and allow longer storage, thereby boosting the efficiency of biomass handling, transport and use. The main target is to increase the energy density of the feedstock. Figures 1 and 2 provide a general overview of different routes for harvesting and processing lignocellulosic biomass.

Figure 1 – Overview of different routes for harvesting and processing lignocellulosic biomass

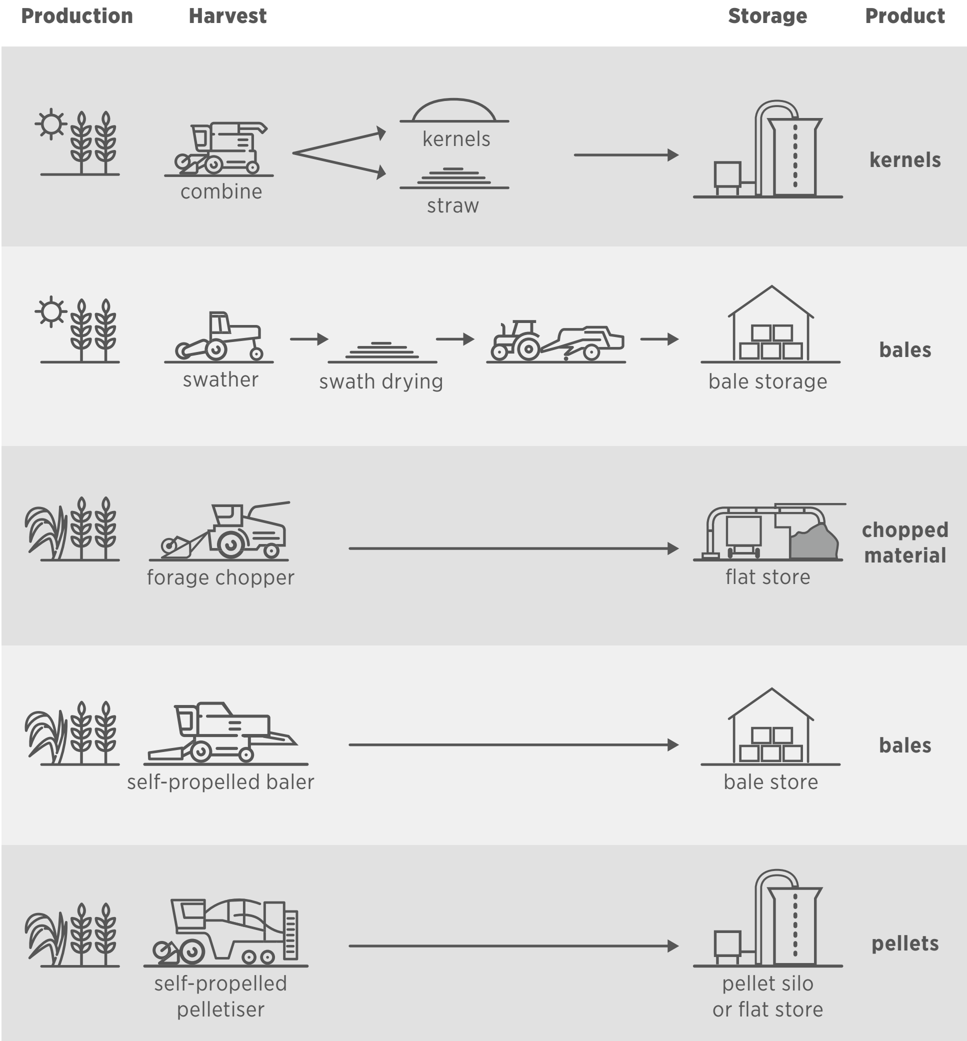
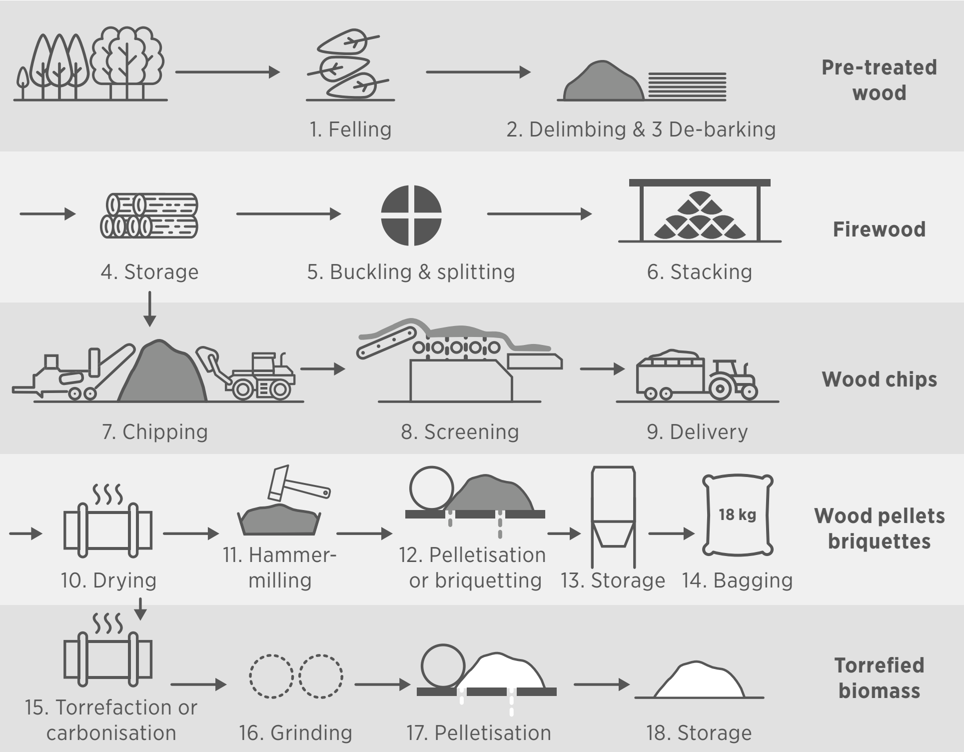


Figure 2 – Overview of different routes for harvesting and processing lignocellulosic biomass



Processing of low-cost feedstock by the methods shown in the figures results in higher calorific value and consequently more efficient combustion. It also reduces the capital investment required for conversion of biomass to energy, as lower moisture content allows smaller boilers and narrower flue gas channels. Energy content and moisture content are strongly correlated. The ability to extract the maximum from the fuel being burned depends on the boiler design and how well the fuel is suited to that design.

Baling and ***sizing*** are densification processes that can occur early in the supply chain and which may also occur at the collection site. Baling is the most common method to reduce the transport and storage capacity required for herbaceous biomass (such as cereal straw, corn stover, Miscanthus or switchgrass). It facilitates handling during the several logistical steps because baled biomass is denser than chopped materials (BISYPLAN, 2012). Sizing processes, such as chipping, grinding and shredding, are also used to facilitate biomass handling.

Drying is a crucial process to reduce transport costs, increase combustion efficiency and also to avoid fungal growth, which leads to decomposition and loss of matter, especially in wood chips given their size and moisture level. Alternatively, biomass can be chipped as late as possible in the logistics chain. Types of dryers include rotary drum dryers (biomass moves through a drum as it rotates and makes contact with hot air), fluidised bed dryers (a gas flows across a bed made of biomass particles and particles such as sand) and steam-based recompressive dryers.

Pelletisation and ***briquetting*** are typical methods for densifying woody biomass feedstock. They are commercially available and relatively simple technologies. The result is refined fuels that match the convenience and energy density of conventional fossil fuels. Briquettes come as either cylindrical extrusions measuring 25 millimetres (mm) to 80 mm in diameter and up to 300 mm long, or individually pressed bricks of various sizes. Pellets are small (68 mm diameter, 612 mm long) cylinder-shaped pieces of compressed biomass particles that are agglomerated. Pellets and briquettes have some drawbacks, including dust and the need to protect from moisture. But they also have considerable advantages: they are dry, conveyable, easily combustible and homogeneous. Their consistent fuel properties are ensured by a number of processes upstream and downstream of their production.

Production of wood pellets or briquettes involves acquiring feedstock (e.g. sawdust), drying, screening to remove unwanted materials (e.g. stones), hammer-milling, pressing (usually at a temperature of more than 100 °C), cooling, and packaging. The bonding of the biomass in the case of wood particles is done by lignin, a chemical component naturally occurring in wood. Compressing or extruding the wood particles creates temperatures that can liquefy the lignin. During cooling, the lignin solidifies again, acting as a natural adhesive. Some manufacturers add binders, such as corn starch, during the extrusion process to improve the bonding characteristics and durability of the pellet. Binders reduce dust that might be created when transporting, conveying or handling the fuel. This generally is only done for feedstock with low (< 25 %) lignin content, such as agricultural byproducts or perennial grasses (IRENA, 2017b).

Thermochemical processes cause the controlled transformation of solid biomass through volatilisation and consequent production of other solid, liquid or gaseous materials under the influence of temperature and pressure, normally with little or no oxygen. There are several options depending on whether the objective is to maximise production of solids, liquids or gases. These processes happen in closed reactors that are heated, usually from the outside. At the temperatures typical of such processes, most dry biomass would start igniting. To avoid that, combustion air – and thus oxygen – is removed from the reactor. In the absence of oxygen, or with less oxygen than necessary for combustion, and under elevated temperatures, the biomass starts to volatilise: the volatile components, such as lignin, start turning into liquids and/or gases; only the so-called “fixed carbon” remains.

The higher the temperature and the longer the retention time in the reactor, the more biomass is turned into a gas and the less is left as a solid bioproduct. Common types of thermochemical process include gasification, pyrolysis (which, in turn, can be divided into different types such as slow, flash and fast pyrolysis), torrefaction, carbonisation, and hydrothermal carbonisation. The most relevant methods that result in solid upgraded products are torrefaction, carbonisation and hydrothermal carbonisation.

Torrefaction is a thermochemical treatment process used to upgrade lignocellulosic biomass and turn it into charcoal. The resulting material resembles coal and features similar energy content, grindability and moisture. The biomass is heated to a temperature of 200–350 °C at low oxygen concentrations and atmospheric pressure. During the torrefaction process, all moisture is removed from the biomass and it partly devolatilises, leading to a decrease in mass and accumulation of energy per unit of mass. The biomass is transformed into a very grindable material that can easily be processed into a fine powder. Torrefied biomass has higher calorific value and bulk density, is hydrophobic (which may allow storage in the open air), allows easy grinding, and offers coal-like combustion characteristics. For these reasons, it can be more easily co-fired in coal power plants in higher proportion than non-torrefied biomass. Densification gives it more energy per unit volume, so it has lower transport, handling and storage costs (IRENA, 2017b; Thraen *et al.*, 2017).

Carbonisation (slow pyrolysis) is similar to torrefaction, but is done at higher temperatures, evaporating all volatiles in the wood and devolatising hemicelluloses contained in the wood. Carbonisation and torrefaction are both thermochemical treatment processes. Torrefaction can be considered a "mild" form of carbonisation. Carbonisation is similar to making charcoal and results in a higher carbon content in the final product. The end product thus has higher energy content per unit of mass than torrefied products. However, there will be greater loss of mass in the transition from feedstock to product (as CO_2).

Hydrothermal carbonisation (HTC) is a thermochemical biomass treatment conducted in the presence of subcritical and liquid water. In the HTC process, biomass is treated in a pressure vessel at a temperature of 180–250 °C for one to several hours. This converts it into a solid material (often referred to as biochar, hydrochar or biocoal) with enriched carbon and chemical characteristics similar to fossil coals (Libra *et al.*, 2011; Fiori *et al.*, 2014). HTC technology has the advantage of utilising very wet biomass, but is generally at a less advanced readiness level than torrefaction.

Tables 3 and 4 summarise the types of processed lignocellulosic biomass and their characteristics.

Table 3 – Description of solid biomass feedstock

Bales	Compressed, shaped and bound solid biomass (0.1–4 m^3 squares or cylinders). Field drying before or after baling is an option.
Chips	Chipped woody biomass in the form of pieces with a defined particle size (a length of between 5 and 50 mm) produced by mechanical treatment, usually with high moisture content before drying and relatively low energy density. More difficult to handle than pellets; require large fuel storage volume and regular deliveries.
Pellets	Densified solid biofuel made from pulverised biomass with or without additives, usually in cylindrical form (diameter less than 25 mm), random length typically of 5–40 mm with broken ends. Low moisture content. Easy to handle. Raw material can be woody, herbaceous or fruit biomass, or their blends.
Briquettes	Densified solid biofuel made with or without additives in cubic or cylindrical form, produced by compressing pulverised biomass. Briquettes are similar to pellets, but physically larger. Low moisture content. They offer an alternative to firewood logs (controlled fuel value). Raw material is woody biomass, herbaceous biomass, or their blends.
Firewood	Cut and split, oven-ready fuelwood used in household wood-burning appliances such as stoves, fireplaces and central heating systems. Firewood usually has a uniform length, typically in the range of 200–1 000 mm.
Charcoal/ torrefied wood pellets	Densified solid biofuel of black colour that can be used as a coal-like substance, featuring similar energy content, grindability and moisture content. It is produced through carbonisation (or slow pyrolysis) of biomass, whereby water and organic volatile components are evaporated, leaving mostly black carbon.

Note: m^3 = cubic metre.

Sources: EUBIONET3 (2011), “Summary of the EUBIONET III project results”, https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/eubionet_iii_publishable_report_en.pdf; Kofman (2010), “Preview of European standards for solid biofuels”, www.woodenergy.ie/media/coford/content/publications/projectreports/cofordconnects/pp23.pdf.; BISYPLAN (2012), The Bioenergy System Planners Handbook, http://bisyplan.bioenarea.eu/; FAO (2015), Wood Fuel Handbook.

Table 4 – Typical characteristics of biomass feedstock compared to coal

Feedstock	Moisture content (%)	Bulk density (kg/m^3)	Low heating value (GJ$_{NCV}$/tonne)	Energy density (GJ$_{NCV}$/m^3)
Fresh wood	35–58	200–250	9–12	2–3
Baled straw	15 (air dried)	140	15	2
Wood chips	20 to 25 (air dried)	200	15	3
Sawdust	20 to 25 (air dried)	160	15	2.4
Solid wood	20 (air dried)	550	15	8
Briquettes	8	650	16	10
Charcoal	2–3	300	27	10
Wood pellets	8	650	17	11
Torrefied wood pellets	2	700	20–21	15
Coal	12	825	20–30	21

Notes: GJNVC = gigajoule net calorific value; kg = kilogram.
Sources: IEA (2012), Technology Roadmap: Bioenergy for Heat and Power, www.iea.org/publications/freepublications/publication/2012_Bioenergy_Roadmap_2nd_Edition_WEB.pdf; Koppejan et al. (2015), Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction, https://sector-project.eu/fileadmin/downloads/deliverables/SECTOR_D10.2_Procede__FINAL.pdf.

Storage of biomass feedstock is often necessary due to the seasonal production, drying and pretreatment processes, and the need to ensure appropriate and continuous supply. While storage contributes to the air drying of biomass, if stored in large piles, some biomass feedstocks (e.g. straw, wood chips) present a risk of fire due to mould and bacterial action, which also causes dry matter losses and health risks. Frequent pile turning may help reduce this risk. Large, long-term storage facilities are needed because of seasonal production, while large storage volumes are needed for large users of biomass (e.g. biorefineries and power plants).

Transport of solid biomass includes both short-distance movements (for collection) and long-distance movements (to markets). Biomass has a lower energy density than fossil fuels (per unit of volume or mass). This translates into a higher cost of transport per unit of energy content. Biorefineries are therefore often better sited close to feedstock collection sites rather than biorefinery markets. Biomass densification before long-distance transport is key to keeping overall costs down.

The choice of transport mode depends on several factors, including the cost, form and bulk density of the biomass, as well as transport distance, existing infrastructure and seasonality. Loading, unloading and intermediate storage of biomass are also to be taken into account, as they represent a non-negligible share of the overall transport cost. As a general guide:

- Trucks are best suited to short transport distances (< 100 kilometres [km]) when flexibility is required for multiple small biomass production sites, or when no train and ship infrastructure exists.
- Trains are used for longer overland transport distances and may compete with ships for mid-range transport distances.
- Ships (dry bulk carriers) are preferred for long distances and large amounts of biomass. They are the cheapest and least energy-consuming transport mode.

COSTS AND PRICES

The total cost of supplying solid biomass feedstock for energy use can be expressed as the sum of the **production** (cultivation, harvest and collection), **pretreatment**, **transport** and **storage** costs. All these costs are highly sensitive to local conditions, including the opportunity cost of land and logistics. Costs and prices are also highly variable depending on the specific market and biomass type. This brief, therefore, is not intended to provide a comprehensive picture of costs and prices for solid biomass feedstocks. Rather, it provides a general overview with examples that illustrate the market landscape for solid biomass.

Solid biomass markets operate in a highly informal manner in many world regions where biomass is used as a cooking fuel. Sometimes there is no market per se, but instead the cost to individual households of picking and gathering biomass from forests and agricultural fields for their own use. In other cases, markets develop, but tend to be local and sometimes involve the barter of biofuels for other items instead of a monetary transaction.

Informal solid biomass markets also exist where conditions allow local industries to use agricultural and forest residues without long-distance trade or transport. A typical example is the use of rice husks for the production of heat and power in rice-producing regions. Electric power plants or combined heat and power plants are often built in regions where sufficient residues are available. Industrial facilities such as cement plants also tend to attract large flows of residual biomass that can be brought in from the region in which they are established. Municipalities may see such facilities as an important outlet for disposing of their waste and even pay them to accept it.

Biomass-based industries that produce large amounts of biomass residues often use them to supply heat and power for their own operations. A good example of this is the sugarcane industry, which traditionally uses sugarcane bagasse, a byproduct of sugarcane crushing, as fuel in cogeneration systems. The most modern mills can use all their bagasse, supply all their internal heat and power needs, and still produce surplus electricity that can be exported to external users nearby or the electricity grid. The pulp and paper, lumber and palm oil industries also use solid biomass residues to meet all or part of their energy needs. In most such cases, a market for the solid biofuel is not established as the biomass is produced and used internally as part of the industry's operations. Even given the opportunity to sell the biomass, such sales are often not profitable enough to forego its use for internal operations.

Below is a summary of the production and collection costs of various sustainable feedstocks in regions around the world. These data are estimates based on a meta-analysis of existing studies, as well as interviews with experts in the field conducted by IRENA (2016a):

- Agricultural residues are generally low in cost, reflecting easy collection and short transport distances. Their current cost range is USD 1.8 to USD 3.7 per GJ (Bain, 2007; de Wit, Lensink and Londo, 2010; Gerssen-Gondelach *et al.*, 2014; IRENA, 2014; Panoutsou, Eleftheriadis and Nikolaou, 2009).

- Forest residues are also relatively low in cost. They benefit from an established and growing market in heat and electricity generation. Their current cost range is USD 2.3 to USD 2.9 per GJ (Gerssen-Gondelach *et al.*, 2014; Panoutsou, Eleftheriadis and Nikolaou, 2009; Brinsmead, Herr and O'Connell, 2014).

- Supply chains for dedicated non-food energy crops are at an early stage of development, and cost estimates vary widely due to differences in yields between crops and regions. Woody energy plants, such as short-rotation coppice poplar and willow, have a cost range of USD 2.4 to USD 4.3 per GJ (Brinsmead, Herr and O'Connell, 2014; de Wit, Lensink and Londo, 2010; Gerssen-Gondelach *et al.*, 2014).

- Agricultural and forest residue costs are expected to remain stable or increase slightly over the next three decades, while costs for non-food energy crops are projected to decline.

Wood pellets and torrefied pellets are expected to play an increasingly important role in the bioenergy market. Thraen *et al.* (2017) conducted an extensive literature review of the estimated costs of producing and transporting wood pellets. They found that costs ranged from USD 61 to USD 189 per tonne (normalised to 2016 price levels). Some of the variations in cost are due to differences in geographic scope, which affects not only transport distances, but also country-specific costs: feedstock, labour, transport and electricity. Feedstock costs for pellet plants, for instance, ranged from USD 15 per tonne in Argentina to USD 65 per tonne in Austria. In their own assessment, the authors show that half the cost of pellets at the plant gate is due to the cost of fibre, which is to say the cost of feedstock.

They find that the CIF-ARA price (cost, insurance, freight at Amsterdam-Rotterdam-Antwerp) is fairly evenly divided between fibre costs, pellet production and plant costs, and transport and handling costs. Supply chain integration and optimisation strategies can reduce some non-fibre costs, for example by reducing storage times or optimising rail cargo operations from production to port facilities. But bringing the CIF-ARA price below USD 118 per tonne is difficult (Thraen *et al.*, 2017). Table 5 shows estimated cost ranges for pellet production.

Table 5 – Pellet production cost ranges (USD/tonne)

Supply chain step	Low	Medium	High
Fibre cost and transport	39	55	70
Pelletising OPEX	20	23	25
Pelletising EBITDA	25	33	40
Plant gate	**84**	**110**	**135**
Mill to port	8	10	12
Port storage and handling	8	10	12
FOB	**100**	**130**	**159**
Ocean freight and handling	18	20	22
CIF-ARA	**118**	**150**	**181**

Notes: EBITDA = earnings before interest, tax, depreciation and amortisation; FOB = free on board; OPEX = operating expense. Source: Thraen *et al.* (2017), Global Wood Pellet Industry and Trade Study 2017.

De Jong *et al.* (2017) evaluated the impact of four strategies to reduce the cost of biofuel production: economies of scale, intermodal transport, integration, and distributed supply chain configurations. The economic performance of a bioenergy supply chain can be optimised by making strategic choices regarding production capacity, supply chain configuration, transport modes and conversion location.

Key to a cost-effective supply chain is the trade-off between economies of scale and transport cost: while higher production volume brings cost reductions through economies of scale, it requires biomass to be mobilised over larger distances. Distributed configurations use an intermediate densification step early in the supply chain (such as chipping, pelletisation or liquefaction) to decrease transport cost, even though this may increase the capital or operational expenditures (CAPEX or OPEX). Furthermore, co-location of production at existing industrial sites may decrease production cost when integration benefits can be leveraged.

Tables 6 and 7 provide details on pellet production and torrefaction from the literature, reflecting the importance of the pellet industry in solid biofuel markets today and the good prospects for torrefaction. Interesting conclusions can be drawn:

- The torrefaction process demands greater raw material input, i.e. 1.2 tonnes of dry input or 2.5 tonnes of wet input (50 % moisture) per 1 tonne of dry output, as compared with 2 tonnes of wet input (50 % moisture) for 1 tonne of dry output for non-torrefied wood pellets. Furthermore, investment costs for torrefied pellets are higher as compared to conventional pellets.

- The consumption of electricity to produce torrefied pellets is about 50 % higher than that for conventional pellets.

- The energy penalty (energy consumed to process the biomass feedstock) is far exceeded by the increase in net calorific value. In the case of wood pellets, the energy penalty is 171 kilowatt hours (kWh) per tonne (or 0.61 GJ/tonne), yielding an increase in net calorific value from fresh wood to wood pellet of 8.5 GJ/tonne. And in the case of torrefied pellets, with an energy penalty of 263 kWh/tonne (or 0.95 GJ/tonne), an increase of 12.7 GJ/tonne is achieved.

- Both processes represent very significant improvements to energy content per unit of volume and mass output when compared to fresh wood (assuming woody biomass has a net calorific value of 9 GJ/tonne and a bulk density of 250 kg/m^3), with very low loss of output energy. This results in very significant improvements in downstream logistics.

- For the same feedstock input (255 000 tonnes), both processing plants produce the same absolute output of energy (2.17 petajoules [PJ]), but the torrefied pellet plant generates almost 20 % less mass output and almost 40 % less volume output.

Table 6 – Example of performance and costs of pellet production

	Wood pellets	Torrefied pellets
Feedstock intake (tonnes, 50 % moisture)	255 000	255 000
Output capacity (tonnes)	123 800	100 000
Product net calorific value (GJ/tonne)	17.5	21.7
Product bulk density (kg/m^3)	620	800
Product energy density (GJ/m^3)	10.8	17.4
Electricity consumption (kWh/tonne)	171	263
Wood yard	20	20
Pre-dryer	45	33
Hammer mills	50	–
Torrefaction	–	60
Pellet mills	56	150
Investment cost (million USD) for plant capacity of 255 000 green tonnes per annum in	19.5	29
Wood yard	5.0	5.0
Pre-dryer	4.5	3.6
Hammer mills	2.0	–
Torrefaction reactors	–	13
Pellet mills	4.0	3.1
Silos	1.0	–
Civil works	3.0	4.3
Annual – Operation and maintenance	2 % of investment costs	4 % of investment costs
Annual – Other costs	4 % of investment costs	4 % of investment costs

Sources: Koppejan et al. (2012), Status Overview of Torrefaction Technologies, www.ieabcc.nl/publications/IEA_Bioenergy_T32_Torrefaction_review.pdf; Ehrig et al. (2013), "Economic comparison of torrefaction-based and conventional pellet production-to-end-use chains".

Table 7 – Summary of results based on the case above

Case	Gross energy output (PJ)	Energy penalty (PJ)	Net energy output (PJ)	Mass output (tonnes)	Volume output (million m^3)
Fresh wood	2.29	0	2.29	255 000	1 (as chip)
Wood pellets	2.17	0.07	2.10	123 800	0.20
Torrefied wood pellets	2.17	0.09	2.08	100 000	0.12

When increasing the capacity of pellet production, the cost per unit of delivered energy usually decreases because of the economies of scale. However, more biomass feedstock is required, creating a larger procurement area. This results in longer transport distances and therefore higher transport cost. The optimal production capacity can be set by determining the trade-off between the cost reduction due to the scaling-up effects and the increasing cost of transport (Batidzirai *et al.*, 2014).

The impact of feedstock choices is also important to consider. For instance, selecting wood chips as feedstock instead of sawdust results in a higher investment cost, since additional grinding is needed before drying, with additional energy consumption. Wood chips, however, have higher bulk density compared to sawdust and allow a saving in raw material storage (Thek and Obernberger, 2009).

Biomass **transport costs** are another important aspect of biomass supply cost. They can be divided into local transport costs (i.e. collection and transport to local storage and processing facilities, local delivery), and long-distance transport costs. In general, on the one hand, truck transport has low fixed costs (i.e. truck, loader) and high variable costs (e.g. fuel, labour, tyres and wear and tear), while on the other hand, train and ship transport have high fixed costs (i.e. railcar, ship, freighter) and low variable costs.

The cost of train transport can be dependent on the availability of freight for the return trip, transfer terminal policies and the route (Miao *et al.*, 2012). The cost of truck transport can be affected by: the required biomass volume; biomass productivity and the spatial distribution of biomass production in an area; road infrastructure and average truck speed; and truck capacities and return freight (back loads) (Batidzirai *et al.*, 2014).

Notably, international shipping usually accounts for a small part of the final biomass cost, and long-distance biomass transport costs, especially shipping costs, are expected to remain modest at least for the next decade, dependent on global fleet cost trends and volatility (Goh and Junginger, 2014). In contrast, local transport by trucks from field to storage and processing facilities accounts for a significant share (30 % to 50 %) of the total cost, as these are dedicated transport modes, with no return freight and a large spatial spread.

The impact of transport costs makes some of the economic trade-offs between wood chips, wood pellets and torrefied pellets more evident. Assuming an application that could use any of those options, the cost of delivering a tonne of fuel (wood chips, wood pellet or torrefied wood pellet) can be calculated from the example data provided above.

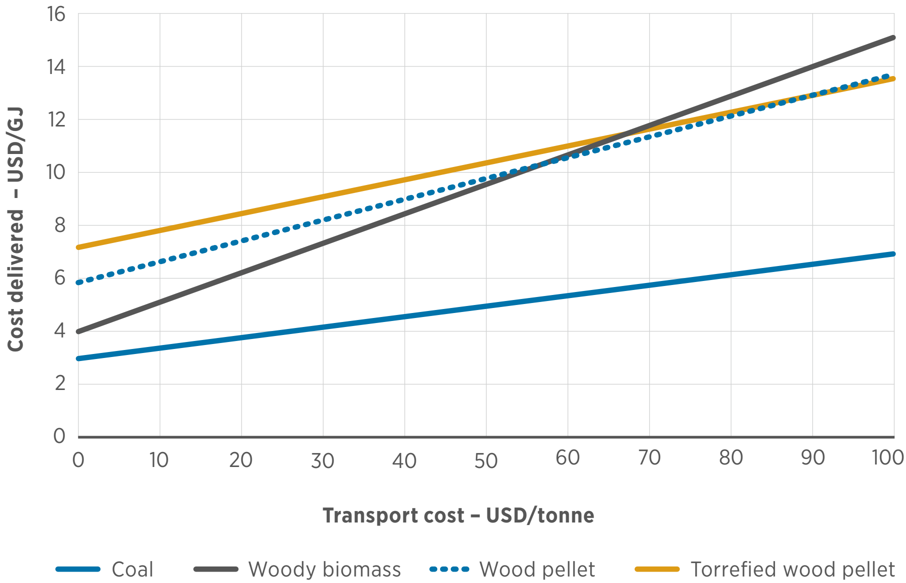
Assume that the cost of woody biomass is 4 USD/GJ, which is consistent with Figure 3 (energy plants, woody, 2010–2020). Using the data from Table 6 and applying a 10 % discount rate over a 20-year period, unit costs are 5.83 USD/GJ for regular wood pellets and 6.87 USD/GJ for torrefied pellets at the plant gate, significantly higher than for wood chips. But as transport costs are introduced, pellets become more competitive due to their greater energy density.

At a transport cost of around 35 USD/tonne, wood pellets become competitive with wood chips. And at a transport cost of around 95 USD/tonne, torrefied pellets become competitive with wood pellets. These results are summarised in Figure 3.

Assuming a unit transport cost of USD 0.42/tonne-km, a total transport cost of USD 35/tonne would correspond to a trip of 83 km, and a total transport cost of USD 95/tonne to a trip of 226 km. In other words, end users within a radius of 83 km would be better off using woody biomass, those between 83 km and 226 km away would be better off using wood pellets, and those beyond a radius of 226 km would be best off using torrefied pellets.

A large potential market for solid biomass is for co-firing in existing coal-fired power plants, which allows a portion of the carbon emissions from these plants to be displaced while they remain in operation. Assuming a price of coal equal to USD 70/tonne at 25 GJ/tonne (USD 2.80/GJ), solid biomass fuel cannot easily compete on a cost basis unless it has a very low or negative production cost (such as where farm residues are being burned in the field, logging residues are being left in the forest, or municipalities are willing to pay plants to take waste they cannot readily dispose of elsewhere) and it is located nearby. However, co-firing prospects may improve as carbon emissions are priced in the marketplace.

Figure 3 – Comparison of unit costs at different transport costs



GLOBAL MARKETS FOR SOLID BIOFUELS

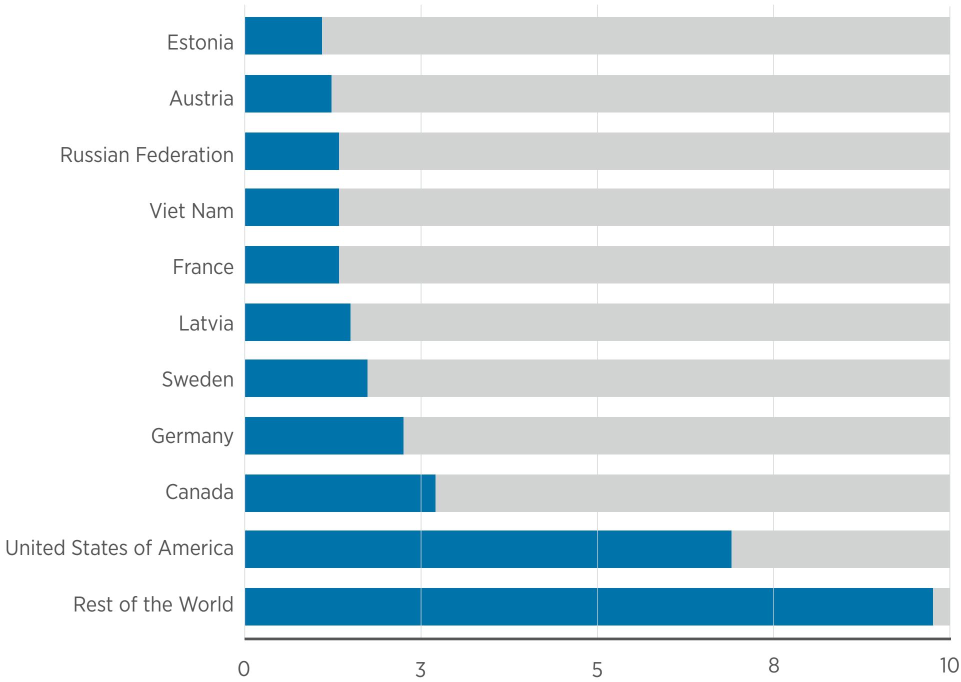
Wood pellets and ethanol are the most widely traded biofuels and have commodity-type markets according to Proskurina *et al.* (2017). Other biofuels do not have the same commodity status on world markets. The authors found that during the period from 2004 to 2015, the international trade in biomass for energy almost doubled, from around 800 PJ to 1 300 PJ. This is equivalent to about 5 % of the total bioenergy use globally in 2015. In respect of solid biofuels, the global trade in wood pellets increased from 30 PJ in 2004 to 220 PJ in 2015. The trade in charcoal increased from 30 PJ to 65 PJ over the same period, with fuel wood trade increasing from 35 PJ to 50 PJ.

The largest and most well-established global market for solid biomass is that of wood pellets. This a market that has gained worldwide coverage, and wood pellets are traded across different regions of the world. Although there has been a significant and growing trade in non-wood pellets (e.g. sunflower husks from Ukraine to Germany, palm kernel shells [PKS] and empty fruit bunches from Indonesia and Malaysia to Japan and Korea), the wood pellet market still dominates the global landscape.

The distribution of current wood pellet production is shown in Figure 4 and Table 8. In 2017, the global production of wood pellets reached 31.7 million tonnes (Mt). Europe is currently the major market for wood pellets. The region is the largest consumer, the largest producer and the largest importer in the world. North America (Canada and the United States) follows in second place. Europe is also a key region for the international wood pellet trade. While most European consumption is produced within Europe, a significant share of demand is supplied from abroad, mainly from Canada and the United States. This is currently the largest intercontinental trade flow. From 2009 to 2016, the spot price for industrial wood pellets at ARA (Amsterdam, Rotterdam, Antwerp) fluctuated between around USD 140/tonne and USD 180/tonne (Hoefnagels, Junginger and Resch, 2015; Argus Biomass Markets, 2016). In addition, growth in the Asian market, especially Japan and South Korea, has been seen recently.

The wood pellet industry has come a long way in developing the logistics infrastructure, standardisation of quality requirements and trade terms needed for large-scale, global biomass supply. Learning from that experience is an excellent starting point to scale up biomass supply from other sources and for other applications.

Figure 4 – Wood pellet production in major countries and the world in 2017 (Mt)



Source: FAO (2018), http://faostat3.fao.org/home/E.

Table 8 – Wood pellet production, trade and consumption in 2017 (Mt)

	Production	Imports	Exports	Consumption
Europe	17.8	14.6	9.4	23.0
North America	9.6	0.2	7.4	2.5
Asia	3.4	2.2	1.8	3.8

Source: FAO (2018), http://faostat3.fao.org/home/E.

CASE STUDIES: SOLID BIOFUEL LOGISTICAL SUPPLY CHAINS

This section highlights logistical supply chains for a variety of solid biofuel sources and applications:

- wood chips for electricity generation in Japan
- co-firing of wood for electricity generation in the Netherlands
- wood chips and pellets for heat and power production in Lithuania
- agricultural residues for heat and power production in India.

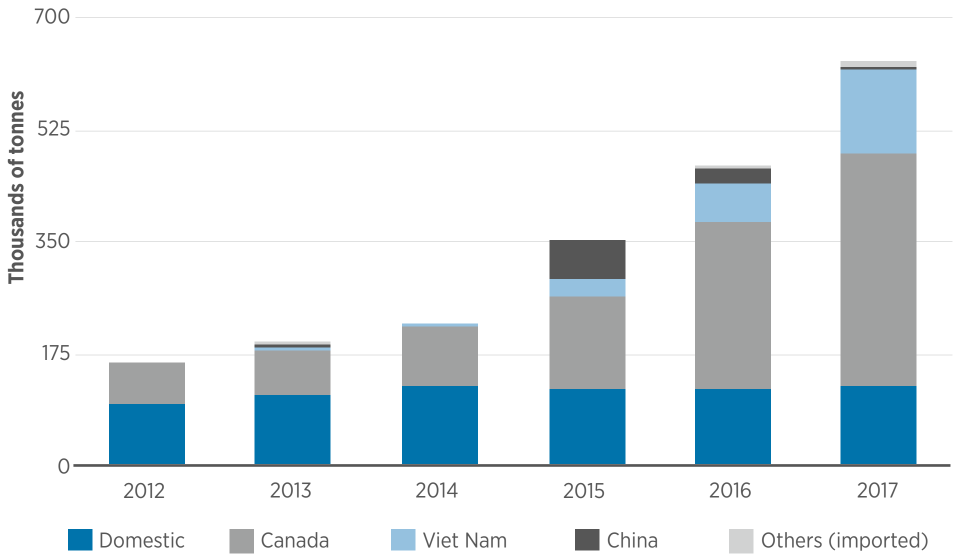
WOOD CHIPS FOR ELECTRICITY GENERATION IN JAPAN

The use of wood for energy has been expanding in Japan, where two-thirds of the land is covered by forests in which some 100 million m^3 of wood stocks grow each year. In 2016 solid wood biomass used for heat and power amounted to some 8.89 Mt, of which seven-eighths (87 %) were chips (MAFF, 2016).

Over half of the chips (51 %) are derived from demolished **building materials**, a quarter are from thinned wood and logging residues, and most of the rest (21 %) are from lumber production processing residue. The heavy reliance on used building materials is largely due to the Construction Material Recycling Act of 2000.

Thinned wood and **logging residue**, such as treetops and branches that are not suitable to be sawn into lumber, are of relatively low value and typically left in the forest due to the cost of transporting them to market. But the Forest and Forestry Basic Plan adopted in 2016 sets an aspirational goal to expand domestic wood supply from 24 million m^3 in 2014 to 40 million m^3 in 2025. The volume of thinned wood and logging residue for bioenergy feedstock is forecast to quadruple from 2 million m^3 to 8 million m^3 over the same period.

Figure 5 – Supply of wood pellets for energy in Japan



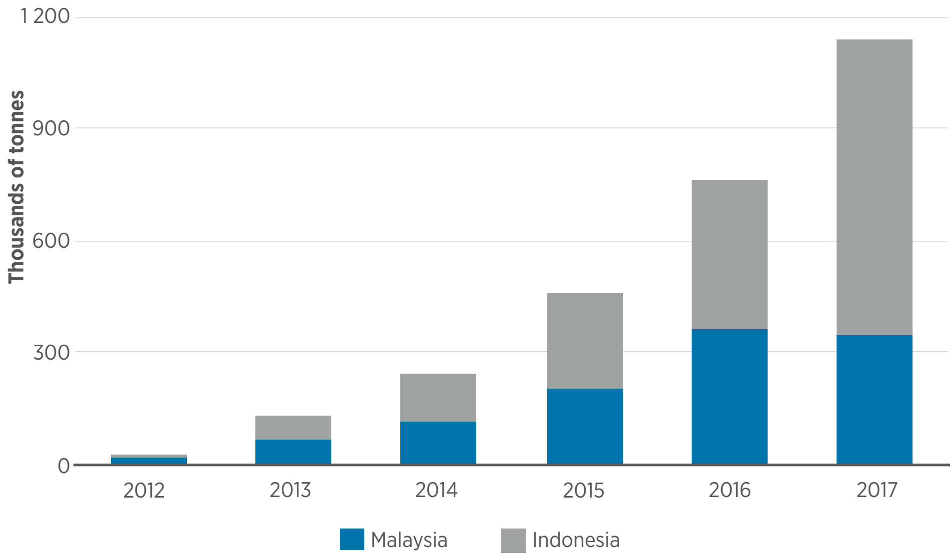
Notes: Data on import refer to customs code 4401.31.000 in the foreign trade statistics; t = tonne.
Source: Japan Forestry Agency (2018), "Production trend of wood pellets in 2017", www.rinya.maff.go.jp/j/press/riyou/attach/pdf/180907-4.pdf.

About 50 % to 60 % of wood processing residue is utilised for energy purposes. While 56 % of wood chips for energy use derived from wood processing residue are self-consumed at wood processing plants, the remaining 44 % are purchased by energy producers, including power plants.

Wood pellets are starting to gain market share as demand for renewable electric power increases. Pellet use has tripled in just three years to over 600 000 tonnes (600 kt), mostly through imports from Canada and Viet Nam (Figure 5).

Palm kernel shells (PKS) from Indonesia and Malaysia are also increasingly being used to provide fuel for power plants, as they can be supplied reliably in bulk to provide the large-scale inputs that such plants require (Figure 6). Some plants blend PKS with logging residue as feedstock to boost the overall heat content of the fuel.

Figure 6 – PKS imports for energy in Japan



Note: Data refer to the sum of customs code 2306.60.000 in the foreign trade statistics.
Source: Japan Forestry Agency (2018), "Production trend of wood pellets in 2017", www.rinya.maff.go.jp/j/press/riyou/attach/pdf/180907-4.pdf.

Resurgent use of wood for energy in Japan has been led by the expansion of biomass generating capacity since the introduction of a feed-in tariff (FIT) system in 2012. By September 2017, 473 wood biomass power plants with a capacity of 11.67 gigawatts (GW) had been approved under the FIT system, of which 82 plants with 0.48 GW of capacity had begun operation. Of those in service, 53 plants with 0.40 GW of capacity use thinned wood and logging residue as feedstock as these fuels enjoy the highest FIT premium.

Example of biomass-fuelled power plant in Oita Prefecture

A power plant owned by Green Power Generation Oita Co. (GPGO), in the town of Hita, was one of the first in Japan to operate on thinned wood and logging residues. It has been in operation since 2013 with a generating capacity of 5.7 MW, using 70 kt of feedstock (42 kt on a dry basis) per annum. Hita's Chamber for Effective Wood Resource Utilisation plays a central role in procuring a stable supply of feedstock for the plant.

The city has long been a hub for wood distribution and the wood industry in the region, with 330 000 m^3 of industrial roundwood production, 7 roundwood markets trading 540 000 m^3 in 2017, and nearly a hundred sawmills. The chamber was established in 2007 by 18 small local entities to address the challenge of how effectively to harness untapped resources, such as logging residues, small-diameter trees, low-quality trees and trees damaged by deer nibbling (Green Power Generation Oita Co, 2018) (Hita City, 2017).

Under the feedstock supply system established by the chamber, procurement agreements are signed between Japan Forest Co., a chip plant located adjacent to the power plant, and each of the logging companies. Based on these agreements, transaction volumes are set on a monthly basis so that enough feedstock for each month can be stored in the stockyard.

Japan Forest Co. collects wood within a range of 50 km, and the wood is delivered exclusively by carriers that are members of the chamber. This ensures that the Guidelines on Verification of Wood Biomass to be Used for Power Generation, which set the rules and procedures for managing three different categories of wood defined under the FIT, are applied in a transparent and consistent manner. Members of the chamber are encouraged to regularly attend training sessions on how to apply the guidelines.

Japan Forest Co. purchases wood at the fixed rate of JPY 7 000 per tonne, after which the wood is air dried for 6 months to reduce its moisture content to 35 %, crushed into chips, and carried to GPGO's plant by conveyor belt machinery and wheel loaders.

As this example shows, logistical supply chains for wood biomass feedstock to use in power plants are straightforward to set up in locations where forestry provides a steady stream of logging and processing residues.

However, such residues typically make up just 20–30 % of wood volumes harvested. Thus, strong markets are needed for higher-value wood products, such as lumber, from which residues are then generated. Several policies have been put in place to incentivise the use of wood in construction of public and commercial buildings, which can displace large amounts of carbon-intensive materials such as steel and cement.

CO-FIRING OF WOOD FOR ELECTRICITY GENERATION IN THE NETHERLANDS

RWE, the German power company, is partially converting two hard-coal-fired power plants in the Netherlands to generate electricity from wood pellets. To do so, RWE was awarded subsidies in 2016 for a period of eight years, based on a competitive bidding system under the Stimulation of Sustainable Energy Production (SDE+) programme, commissioned by the Ministry of Economic Affairs and Climate Policy of the Netherlands and implemented through the Netherlands Enterprise Agency. As per the subsidy requirement, this partial conversion should be completed in 2019, within three years from the time the subsidies were allocated (RWE Generation NL, 2018).

The subsidies awarded will allow RWE to replace around 15 % of coal use with 0.8 Mt per year of wood pellets at the 1600 MW Eemshaven plant and around 80 % of coal use with 1.7 Mt per year of pellets at the 600 MW Amer plant. Based upon combustion efficiencies of 46 % at the former and 41 % at the latter, one can surmise that the pellets will generate about 3.2 TWh per year at Amer and 1.7 TWh per year at Eemshaven.

The wood pellets are sourced from various locations that differ over time and across contracts. Recent sources of pellets have included Portugal and the Baltic states. The wood pellets are supplied through bilateral contracts with pellet producers, normally for multiple years. The contracts can be wide-ranging and include a number of detailed provisions regarding transfer of ownership, lay time (how long pellets are allowed to lay idle at various points along the supply chain), insurance, force majeure, default, shipping vessels and sustainability. Some of the key provisions vary on a case-by-case basis depending on the supplier, for instance in relation to quality requirements.

In order to safeguard the sustainability of biomass supply, a system of sustainability assessment and control was established by the Ministry of Economic Affairs and Climate Policy. Subsidy recipients need to demonstrate that their biomass supply is sustainable using certification schemes, approved by the Minister of Economic Affairs and Climate Policy, or rely on third-party verification. Both certification and third-party verification require the approval of an independent Conformity Assessment Body recognised by the ministry. The task of this body is to declare that the biomass complies with the sustainability requirements and is thereby eligible for the SDE+ subsidy.[2]

Timely and consistent feedstock delivery is ensured by detailed provisions in the offtake contract, including requirements for delivery times (or time windows), penalties in case of failure to deliver, and quality specifications. The quality specifications for the pellets are all stated in the offtake contract, and quality controls (through specialist third-party companies) are established at various steps along the supply chain to ensure the pellets meet high quality requirements.

Prices and costs are confidential, but the maximum subsidy provided by the programme is EUR 60–70 per megawatt hour (MWh), based on competitive bidding. The power price on top of this is capped in the regulation at EUR 39 per MWh. Hence, an estimate of the maximum production cost is at around EUR 100–110/MWh. The price of wood pellets used in the power plants would presumably be similar to prices observed in the international market for industrial pellets. From November 2017 to September 2018, those prices varied in the range of EUR 130–150 per tonne (CIF-ARA). Using the plant conversion efficiencies stated above, this implies feedstock costs of around EUR 70 per MWh. Since this is higher than the cost of coal, subsidies are needed to allow wood pellets to compete. In the future, if CO_2 prices and/or coal prices increase, subsidies for biomass may no longer be needed.

2 For detailed information on the sustainability criteria of the SDE+ programme, refer to https://english.rvo.nl/subsidies-programmes/sde/sustainability-criteria.

WOOD CHIPS AND PELLETS FOR HEAT AND POWER PRODUCTION IN THE BALTIC REGION

One of the barriers to the widespread deployment of solid biomass fuels is the lack of established markets to mitigate risks associated with product quality, delivery and price. One approach to dealing with this barrier, outside of market regulation or bilateral contracts, is the creation of formal market hubs with established rules, where buyers and sellers can meet and trade their biomass products.

An interesting example of such a market hub for solid biomass trading is the Baltpool Biomass Exchange which operates in Latvia and Lithuania (Baltpool, 2018). Incorporated in 2009, Baltpool has the following objectives:

- to promote competition in and development of the solid biofuel market in Lithuania
- to improve the transparency and reliability of the market, by ensuring conditions for the formation of transparent, objective and economically substantiated prices for traded products
- to increase standardisation of the solid biofuel sector by developing specific rules under which all market participants can compete on equal conditions.

The Biomass Exchange is an online trading venue that allows buyers and sellers to finalise contracts electronically according to established rules and procedures. Sellers (suppliers of biomass) and buyers (normally heat production companies) interact anonymously. Through the Baltpool trading system, participants can quickly and easily sell their products and purchase the required quantity of biomass.

Orders to buy and sell solid biofuels, specifying the quantity and types of products delivered or accepted per week, are placed through an electronic trading system following a fixed schedule. Based on the orders placed, an auction is held each week. During the auction, contracts are finalised according to placed orders to buy and to sell. Contracts are only finalised if the following conditions are satisfied:

- The same product is being purchased and sold, i.e. the biomass type and delivery period match.
- The method used by the buyer to evaluate the quantity of delivered biomass (by volume or weight) coincides with the method specified by the seller at the time the biomass order is placed.
- The distance to the buyer's site does not exceed the maximum transport distance specified by the seller.
- The order quantity (or the remaining unexecuted share of the order) is greater than or equal to the minimum order quantity specified in the respective order placed by the other party.
- The price of the order to sell is less than or equal to the price of the order to buy.

The auction takes place according to the buyer auction principle, i.e. every order to buy is matched against all orders to sell that satisfy the conditions listed above. The final price of orders to sell is calculated with consideration to individual distances between the buyer and the seller. Contracts in the Biomass Exchange are finalised electronically, in accordance with laws regulating trade. Once an auction is completed, electronic trading system contracts are finalised automatically based on the orders placed. When trading results are announced, participants receive electronic copies of the finalised contracts of purchase and sale of biomass. There is no need to sign further contracts of purchase and sale of biomass; contracts signed electronically have the same legal power as paper contracts.

Wood chip products, of which there are four types, must meet the technical specifications listed in Table 9. Raw material categories are defined for each type of wood chip product according to the following list:

1. Stemwood:
   1.1 Broad-leaved trees,
   1.2 Coniferous trees,
   1.3 Mixed.

2. Residues from wood processing industry:
   2.1 Half logs,
   2.2 Timber offcuts,
   2.3 Sawdust,
   2.4 Shavings.

3. Whole trees without roots:
   3.1 Broad-leaved trees,
   3.2 Coniferous trees,
   3.3 Short-rotation coppice,
   3.4 Mixed.

4. Logging residues:
   4.1 Tree stumps,
   4.2 Tops,
   4.3 Branches,
   4.4 Bushes,
   4.5 Stems of small trees,
   4.6 Offcuts (from forestry operation).

5. Non-forest wood:
   5.1 Park, garden, roadside maintenance.

Table 9 – Wood chip technical specifications in Baltpool

Wood chip type	SM1	SM1W	SM2	SM3
Moisture content (minimum-maximum), % as received	20 %–45 %	35 %–55 %	35 %–55 %	35 %–60 %
Ash content, % of dry basis	up to 2 %	up to 2 %	up to 3 %	up to 5 %
Main fraction, minimum mm Main fraction, maximum mm (minimum quantity, %)	≥ 3.15 ≤ 63 (80 %)	≥ 3.15 ≤ 63 (80 %)	≥ 3.15 ≤ 63 (70 %)	≥ 3.15 ≤ 63 (60 %)
Allowable share of small particles (< 3.15 mm), %	Up to 2 %	Up to 5 %	Up to 10 %	Up to 25 %
Large fraction with maximum cross-section of 6 square cm (maximum quantity, %)	> 100 (up to 10 % of weight)	> 100 (up to 10 % of weight)	> 100 (up to 10 % of weight)	> 100 (up to 10 % of weight)
Maximum allowable length, mm	< 150	< 150	< 150	< 220
Chlorine content (% of dry matter)	< 0.02 %	< 0.02 %	< 0.02 %	< 0.03 %
Raw material types (per list page 40)	1	1; 2.1; 2.2	1; 2; 3; 4.1	All
Allowable admixtures	–	–	Dry leaves, dry needles	Leaves, needles

Source: Baltpool (2018), Baltpool Biomass Exchange, www.baltpool.eu/en/about-exchange/.

Table 10 – Wood pellet technical specifications in Baltpool by pellet type

Wood pellet type	*MG1*	*MG2*	*MG3*
Ash, % dry basis	≤ 0.7	≤ 1.2	≤ 2.0
Mechanical durability, % as received	≥ 98.0	≥ 97.5	≥ 97.5
Nitrogen, % dry basis	≤ 0.3	≤ 0.5	≤ 1.0
Sulphur, % dry basis	≤ 0.04	≤ 0.05	≤ 0.05
Chlorine, % dry basis	≤ 0.02	≤ 0.02	≤ 0.03
Ash deformation temperature, °C	≥ 1200	≥ 1100	≥ 1100

Source: Baltpool (2018), Baltpool Biomass Exchange, www.baltpool.eu/en/about-exchange/.

The Biomass Exchange also trades three types of wood pellets. They must all meet a set of common requirements, listed immediately below, and additional requirements by type, listed in Table 10.

- net calorific value: ≥ 4.6 kWh/kg
- bulk density (BD): 600 kg/m^3 ≤ BD ≤ 750 kg/m^3
- moisture, as received, ≤ 10 %
- diameter: 6±1 mm or 8±1 mm, and length (L): 3.15 mm ≤ L ≤ 40 mm
- additives in production are limited to 1.8 % of biomass inputs by weight
- post-production additives (e.g. coating oils) are limited to 0.2 % of the pellet weight
- fine particles in biomass (< 3.15 mm), as received, to be no greater than 1.0 %
- limit for the temperature of pellets at the loading point for end-user deliveries: 40 °C
- maximum concentrations of arsenic, cadmium, chromium, copper, lead, mercury, nickel, zinc.

During the 2017–2018 heating season, Baltpool was extremely active:

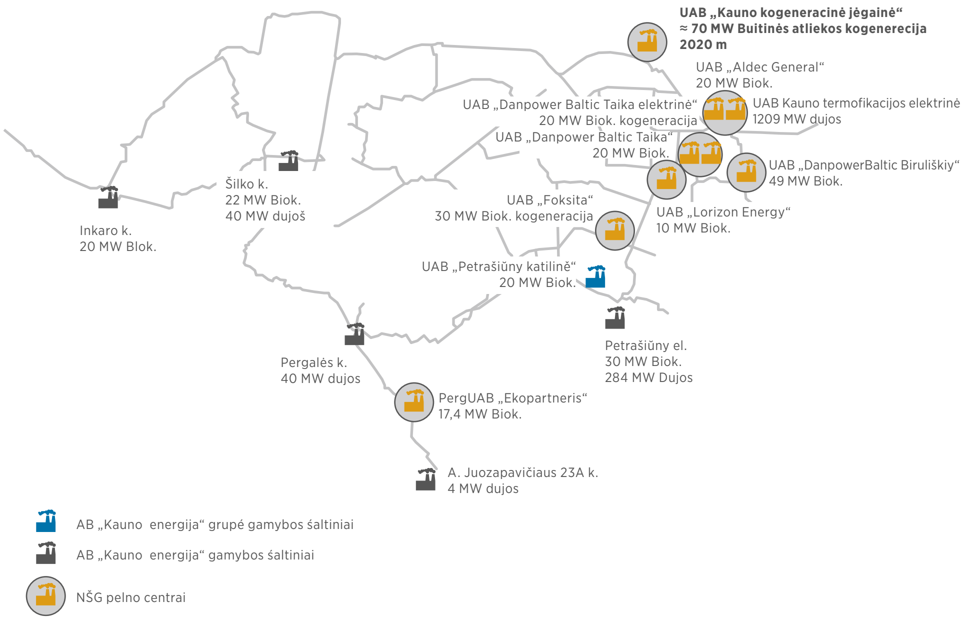
- Biomass amounting to over 296 kt oil equivalent was supplied under 4 067 contracts that were executed between 61 buyers and 102 sellers from Latvia and Lithuania.
- Purchases by heat supply enterprises accounted for 96.5 % of the value of biomass traded.
- The value of biomass supplied totalled EUR 53.6 million at an average weighted price of EUR 180.98 per tonne of oil equivalent (toe).
- Long-term supply contracts covered 42 % of biomass supplied at a price averaging EUR 161.79/toe.
- One-month contracts covered 14 % of biomass supplied at an average price of EUR 180.60/toe.
- One-week contracts covered 44 % of biomass supplied at an average price of EUR 199.08/toe.

Example of district heating systems in Kaunas, Lithuania

Kaunas is a town in Lithuania of some 288 000 people. It has an integrated network of 13 district heating plants (Figure 7), which bid against each other in a competitive heating market. Four of these plants are owned by Kauno Energija and the other nine by independent heat producers (of which eight are biofuel based and one is gas based).

The output of the biofuel plants ranges from 13 megawatts thermal (MWth) to 48 MWth. They operate throughout the heating season, which extends approximately from mid-October to mid-April. In 2017, 72 MW of capacity and 434 000 MWh of heat were provided to the grid from the four facilities owned by Kauno Energija, the grid operator and heat producer, of which 395 708 MWh (91 %) were produced using biofuel. An additional 195.5 MW of capacity and 858 018 MWh of heat were provided by independent heat producers, whose joint capacity is projected to expand to over 265.5 MW by the end of 2019.

Figure 7 – Map of heat producers in Kaunas, Lithuania



Source: Kauno Energija (2018).

Disclaimer: Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

Overall solid fuel demand on the integrated heating grid, including wood pellets and chips, ranges from 2 800 toe in the warmest month to 16 500 toe in the coldest month. In cold months, all the plants win bids to supply heat to the grid. In warm months, just a few of the plants win bids, and the others are idle. The bids are sufficient, on an annual basis, to keep all the plants running profitably. Solid biofuel has increasingly displaced natural gas as fuel for the grid and by 2017 accounted for 90 % of the fuel demand to generate heat. Most plants procure their biomass through the Baltpool Biomass Exchange.

When a plant wins a bid to supply heat to the grid, a mix of long-term, monthly and weekly biofuel purchase and sale contracts is used.

Suppliers from all over Lithuania participate in fuel delivery. Fuel is usually brought from the nearest supplier's storage facility or production area, but may also come from more distant places if not too costly; some is even imported from abroad, such as Belarus. The Kaunas region is served by 30 to 40 suppliers, of which the largest 3 cover roughly three-fifths of biofuel demand.

Once biofuel purchase and sale contracts are finalised, fuel is delivered throughout the contract period, mostly during normal working hours unless otherwise agreed. It is typically carried by heavy trucks with 90 m^3 capacity, except in the case of one district heating plant that is served by railway. There have been no essential fuel delivery breaks; Baltpool rules providing financial remedy for delivery breaks ensure they are rare.

AGRICULTURAL RESIDUES FOR HEAT AND POWER PRODUCTION IN INDIA

The development of farm residues as a mainstream biomass fuel faces a major logistical challenge: mobilising them from their widespread sources. The core business of farmers is not in establishing reliable biomass supply chains, but in producing food. And most farms are too small to establish the necessary supply chains at scale individually. So a key logistical role may be played by companies that are able to source and supply biomass at large scale, of suitable quality, at an affordable price.

One such company in India is the Punjab Renewable Energy Systems Pvt. Ltd. (PRESPL), which was organised in 2011 to meet the fuel needs of Punjab Biomass Power Ltd., a 12 MW paddy straw power plant in India. Since its founding, the company has expanded to offer fuel supply services to other power plants and combined heat and power plants, including those used in the agro-processing sector.

It organises biomass collection, aggregation, processing, transport and storage, with supply chain management from field to energy plant. It handles up to 1 kt of solid biomass per day during the peak season, and is thus established as the largest provider of biomass fuel aggregation and supply services in India (PRESPL, 2018).

Agricultural residues are often burned or left to decay in the fields after harvesting, causing severe air pollution problems in many regions of India. Since many farmers have limited time after harvest to prepare their land for the next crop, they often do so simply by setting the residues on fire, rather than making the effort to collect them. PRESPL offers a convenient system for collecting these residues, within established timeframes, at agreed prices.

The firm arranges to collect residues from the field, bring them to a storage centre, and process them according to end-user needs, such as comminution (reduction of particle size), homogenisation, drying, briquetting or palletisation and storage. It also arranges long-term purchase agreements to deliver biomass products of specified price and quality according to the schedule that end users require. Further, it ensures sustainability through audits by Zurich Responsibility, which has a minority stake in the firm. Some 500 Mt of residues may be burned in India each year, so they represent a large potential resource.

PRESPL aggregates agricultural residues for bioenergy projects through its central biomass supply depots. These depots are responsible for processing the biomass residues, storing the final product and delivering feedstock to end users. They are supplied by several collection centres located around the depot, which in turn are fed by village-level entrepreneurs (VLEs).

VLEs are active village members who are responsible for collecting biomass residues from farmers and transporting the residues to collection centres, where they are paid upon delivery according to established prices and quality requirements. They play a vital role in the overall logistical chain and biomass supply scheduling. A typical VLE works with eight to ten farmers, whose plots vary in size and in food and residue production per unit of land from the crops planted. A farm plot of about one acre (0.405 ha) is required to aggregate and collect 1 Mt of cotton stalks or 1.5 Mt to 2 Mt of sugarcane trash.

VLEs are recruited in the region amongst candidates who have a good network of farmers in the nearby area, good interpersonal skills, past business experience of some sort, and sound financial condition. Owning farming assets such as tractors or trailers is an added advantage.

VLEs are trained in how to organise resources, plan for the biomass collection and delivery, work with the team of farmers, and manage assets such as tractor, load carrier and small working capital. They are also provided with the necessary machinery, such as cutters, rakers, shredders and balers. PRESPL has developed equipment customised for various operations and adapted to Indian conditions of land holding in order to speed up biomass collection and aggregation. Customised trolleys, suitable for transporting residues on the scale produced by each farmer, are illustrated in Figure 8.

Figure 8 – Customised trolleys for transporting agricultural residues

Photographs: PRESPL (2018).

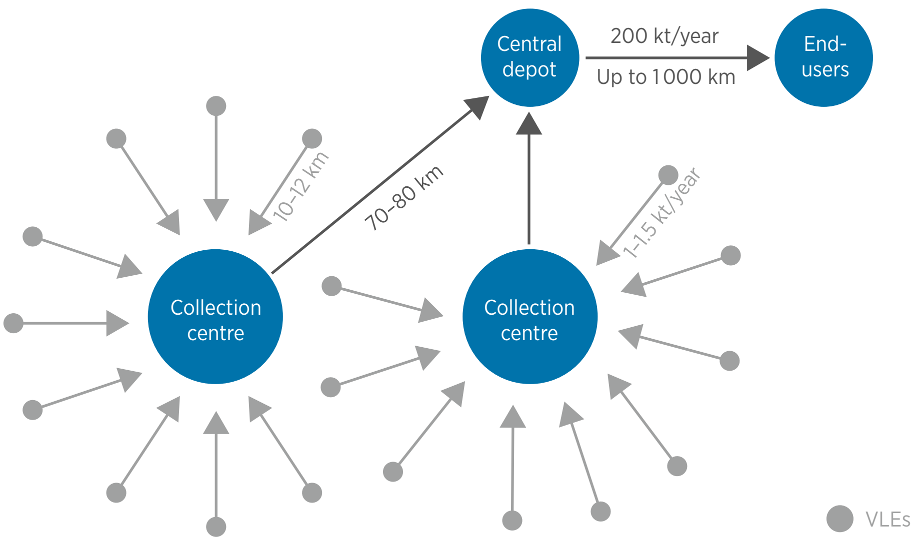
A typical biomass depot processes around 200 kt of biomass per year, collected from land spread over a 70–80 km radius (Figure 9). This central depot is served by 15 to 20 collection centres, each of which aggregates 10–12 kt of biomass per year from farms within a 10–12 km radius. A typical collection centre is fed by 10 to 15 VLEs, each delivering around 1.0 to 1.5 kt of biomass annually.

Before the 12 MW Punjab Biomass Power plant was built, a survey was conducted in 95 villages within a 13 km radius. These villages proved able to supply nearly 100 kt per year of fuel, or 80 % of the plant's needs.

The procurement area for biomass residues to fuel the plant spans a radius of some 25 km (Figure 10).

PRESPL has supplied various energy projects with diverse types of biomass (such as paddy straw, cotton stalk, cane trash, mustard residue, rice husk, bagasse, Prosopis Juliflora, maize cob). It has also supplied the biomass in various forms – loose, baled, shredded and briquetted. The projects include biomass-based power plants and processing plants using biomass in their boilers under fuel supply agreements.

Figure 9 – Schematic of crop residue collection by VLEs



Source: PRESPL (2018).

Figure 10 – Farm residue supply area for Punjab Biomass Power plant

Sources: PRESPL (2018)/Google Maps.

Disclaimer: Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

REFERENCES

AEBIOM (European Biomass Association) (2008), New Dedicated Energy Crops for Solid Biofuels.

Argus Biomass Markets (2016), Weekly Biomass Markets News and Analysis, Issue 16-014.

Bain, R.L. (2007), World Biofuels Assessment – Worldwide Biomass Potential: Technology Characterizations, Milestone Report, NREL/MP-510- 42467, National Renewable Energy Laboratory (NREL), www.nrel.gov/docs/fy08osti/42467.pdf.

Baltpool (2018), Baltpool Biomass Exchange, https://www.baltpool.eu/en/about-exchange/.

Batidzirai, B. *et al.* (2014), "Optimization potential of biomass supply chains with torrefaction technology", Biofuels, Bioproducts and Biorefining, Vol. 8, Issue 2.

BISYPLAN (2012), The Bioenergy System Planners Handbook, http://bisyplan.bioenarea.eu/.

Brinsmead, T.S, A. Herr and D.A. O'Connell (2014), "Quantifying spatial dependencies, trade-offs and uncertainty in bioenergy costs: an Australian case study", Biofuels, Bioproducts and Biorefining, Vol. 9, pp.21–34, Society of Chemical Industry and John Wiley & Sons Ltd.

De Jong, S. *et al.* (2017), "Cost optimization of biofuel production – The impact of scale, integration, transport and supply chain configurations", Applied Energy, Vol. 195, pp. 1055–70, http://dx.doi.org/10.1016/j.apenergy.2017.03.109.

De Wit, M., S. M. Lensink and M. Londo (2010), "Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part I: Land productivity potentials", Biomass and Bioenergy, Vol. 34, pp. 159–72.

EUBIONET3 (2011), Solutions for Biomass Fuel Market Barriers and Raw Material Availability: Summary of the EUBIONET III Project Results, https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/eubionet_iii_publishable_report_en.pdf.

Ehrig, R. *et al.* (2013), "Economic comparison of torrefaction-based and conventional pellet production-to-end-use chains," 21st European Biomass Conference & Exhibition, Copenhagen.

FAO (Food and Agricultural Organization of the United Nations) (2018), FAO Statistics Division website, http://faostat3.fao.org/home/E

FAO (2015), Wood Fuel Handbook, FAO, Rome.

Fiori, L. *et al.* (2014), "Hydrothermal carbonization of biomass: design of a batch reactor and preliminary experimental results", Chemical Engineering Transactions, Vol. 37, pp. 55–60, DOI: 10.3303/CET1437010.

GBEP (Global Bioenergy Partnership) (2018), GBEP website, http://www.globalbioenergy.org/.

Gerssen-Gondelach, S. *et al.* (2014), "Competing uses of biomass: Assessment and comparison of the performance of bio-based heat, power, fuels and materials", Renewable and Sustainable Energy Reviews, Vol. 40, pp. 964–88.

Goh, C.S. and M. Junginger (eds) (2014). Low Cost, Long Distance Biomass Supply Chains, IEA Bioenergy Task 40.

Green Power Generation Oita Co. (2018), email correspondence on feedstock procurement system, 22 October 2018.

Hita City (2017), Vision for Transforming Forestry into Growth Industry, www.city.hita.oita.jp/material/files/group/28/kouso.pdf.

Hoefnagels, R., M. Junginger and G. Resch (2015), "Coordination of biomass resource availability import strategies and demand". http://www.diacore.eu/images/files2/Coordination_of_biomass_resource_availability_import_strategies_and_demand.pdf.

IEA (International Energy Agency) (2012), Technology Roadmap: Bioenergy for Heat and Power, OECD/IEA, Paris, www.iea.org/publications/freepublications/publication/2012_Bioenergy_Roadmap_2nd_Edition_WEB.pdf.

IRENA (2017a), Perspectives for the Energy Transition – Investments Needs for a Low-Carbon Energy System, International Renewable Energy Agency, Abu Dhabi.

IRENA (2017b), IRENA Project Navigator – Technical Concept Guidelines for Solid Biofuels from Woody Biomass, IRENA, Abu Dhabi.

IRENA (2016a), Innovation Outlook: Advanced Liquid Biofuels, IRENA, Abu Dhabi.

IRENA (2016b), Boosting Biofuels: Sustainable Paths to Greater Energy Security, IRENA, Abu Dhabi.

IRENA (2014), Global Bioenergy Supply and Demand Projections: A Working Paper for REmap 2030, www.irena.org/remap/IRENA_REmap_2030_Biomass_paper_2014.pdf.

I**RENA (2012)**, Biomass for Power Generation, Renewable energy technologies cost analysis series, Vol. 1: Power Sector, Issue 5/5, IRENA, Abu Dhabi, www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-BIOMASS.pdf.

ISO (International Organization for Standardization) (2018), ISO 13065:2015 Sustainability Criteria for Bioenergy, www.iso.org/obp/ui/#iso:std:iso:13065:ed-1:v1:en.

Japan Forestry Agency (2018), "Production trend of wood pellets in 2017," press release on 7 September 2018, www.rinya.maff.go.jp/j/press/riyou/attach/pdf/180907-4.pdf.

Kauno Energija (2018), e-mail correspondence with Rimantas Bakas, Director General, 17 August and 12 September 2018.

Kofman, P. D. (2010), "Preview of European standards for solid biofuels", Programme of Competitive Forestry Research for Development, Ireland, www.woodenergy.ie/media/coford/content/publications/projectreports/cofordconnects/pp23.pdf.

Koppejan, J. *et al.* (2015), Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction, SECTOR project, https://sector-project.eu/fileadmin/downloads/deliverables/SECTOR_D10.2_Procede__FINAL.pdf.

Koppejan, J. *et al.* (2012), Status Overview of Torrefaction Technologies, IEA Bioenergy Task 32, www.ieabcc.nl/publications/IEA_Bioenergy_T32_Torrefaction_review.pdf.

Libra, J. A. *et al.* (2011), "Hydrothermal carbonization of biomass residuals: A comparative review of the chemistry, processes and applications of wet and dry pyrolysis", Biofuels, Vol 2, pp. 71–106.

MAFF (Japan Ministry of Agriculture, Forestry and Fisheries) (2016), Statistics on Wood Biomass Use 2016, www.maff.go.jp/j/tokei/kouhyou/mokusitu_biomass/index.html.

Miao, Z. *et al.* (2012), "Lignocellulosic biomass feedstock transportation alternatives, logistics, equipment configurations, and modeling", Biofuels, Bioproducts and Biorefining, Vol. 6, pp. 351–362.

NREL (National Renewable Energy Laboratory) (2011), International Trade of Wood Pellets, www.nrel.gov/docs/fy13osti/56791.pdf.

Panoutsou, C., J. Eleftheriadis and A. Nikolaou (2009), "Biomass supply in EU27 from 2010 to 2030", Energy Policy, Vol. 37, pp. 5675–86.

PRESPL (Punjab Renewable Energy Systems Pvt. Ltd.) (2018), company brochure, telephone interview and email correspondence, August/September 2018.

Proskurina S., *et al.* (2017), "Global biomass trade for energy – Part 1: Statistical and methodological considerations", Biofuels, Bioproducts and Biorefining, DOI: 10.1002/bbb.1841.

RWE Generation NL (2018), email correspondence, Technology and Innovation Group,30–31 August 2018.

Thek, G. and I. Obernberger (2009), "Wood pellet production costs under Austrian framework conditions", Proceedings of the 17th European Biomass Conference & Exhibition, Hamburg, pp. 2129–37, ETA-Renewable Energies, www.bios-bioenergy.at/uploads/media/Paper-Thek-Pellet-Production-Costs-2009-06.pdf.

Thraen *et al.* (2017), Global Wood Pellet Industry and Trade Study 2017, IEA Bioenergy Task 40.

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