World forest and agricultural crop residue resources for cofiring

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Preface

This report has been produced by IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member countries.

IEA Clean Coal Centre is an organisation set up under the auspices of the International Energy Agency (IEA) which was itself founded in 1974 by member countries of the Organisation for Economic Co-operation and Development (OECD). The purpose of the IEA is to explore means by which countries interested in minimising their dependence on imported oil can co-operate. In the field of Research, Development and Demonstration over fifty individual projects have been established in partnership between member countries of the IEA.

IEA Clean Coal Centre began in 1975 and has contracting parties and sponsors from: Australia, Austria, China, the European Commission, Germany, India, Italy, Japan, New Zealand, Poland, Russia, South Africa, Thailand, the UK and the USA. The Service provides information and assessments on all aspects of coal from supply and transport, through markets and end-use technologies, to environmental issues and waste utilisation.

Abstract

Biomass could have an important role in the strategy to reduce greenhouse gas emissions from large coal plants. Amongst the plethora of different biomasses, wood pellets have emerged as one of the most successful and fast growing internationally-traded commodities. Wood (and straw) pellets offer a more energy dense and transportable alternative to the traditional wood chip, a product most commonly associated with the paper and pulp industry.

A few large-scale projects in Europe have drawn on North American sources to supplement local supplies of biomass without any major problems. At current levels of demand, there appears to be an abundance of wood resource.

However, extending cofiring at low rates (5–10%) to the world's coal-fired fleet will increase demand for wood pellets significantly. Meeting this demand will offer opportunities and challenges for the entire biomass supply chain, not least forest resources. This report reviews the current understanding of world biomass resources using published forestry data from the UN Forestry and Agricultural Organization (FAO). From these data, the author attempts to identify a global and regional resource figure for wood in the form of residues and waste by-products that arise from the forestry industry and discusses the broad issues that affect forest resources worldwide.

Acronyms and abbreviations

ACFB	atmospheric fluidised bed
bcm	billion cubic metres
CFBC	circulating fluidised bed
CHP	combined heat and power (also known as cogeneration)
CO_2	carbon dioxide
DONG	Danish utility (formerly Dansk Olie og Naturgas)
EFB	empty fruit bunch
EJ	exajoules (1,000,000,000 GJ)
EU	European Union (28 member states as of 2014)
FAO	Forestry and Agricultural Organization (United Nations)
FFB	fresh fruit bunch
FOB	free-on-board
Gha	gigahectares
GJ	gigajoules
Gm^3	giga cubic metre
Gtoe	gigatonnes of oil equivalent
GWe	gigawatts electrical (1000 MWe)
ha	hectare (10,000 m^2 or 2.47 acres)
IEA	International Energy Agency (Paris)
IPCC	Intergovernmental Panel on Climate Change (United Nations)
IRENA	International Renewable Energy Agency
kg	kilogramme
kW	kilowatt
LCOE	levelised cost of electricity
m^3	cubic metre
Mha	million hectares
MJ	megajoule
Mm^3	million cubic metres
Mt	million metric tonnes (unless otherwise specified)
NOx	nitrogen oxides
PM	particulate matter
POME	palm oil mill effluent
PPF	palm pressed fruit
SO_2	sulphur dioxide
SOx	sulphur oxides
SC	supercritical (fluid at a temperature and pressure above its critical point where there is no distinction between liquid and gas phase)
USC	ultra-supercritical
t/ha	metric tonnes per hectare
TWh	terrawatt hours (1000 GWh)
WBA	World Biomass Association
WEC	World Energy Council

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1 Introduction

In 2012, global primary energy supply reached 560 EJ, equivalent to 19,000 Mtce (IEA, 2014). More than 81% comprises fossil fuels, 5% is nuclear power, and approximately 3% is renewable energy (hydropower, geothermal, solar, wind, and tidal). The balance is made up almost entirely of biomass and waste, which accounts for 10% of the global market. This considerable contribution supplies 56 EJ/y; equivalent to three times the energy provided by all other renewable energies combined. Yet, with regards to the reporting of resources and reserves, biomass attracts little interest and data are not as widely available as those for oil, gas, coal, although reasonably good data are available for the demand and supply of biomass.

Seventy per cent of biomass is used as a heating and cooking fuel in much of the world's poorest households. However, the role of the commercial power and heat sector has increased considerably in the last decade where the growth rate of biomass used in electricity generation increased by 8%/y, while growth in other sectors averaged just 1%/y. Biomass production is carried out at varying scales. Supplies to power stations in OECD nations require large investments in infrastructure and a secure and well managed logistical network in place, with strict quality controls and safety monitoring throughout. Reliability and consistency of both fuel quality and supply volumes are becoming essential.

While global biomass demand was 56 EJ (solids and liquids), the power and CHP sector accounted for just 5.6 EJ in 2012 (IEA, 2014). Most of this demand was in the OECD nations which consumed almost 4 EJ/y, half of which was Europe. Geographically, some of the highest growth occurred in non-OECD Asia where biomass in power generation grew 21%/y (OECD Asia, 8%/y). In North America, demand in this sector grew by just 1.5%/y. OECD Europe has the largest market for biomass power, and is growing rapidly at 10%/y (IEA, 2014). Globally, there are around 95 GWe of power plants burning solid and liquid biomass and waste as a primary fuel; around half of this burns solid fuels. Of this solid fuel capacity, half is harvested or waste biomass, the remainder is a range of industrial and municipal wastes (derived from Platt's, 2014).

Biomass has also been considered a viable supplement for fossil fuels. More than 150 power plants worldwide have experience of cofiring biomass or waste fuels, at least on a trial basis. Approximately 40 pulverised coal plants cofire biomass on a commercial basis with an average 3% energy input from biomass (Adams, 2013). As of 2014, the global coal fleet had a total generating capacity of 1848 GWe; of this, 36 GWe was capable of burning biomass as a secondary fuel, whether in cofiring or as a temporary substitute for the primary fossil fuel (Platt's, 2014). Based on the age profile of the world's coal-fired fleet, retirements and new plants currently under construction could mean the world's coal fleet in 2020 might be at least 1645 GWe (excluding plants that are currently at the planning stage).

The cofiring fuel market is becoming increasingly sophisticated, with processed wood pellet fuels being sourced in North America that are carefully matched with power plants in Europe. The heating values and moisture contents of pellets are not too dissimilar to some Indonesian coals. Yet Indonesia is the world's leading exporter of steam coal and shipping high-moisture, low-sulphur coals is commonplace. Geographical disparities between resources and customers begin to broaden if domestic resources are too expensive, insufficient, or less compatible with the power plant. International and intra-national trade are therefore becoming more important, but transporting biomass over longer distances means more challenges for handling and storage operators. As such, drying and pelletising makes transportation cheaper and less risky.

Modern material handling, storage, transportation and even international trade are now commonplace and expanding in the wood pellet sector. Cofiring pellets into coal–fired stations occurs at a commercial scale in a number of European economies, such as the UK, Netherlands and Belgium. In countries such as UK and Denmark coal units are being converted entirely to biomass plants. Raw biomass can be burned, but processed and compacted dry pellets manufactured from wood chips and straw are becoming the preferred fuel.

In 2013, the biomass pellet market reached 25 Mt/y, with much of the demand coming from Europe; opportunities to expand this further to serve the world's coal-fired power stations are abundant (Schill, 2014). This is bolstered by the European Council of Ministers who endorsed a binding European Union target of a 40% reduction in greenhouse gas emissions by 2030 (base year 1990). A binding target of 27% of final energy demand must also come from renewable energy, and biomass could play a critical role. Sustainably sourced biomass can provide a potentially carbon neutral source of fuel, and if it replaces part of the coal feed, can be effective in reducing CO_2 emissions from the plant. In response to regulatory pressure arising from greenhouse gas reduction legislation, more coal-fired power stations could easily adopt cofiring as a means of boosting output from renewable sources. Yet, due to the dearth of detailed biomass resource information, it is not clear whether the world's forest and agricultural activities will yield enough to supply a possible increase in demand over the long term.

1.1 Biomass – a challenge and opportunity for coal power

In 2011, the IEA World Energy Outlook focussed on climate change, stating that without immediate action to tackle a reduction in greenhouse gas emissions, specifically CO_2 from energy sources, the world would be locked into an energy path leading to an increase in global temperature of more than 2°C (IEA, 2011).

To meet the challenges of reducing CO_2, the world's 1848 GWe of coal-fired capacity could be upgraded to higher efficiency technologies to greatly reduce emissions (per MWh) under a comprehensive programme of unit replacement of old subcritical plants(Barnes, 2014). However, as a complementary measure, if the world's coal-fired fleet replaced just 5% of the fuel feed (by energy) with sustainably produced biomass, this could create a virtual biomass fleet of 82 GWe (roughly the same as the entire dedicated biomass capacity operating today). The market for biomass pellets could be as high as 235 Mt/y, even at these modest rates of cofiring. This would present major opportunities for growth in the world's transportation, handling, port and dry bulk freight industries. The pellet market could be larger than today's global coking coal demand and could save many millions of tonnes of CO_2 every year compared with burning 100% coal.

Biomass generation could also benefit from the high efficiencies and economies of scale achievable by burning in large-scale, coal-fired plants, compared with the lower efficiencies typical of smaller dedicated biomass plants. Higher percentages of cofiring are easily attained, and can even reach in excess of 15% without requiring major modification of the power plant, however this is dependent on the nature of the biomass being fired. Torrefaction offers even greater opportunities to increase injection rates, but as yet is not carried out at utility scale. The technical aspects of cofiring of biomass in coal-fired boilers are covered in a number of reports by Fernando (2005, 2009, 2012), Sloss (2010).

The success of high rates of cofiring with coal and coal conversions to biomass has been proven in Europe where fairly tight CO_2 reduction targets and strict air pollutant emissions (SOx, NOx, and PM) regulations place greater pressure on coal-fired plant operators. A third spur is a number of renewable energy objectives. Biomass can fulfil all of these for existing operators of coal-fired plants, but like all renewables, the costs and risks are high.

1.2 Why look at biomass resources?

Understanding energy resources is essential for long-term policy and planning, but in the wider audience, biomass is yet to be treated as a conventional resource. Global fossil fuel resources are published regularly by major energy and analytical groups such as the *German Federal Institute for Geosciences and Natural Resources* (BGR), BP, the *World Energy Council* (WEC), and *World Resource Institute* (WRI). Renewable resources are also considered, particularly hydroelectricity, wind and solar power, but biomass is probably more complex due to the wide variety of different solid, liquid and gaseous biomass from both primary and secondary sources (such as waste or other economic activities).

Many national and/or regional studies have attempted to determine the future scale of biomass resources, however, according to Mills (2013) there has been little consistency and many have adopted different assessment criteria; available assessments often differ in methods, time horizons, framework conditions, and specific biomass resources. As a consequence, in terms of future potential, there is frequently considerable disagreement between studies (Thrän and Bunzel, 2010). This report aims to clarify and understand the main sources of wood and straw in the world's forest and cereal crop industries.

According to the IEA (2014), the world's primary energy production was 564 EJ in 2012. The supply potential for biomass is therefore high, possibly contributing a fifth of world energy and a massive proportion of renewable energy. Research into supply and resources has been carried out but with a wide variety of outcomes depending on assumptions on growth in primary energy demand and land use. More recent studies tend to be more cautious than assessments made a decade ago due to the additional requirement to be more sustainable along the entire supply chain. Yet in all cases, studies looking at global resources tend to treat biomass as homogenous material expressed in energy terms (typically exajoules) for convenience. Standardising units is very useful for comparative purposes, but biomass trade journals are increasingly reporting solid biomass trade and prices as a dry bulk commodity, similar to coal or iron ore, which are expressed in units of mass, usually tonnes. This report therefore aims to compile and understand resource assessments done in exajoules, and carry out an in-house analysis based on (biomass) tonnage data reported for living forest, industrial wood production, and agricultural activities.

1.2.1 Scope of this study

This report look chiefly at two fuels which have been tested and commercially proven as power station fuels at a large scale: ***wood*** and ***straw***. Minimising impacts on the environment, land use, energy and water are desired, so it is assumed for this analysis that only wood residue and waste is used, and straw which is a by-product of cereal crop production. Non-cereal crop residues such as palm oil are also discussed briefly.

It is assumed that the collection of waste for cofiring should be incorporated in the normal routine clearing of waste for these industries and should not be a significant additional burden on the environment other than that arising from collection, processing and the transportation of the waste residues to the power plant. However, analysis of the supply chain of biomass residues is an area that requires further research. These industries may well be already managing forests to meet the needs of lumber and timber used in construction, furniture manufacture, or the paper and pulp industries. The analysis carried out by the IEA Clean Coal Centre attempts to derive resources in two ways:

- firstly, calculate the mass of a tree (and/or forest) that would be treated as residue if it were utilised. This determines the total resource within the current living forest stock (for example, bark, woody edgings and offcuts separated from wood during felling and cutting;
- a second assessment determines the residue produced from current forest activities every year, derived from roundwood production data. This provides an estimate for the current annual supply of waste and residues that could be used to produce biomass pellets. Assessments of straw resources are also carried out based on global data for cereal production.

1.2.2 Sustainability - a necessary but major constraint on biomass utilisation

Sustainability is an important feature of biomass resource assessment. To minimise the direct impact on the environment from biomass production (for energy), this report does not consider the whole tree or crop to be available for cofiring.; only part of the plant or tree that would otherwise be disposed of is treated as a potential feedstock. This way, primary crops and forest are avoided and fuel sourcing for cofiring is assumed to be from waste only.

Residue production resulting from forestry and agricultural activities may not be fully sustainable if the primary forestry and agricultural practice of tree felling and farming does not adhere to sustainable practice as outlined in Adams (2013). However, the topic of sustainable agriculture and sustainable forestry requires a great deal more research. To simplify the analysis, and minimise further conflicts with sustainability, this report excludes other biomass sources as follows:

- biofuels (dedicated biomass crops for liquid fuels for transportation and similar sectors);
- biomass otherwise allocated to timber production for construction and furniture, or wood for pulp/paper manufacture;
- short-/medium-term rotation crops (for example miscanthus and switch grasses) that use agricultural land that could conflict with food production. While waste land is often used for such crops, it could be used for food production.

Biomass harvested for liquid gasoline and diesel alternatives may affect indirect land use change (iLUC) accounting, a relatively new method of accounting that requires a great deal more scientific research (IEA, 2015). Sustainability assessments include the payback period for greenhouse gases resulting from trees/coppice that are felled and used for energy purposes only. Even for slow rotation forestry, species selection and the rate of growth of the replanted forest must be carefully selected and managed to ensure that sustainable practice is being carried out. Sustainability policies are being implemented for major cofiring projects across Europe to include extensive auditing of the biomass sources and reject any biomass that does not meet sustainability criteria (Henderson, 2015).

1.2.3 Structure of the report

In terms of report structure, Chapters 1 and 2 provide an introductory background on biomass. The report is then split up into four broad topics:

- **Chapter 3 – use and scale of biomass in the world's coal-fired power station**s as both a primary and secondary fuel (the latter assumed to be in cofiring with coal); the potential market for cofiring fuels in the world's existing fleet of coal-fired power stations under a low 5% cofiring rate is discussed;
- **Chapter 4 – global resource estimates for wood residue from forests,** derived from published material and own analysis based on FAO forestry data; an ultimate forest resource based on forest designated to industrial production (represented by the red perimeter in Figure 1):

- **Chapter 5 – an annual resource based on actual industrial roundwood production** (represented by black perimeter in Figure 1), but subject to the production of timber and paper/pulp. Presents the global resource of wood residue supply from 'current' production levels for 2013;
- **Chapter 6 – agricultural crop residues, chiefly straw from cereal crops,** but there is also a brief discussion on residues from tropical palm oil. Cereal crops are more complex in terms of resource estimation as residues such as straw have a multitude of uses. Power plant operators may need to compete with the agricultural market itself, which uses straw in both arable and pastoral (livestock) farming.

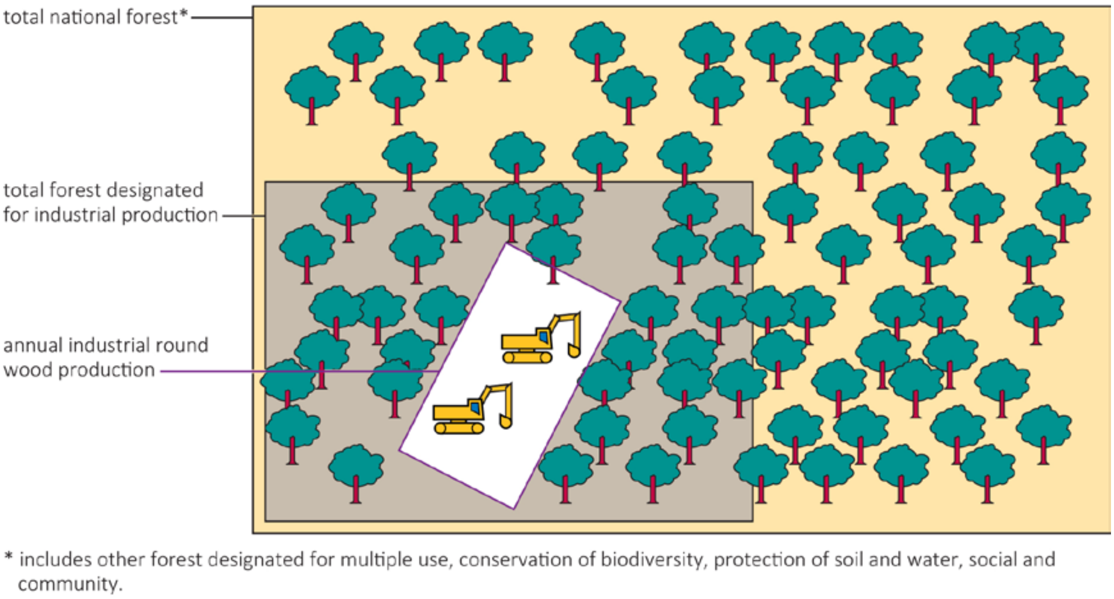


Figure 1 Broad categories of forest designated by function for resource estimation (IEA CCC, 2014)

1.2.4 Definitions

Waste wood can come from the construction industry and reclaimed furniture, but wood residue is a raw material that generally comes from felled forest and saw mills. For resource calculations, only forest areas that are officially designated for *industrial production* are considered. Forest designated for other uses which includes a mix of habitat and biodiversity *conservation*, *protection of soil and water*, and *social and welfare* (such as forest communities in Brazil) are not considered in the resource assessment to avoid any conflict with land use (*see* Chapter 4). Forest designated for *multiple uses* has a mix of all of these including industrial production, but without a clear demarcation of what is protected, forests for multiple uses are excluded.

The FAO obtains data on forest area, designation, biomass, land use and agricultural output from detailed land and satellite surveys, official national statistics, and national forest and agricultural associations. Crop production is by definition a managed resource, and so the resource is in direct relation to the crop harvest performance from the agricultural sector. For wood residue, the 'reserve' is calculated as a proportion of the growing forest designated for productive use only, while the annual resource (actual global residue production) is provided by yearly industrial roundwood (effectively the main trunk of a harvested tree) production. Short to medium rotation energy crops such as miscanthus and switchgrass are strictly energy crops and not residue. The wide-scale development of these crops has land use implications that could conflict with other crops unless these are developed on unused land.

1.2.5 Data sources

The source forest, roundwood production and agriculture output data are typically obtained from official national sources from the FAO. Problems with obtaining accurate biomass resource data could result in unclear political developments, a lack of consistent definitions for specific biomass fractions (such as logging residues), and interpretation of what constitutes degraded land. Furthermore, overall global biomass potential is likely to be significantly influenced by future food and feedstock demand. Competition for biomass from different end user markets can be intense and can narrow the potential resource available for the coal-fired sector. This competition is driven by population growth, per-capita consumption, development of yields for food, fodder and biomass production, and issues associated with possible climate change. The future scale and availability of sustainably-produced biomass resources will depend heavily on national and global political agreements concerning food security and sustainability, as well as consumer demand for food agricultural and forest derived products.

2 Biomass for power generation

The decision to convert part of the coal supply to a power station with biomass has been both technically and economically demanding in the past, but more recently, support for biomass schemes by some governments has greatly boosted interest. Power station operators can therefore benefit from the stable and reliable bulk delivery of coal-fired power, while neutralising part of the stations' CO_2 plant emissions.

The IEA World Energy Outlook (2014) suggests renewables could form an increasing proportion of the world's future primary energy mix, up to a fifth of demand (*see* Figure 2), while coal could provide a quarter by 2040. A great deal of this renewable energy could be from hydroelectricity, solar PV, and wind power, but cofiring biomass could complement these sources while not requiring the premature retirement of coal assets, many of which are still in the early days of operation in regions like non-OECD Asia. Before embarking on a review of the global biomass resource, the following sections outline the specific types of biomass that exist and identify those best suited for combustion for power generation. Biomass can be combined with any fossil-fuel, such as:

- cofiring solid biomass particles with coal;
- mixing with synthesis gas;
- landfill gas or biogas with natural gas.

Cofiring solid fuel with coal is a relatively low-cost, low-risk method of adding biomass capacity without a major outlay of capital expenditure (when compared to a dedicated biomass plant).

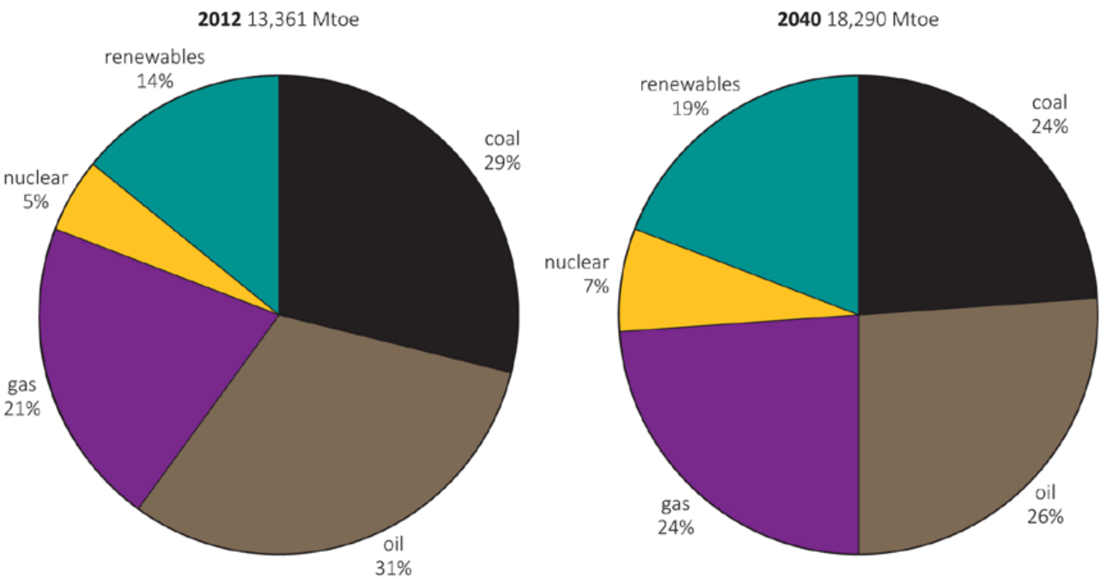


Figure 2 Projected primary energy demand in 2040 (IEA, 2014b)

In the past, more than 150 coal-fired power plants ranging in size (50–700 MWe) have gained considerable operational experience of cofiring woody biomass or wastes (IEA, 2004). Biomass can be cofired with any rank of coal from lignite to anthracite. Almost any biomass can be burned but for long-term operation burning a more carbon neutral fuel must be balanced against its impact on the efficiency and performance of the station.

Typically, raw biomass with a low energy density is dried and pelletised or used only locally. Often, such fuels are reserved for on-site generation in small heat or power plants where the fuel cost is effectively zero. Preferred fuel types, which might include chipped or pelletised herbaceous and woody materials, wet and dry agricultural residues and other energy crops, have been either tested or fired commercially in mixes of up to 15% of the fuel feed (by energy content). Operators of coal-fired or dedicated power stations might test a selection of fuels such as:

- forest wood, (including forest residues saw mill residues);
- urban wood waste (construction residues, furniture, garden waste); and
- agricultural crop residues (straw and maize/corn);
- short rotation (1–5 years) coppiced wood and grasses (switchgrass, miscanthus, eucalyptus, willow and poplar trees);
- waste or recycled paper and cardboard;
- sludges from paper mills and other municipal sources;
- energy crops specially grown for use as biofuels (typically liquid and also woody rotation crops).

As with all fuel, operators of coal-fired stations will require reliability of supply and an alternative source of supply in the event of a particular fuel becoming scarce. This requires thorough testing of the fuel in the fuel processing plant as well as an understanding of the combustion behaviour and the resulting changes in residues, slagging and fouling associated with the accompanying coal (if the fuels are fired simultaneously). Large biomass projects that have switched from coal to 100% biomass can reach 39–40% efficiency, surpassing the expectations of 25% efficiency made by sustainability analysts in the UK (Schill, 2014).

Medium to large plant experience such as that at Essent's Amer 8 plant proved that wood was the best fuel when balancing performance and cost. Firing biomass from a variety of vegetable, oil and fruit crops is not without some technical challenges. In the Netherlands, cofiring with a range of agricultural residues has led to significant corrosion problems when fired with olive kernels, cacao husks, citrus pulp, palm kernel, wheat semolina and Soya (Willeboer, 2012). Agricultural residues and wastes are discussed later.

2.1 Role of biomass in the power and combined heat and power (CHP) sectors

Roughly 10% of the world's primary energy demand is satisfied from biomass, of which a tenth is for the power and CHP generating sector. Therefore, 1% of global primary energy is accounted for by biomass demand in the power sector. Biomass can be used as a primary fuel for dedicated power stations or as a secondary fuel in a fossil fuelled boiler or turbine. Some power plants in Europe are becoming increasingly difficult to classify as they can comprise of multiple units that burn either coal or biomass as the primary fuel. In order to get some context of the global potential for demand, the next section examines the role of biomass in the world's fleet of coal-fired power stations.

2.2 Biomass as the primary fuel – dedicated biomass power stations

According to Platt's (2014), there are 60 GWe of dedicated biomass-fired power (and CHP) stations worldwide. Dedicated biomass power stations are generally located in OECD countries; only three of the top ten countries are in non-OECD countries (Figure 3). The USA has overwhelmingly the largest fleet of dedicated biomass stations with approximately 14,000 MWe burning a variety of fuels. Brazil and India have large fleets, but these are only a third of the size of the USA. In these developing countries bagasse fuel (biomass derived from sugar cane) dominates the market.

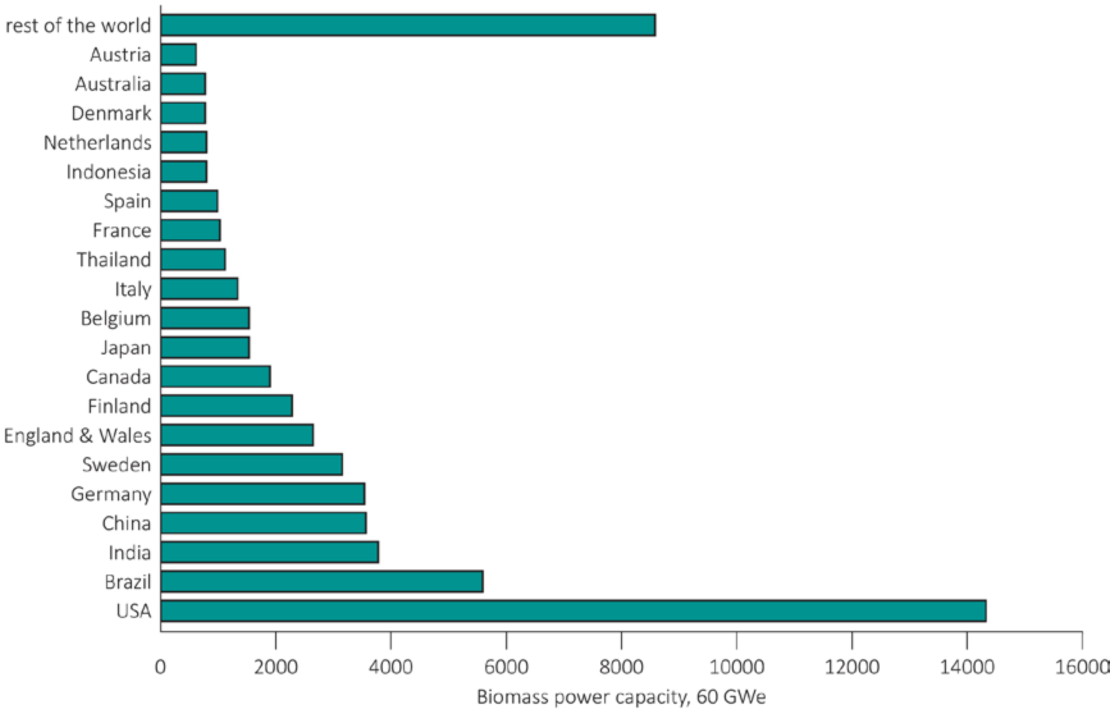


Figure 3 Global (dedicated) biomass power capacity in selected countries as of 2014 (Platt's, 2014)

Due to economies of scale, the small size of most of today's biomass plants roughly doubles the investment cost per kW, and plants operate with lower electrical efficiencies compared with large coal plants. The typical size of individual plants remains much smaller (from 1 to100 MW) than a modern coal-fired plant (300–1100 MWe for a single unit). Biomass plants cost between 4114-8180 $/kWe, while coal and gas plants can cost roughly 2000–3000 $/kWe and 1000 $/kWe respectively (2012 figures based on the USA) (EIA, 2013). Elsewhere, costs will vary, roughly half these levels in China, and double these costs in Japan depending on the site and specification of the power plant needed for local environmental and economic circumstances.

Worldwide there is just 60 GWe of power capacity dedicated to burning biomass, including 3.2 GWe that were under construction in 2014. The long-term future of these stations is often dependent on the financial mechanisms and regulations that assist and enhance profitability of such operations. In terms of installed generating capacity, stations designed to burn solid fuels account for 62% of the biomass fleet (wood 31%; refuse 21%; agricultural waste 10%) (*see* Figure 4). The remaining 38% is fuelled by other biogases and liquids fired through turbines as well as boilers. Municipal wastes such as tyres, refuse, and digester gases are a small percentage of the overall capacity, perhaps 3%. The scope for growth is considerable. Almost all of the market comprises of six major fuel categories:

- wood (from forest management, woody rotation crops, and municipal waste);
- refuse;
- bagasse (from sugar);
- agricultural residues (straw and maize waste);
- pulp liquor (from paper); and
- landfill gas.

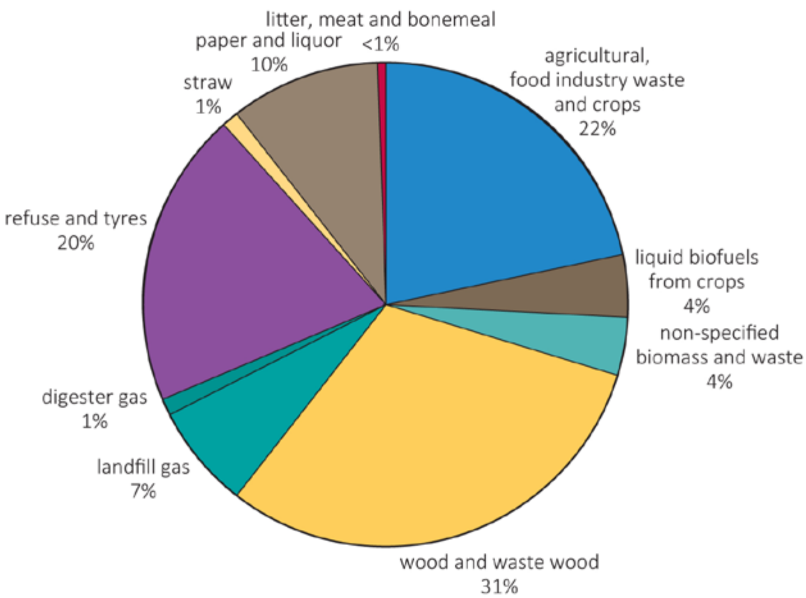


Figure 4 Dedicated biomass-fired* power capacity (Platt's, 2014)

* Gases derived from a gasification process of wood, refuse or agricultural waste are included in the respective sectors, but form a minute proportion of the overall fleet. To avoid confusion, landfill gas is treated as a separate gas source, and not a product of solid refuse from which it is derived.

Currently, one of the largest biomass stations operating today is Drax (United Kingdom). Drax is a former coal-fired station (formerly 6 x 660 MWe), but now burns a range of fuels in several units utilising pulverised coal, wood pellets from North America, and straw (chips and pellets) from local agricultural farmland. Two units have been converted into 600 MWe biomass-fired units. A third unit is undergoing conversion and once fully-operational will make Drax the largest biomass station in the world. Drax is an example where different units fire separately stored and fired fuels.

Units where biomass is fired into the coal boilers can greatly benefit from less ash, sulphur and NOx. The biomass system will therefore help reduce the load on emission control systems such as *electro static precipitator* (ESP), *flue gas desulphurisation* (FGD) and *selective catalytic reductio*n (SCR). However, as studies around the world show, biomass matter can contain compounds (such as alkali metals) that can also inhibit the full effectiveness of some existing sorbents and catalysts in post combustion clean up equipment.

Possibly the single largest biomass (only) unit that is operating today is the Les Awirs plant in Belgium with a gross capacity of 880 MWe (larger than the Drax units). It is fuelled with wood in a tangentially-fired boiler, and equipped with ESP for particulate control. Although biomass is in its early stages of popularity, this particular station in Belgium was commissioned in 1967.

2.2.1 New dedicated biomass capacity

In 2014, 3.2 GWe of new biomass capacity was under construction across the world, with the most notable increases occurring in the UK, USA, India, and Korea. A great deal of this new capacity involved existing plant conversions. The largest greenfield dedicated stations are being built in Sweden, Korea and Brazil, each with a plant capacity of 100–130 MWe. The Vartaverket plant in Sweden is due online in 2016, firing wood in an *atmospheric circulating fluidised bed* (ACFB) boiler system.

In some countries, over-dependency on fossil fuels and a limited uptake of hydro, wind and solar power makes biomass power attractive. In Asia, where some countries are wholly reliant on imported primary energy, wood and agricultural waste is being used, for example the Bugok plant in Korea. The plant is described as using ACFB technology. ACFB (also commonly known as CFBC) is an increasingly popular form of combustion which suspends combustion particles in a bubbling bed of fuel particles. This technology opens up possibilities to burn other opportunity fuels, and is an extremely effective method of burning low-grade fuels with lower heating values. Worldwide, CFBC is used to burn low-cost fuels such as by-products from refuse and waste, by-products from coal preparation plants, as well as biomass.

2.3 Biomass as a secondary fuel – cofiring in existing stations

Cofiring in a large power station however can be a challenge if the biomass is in limited supply due to lack of infrastructure and space for handling extra fuel volumes. Nevertheless, cofiring biomass in a coal station can be cost effective, although some adaptation to fuel handling and boiler design may be needed. Cofiring at low rates can be done easily at a coal plant with no need for subsidies, and so offers an opportunity to test different biomasses and reduce CO_2emissions. However, higher operating and maintenance costs may be incurred if low-quality biomass such as herbaceous crops and wet wood are used that give rise to tar deposits and cause slagging and fouling.

Figure 5 shows the countries where existing and operating coal-fired capacity uses biomass as a designated secondary fuel (totalling 36 GWe); most are built in Europe, some exist in the USA, Japan and Korea. Biomass firing into a coal-fired supercritical (SC) and ultra supercritical (USC) power station has been successful in Japan and the Netherlands.

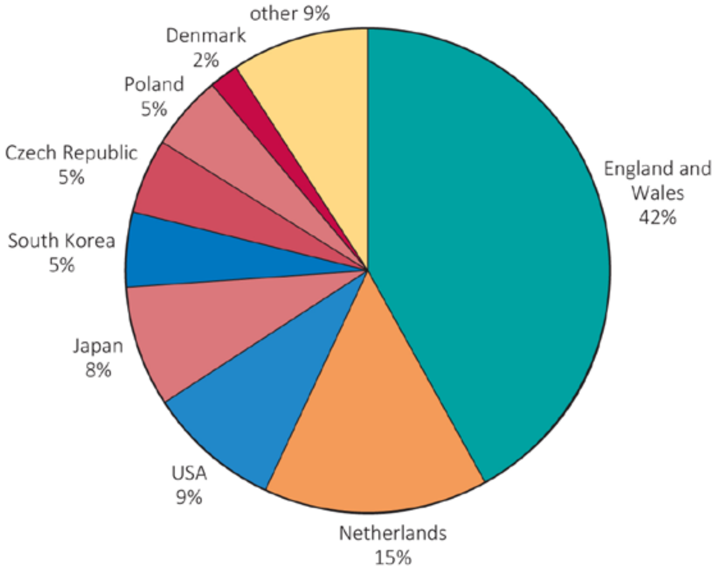


Figure 5 World coal-fired fleet using biomass as a secondary fuel, total = 36 GWe (Platt's, 2014)

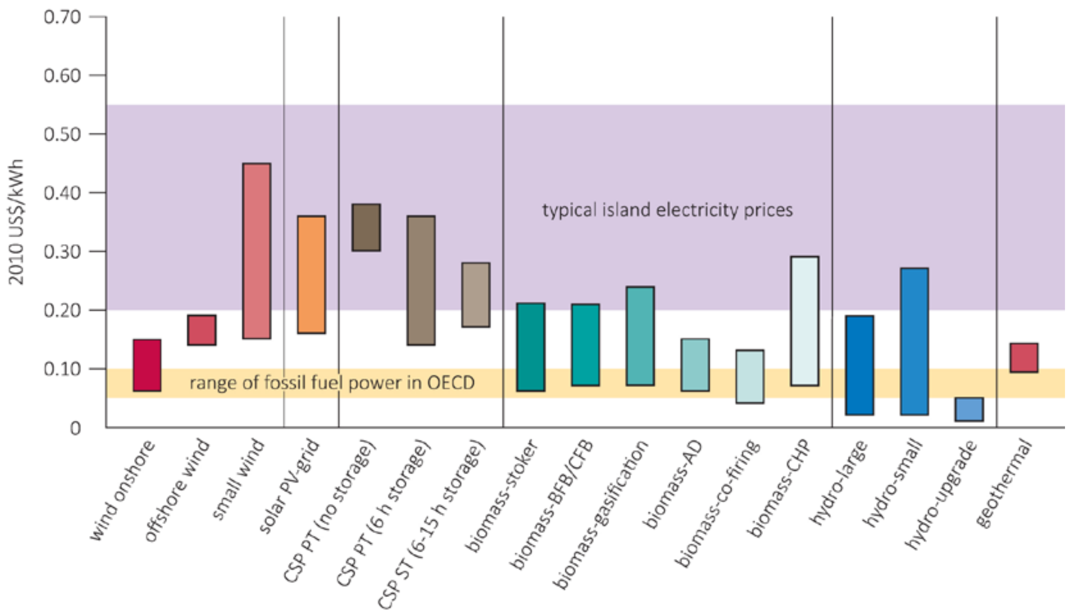
In the past, almost the entire UK coal fleet of 20 GWe was cofiring biomass at low rates under the UK government Renewable Obligation Certificate scheme. A range of fuels were used, including wood (virgin and recycled), olive cake, palm kernel expeller, sewage sludge, and energy crops. In 2005, as much electricity was produced under cofiring than that produced by the nation's wind turbines. Future prospects are dependent on the few remaining coal units that have been converted to biomass or are cofiring. Currently, around 13 GWe has biomass as a designated secondary fuel (Platt's, 2014).

The Netherlands have eight stations capable of cofiring biomass in 4 GWe of coal-fired generating capacity. The latest station to be built in the Netherlands is the Maasvlakte 3 station operated by E.On Benelux in Rotterdam. The station fires imported coal but blends pellets made from sewage sludge, waste wood and paper sludge available in the vicinity of the plant. BioMass Nederland produces 150 kt of pellet fuel with a heating value of 16 MJ/kg (HHV) that will reduce the power plant's coal use by 30 kt/y (EUBIA, 2015).

In Denmark coal power is in decline, but the country's entire fleet is not being decommissioned, it is instead being gradually converted to biomass, through a phase of increased cofiring. One example is the Avedøre supercritical plant where straw and wood are combusted in separate boilers linked to the same steam and heat system. In Denmark, straw is a popular feedstock due to the country's high yields and high cereal production. Animal feed research and a reduction in demand has increased the availability of straw. The moisture content of the straw fuel cannot exceed 30% due to handling problems. Alkali metals are often associated with excessive corrosion in coal-fired power plants, and a particular problem with straw, but alkali content can be reduced by leaching the straw with rain water and then drying, converting the yellow straw to lower alkali grey straw (*see* Chapter 6). There is no pulp production in Denmark so there is potential to use forestry residues although 50% of extracted forest products are used as biofuels (EUBIA, 2015).

2.3.1 The cost of cofiring versus dedicated biomass – a question of scale

Generating costs of renewable energy cannot be standardised as the performance of each project is site specific and the range for any technology can be extremely wide. Figure 6 illustrates the cost range of 17 renewable options in US$/kWh (adjusted to 2010 dollar) published by the IRENA. Renewable energies that suffer most from a wide range of high costs are small-scale wind, solar PV (grid), and concentrated solar power with 6 hour storage. An interesting outcome of this comparison is how ***biomass cofiring is one of the lowest cost forms of renewable generation*** (IRENA, 2012). The costs for cofiring also fall within a very narrow range and are even below the cost of fossil generation.



Note: assumes the cost of capital is 10%. the bands reflect ranges of typical investment costs (excluding transmission and distribution) and capacity factors. pt = parabolic trough, st = solar tower, bfb/cfb = bubbling fluidised bed/circulating fluidised bed, ad = anaerobic, digester, chp = combined heat and power.

Figure 6 The levelised cost of renewable of renewable power generation technologies (IRENA, 2012)

Biomass-fired power generation technologies range from mature solutions to emerging technologies that have not yet been deployed on a large scale. The total installed costs of biomass power generation technologies reflect this diversity, varying between 1880–6800 $/kWe in 2010. When biomass is cofired with fossil fuels there are lower capital costs, between 140–850 $/kWe, (this excludes the original investment in the plant). *Operating and maintenance* (O&M) costs can make up between 9–20% of the total *levelised cost of electricity* (LCOE) for biomass power plants. Cofiring is therefore relatively low hanging fruit provided the fuel supply is cheaply sourced or free and ideally local, and the regulatory regime recognises cofiring as a method of CO_2 reduction (IRENA, 2014).

2.4 The world's coal-fired fleet – an untapped cofiring opportunity

Biomass cofiring offers opportunities to meet renewables commitments using existing coal-fired power stations. CO_2 savings are the most obvious, but the utilisation of wood and agricultural residues means there is greater utilisation of waste. When introducing biomass to a coal-fired power station, 5% of the power station's fuel feed is possible without requiring any major modification. Five per cent cofiring is a typical rate for trialling purposes. Fifteen per cent biomass in the fuel feed is probably a safe upper limit before more costly modifications are needed. Torrefied wood pellets are claimed to offer higher cofiring rates.

DONG Energy of Denmark has embarked on a full conversion of its coal fleet to biomass. While a shift of the world's coal-fired fleet to 100% biomass might seem highly improbable in the foreseeable future, a partial shift to biomass could yield large (net) savings in greenhouse gases provided the biomass comes from sustainably managed forests. A brief overview of the status of the world's coal fleet in 2014 is summarised as follows:

- according to Platt's (2014), there is 1848 GWe of coal-fired capacity in operation;
- of which: 36 GWe was listed as using wood or biomass as an alternative fuel; 60 GWe of dedicated biomass power stations exists;
- a further 152 GWe of coal-fired capacity is under construction and due online between 2015 and 2021;
- by 2020, if no further power plants are built beyond what is under construction, the coal fleet could be 1645 GWe. This figure does not include any stations that are currently in the planning or financing stage, so could therefore be a gross underestimate of the world's coal fleet.

In summary, a potential market for biomass producers of solid fuels, chiefly wood and straw is as follows:

- by 2020, if the world's coal fleet cofired biomass at a rate of 5–10%, the world's demand from coal plants alone could be 82–164 GWe;

- dedicated biomass capacity capable of burning solid fuels is approximately 60 GWe (roughly 2 GWe uses coal as a secondary fuel);
- biomass capacity including dedicated (solid-fuelled) biomass stations and cofired coal stations would amass a fleet equivalent to 142–224 GWe.

The implication for the biomass supply industry in coming years is considerable. Based on some simple assumptions* (see below), the global potential for cofiring in 2020 is as follows (in wood pellet equivalent):

- 5% cofiring would mean a target market of 82 GWe in the world coal fleet;
- the demand for biomass could be around 235 Mt/y (or 4 EJ); this is equivalent to a tenfold increase in the current pellet market; and
- CO_2 savings of 400 MtCO_2/y (versus total global emissions from the power and heat sector in 2012 of 9031 Mt).
- logically, cofiring rates of just 10% will double these figures. (The above assumes: 60% utilisation, 39% efficiency, 925 gCO_2/kWh based on subbituminous (IEA, 2013) and 17 MJ/kg energy content of wood pellets.

2.5 Cofiring – future driver of the European wood pellet market?

Commercial scale deployment of biomass has become common in Europe. Experience shows that raw biomass needs to be available locally at extremely low cost due to the high cost of transportation. Increasing the energy density of biomass by drying and pelletising the wood makes transportation possible over long distances; it is now common for pellets to be shipped internationally in dry bulk vessels.

Wood pellets are mechanically dried and compressed making them easier to handle and transport. However, pellets are more expensive on a per tonne basis, but in terms of cost per GJ (and CO_2 saved versus coal), pellets offer an extremely attractive option that has long been in use by the heating market and now increasingly, at large scale, for power generation.

Pellets are of particular interest as the proximate analysis of some products have heating values and moisture contents comparable to some internationally traded coals, especially some Indonesian brands such as the Adaro Envirocoal 4000 (*see* Table 1); pellets that have undergone an extra stage of torrefaction are particularly comparable, but are more expensive. The *free on board* (FOB) price of standard (non-torrefied) wood pellets is almost double that of steam coal on a per tonne basis. The difference in cost must be covered by passing costs through to the wholesale market whether via a fixed tariff system or a subsidy to lower the fuel price. These mechanisms are common for almost all renewable energy sources in OECD countries.

Table 1 Sample Indonesian export coals and their proximate qualities (Adaro, 2014)			
	Envirocoal 5000	Envirocoal 4700	Envirocoal 4000
Total moisture (AR)	26%	30%	38%
Air-dried moisture (AD)	14.5%	18%	20%
Gross CV (AR)	5100 kcal/kg	4700 kcal/kg	4050 kcal/kg
Net CV (AR)	4800 kcal/kg	4363 kcal/kg	3700 kcal/kg
Ash (AR)	2.0%	2.5%	3.5%
Total sulphur (AR)	0.1%	0.2%	0.25%

The pellet market comprises of many different products, from brick-sized large pellets and briquettes for household heating, to small 2–3 cm pellets which are more versatile and will feed industrial boilers and power stations as well as domestic heating boilers.

The market for pellets is expected to grow worldwide, Figure 7 illustrates the trajectory of pellet production between 2010 and 2020 (Poyry, 2009). All regions of the world will see a rise in pellet supplies, much of which will be driven by the international seaborne market. During the last decade, global pellet production increased by ~25%/y; total production in 2010 exceeded 18 Mt/y. The world's biggest producing regions are North America and Europe. The number of new pellet plants being developed continues to increase; almost all are led by export demand. An estimated 12.6 Mt/y of pellets is exported from the USA; this is forecast to increase to 20 Mt/y by 2020 (Poyry, 2009). More recent report suggest that world production could be as high as 36 Mt/y and by 2020 be as high as 77 Mt/y (Schill, 2014).

Brazilian wood chip exporter Tanac is building the largest pellet plant in Latin America following a long-term contract with Drax which will start in the middle of 2016. Capacity will be 0.4 Mt/y at the same location from which 0.7 Mt/y wood chips are already exported to Asia. The pellets will be made from acacia which has a heating value of 17 MJ/kg and low ash content (Argus, 2014).

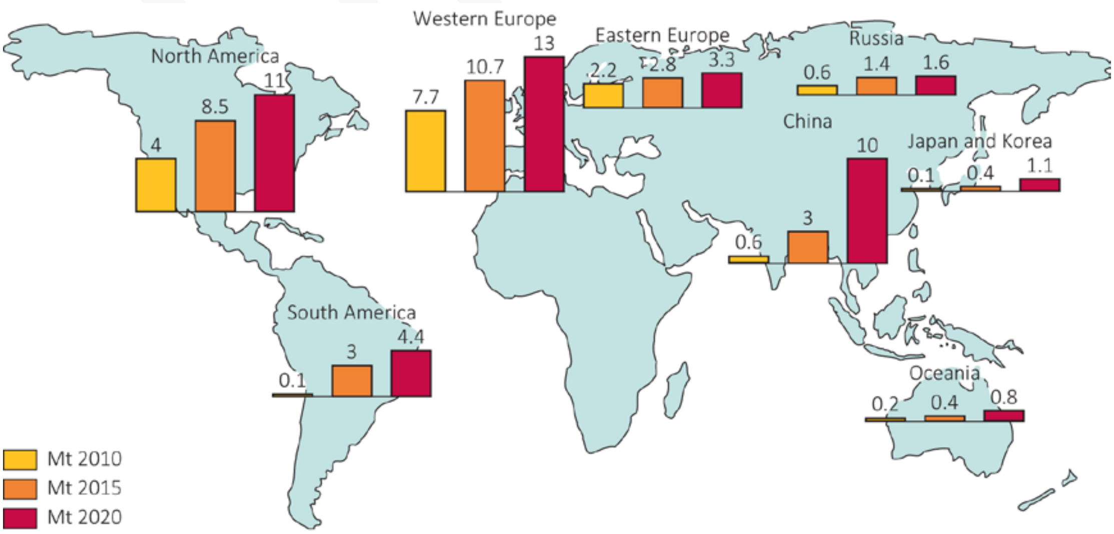


Figure 7 Global pellet production projections between 2010, 2015, 2020 (Poyry, 2009)

The rise in dry bulk trade in wood pellets continues as European buyers secure more overseas supplies from countries like Canada and the USA (*see* Figure 8). Despite the rise in cost of the pellets as a result of drying and pelletising, more biomass can be shipped using traditional dry bulk ships as opposed to the more expensive wood chip carriers.

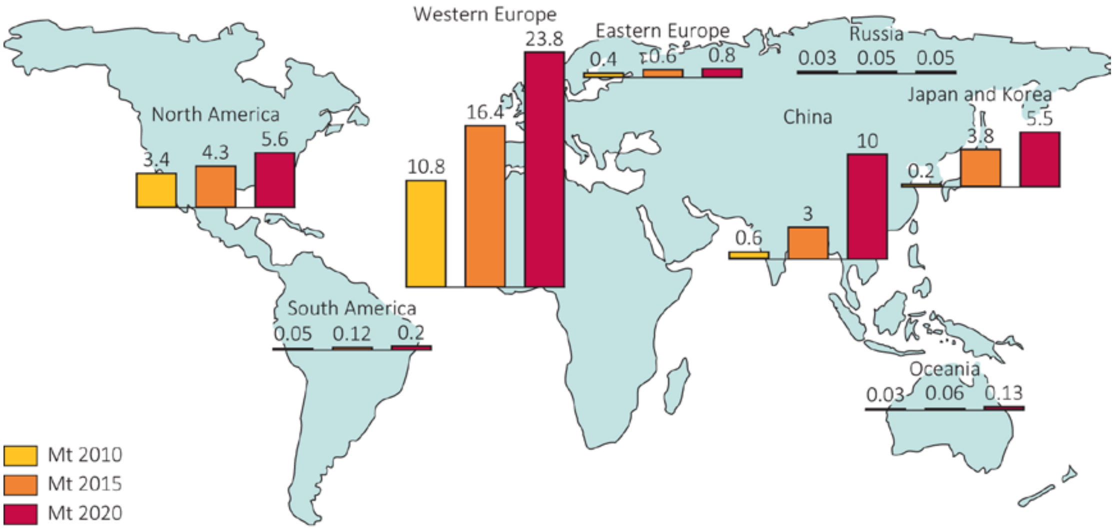


Figure 8 Wood pellet trade flows in 2010 (Poyry, 2009)

When looking at the trends in wood consumption, Western Europe is the driving force for world pellet demand, although growth in other regions cannot be ignored (*see* Figure 9). Pellet demand in the household and district heating sectors in northern Europe has been a key market for some years, while demand from the electricity generating sector (by cofiring or 100% biomass) is rapidly emerging in Belgium, Denmark, Netherlands and the UK. Economies such as China, Japan and Korea will spearhead pellet demand in Asia, but as this report discusses later, agricultural crop residues in Indonesia and Malaysia have immense potential also. For now, the focus remains on wood due to the potential for meeting world demand for power station biomass via international seaborne trade.

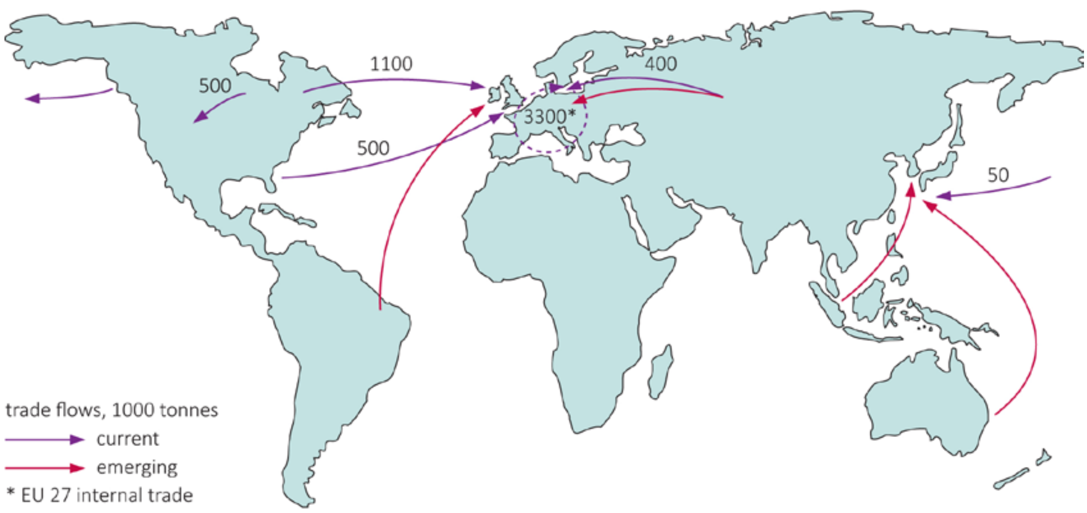


Figure 9 Global pellet consumption projections between 2010, 2015, 2020 (Poyry, 2009)

Like all renewable energies, the future of cofiring is not without its financial risks if subsidies are not secured for a reasonably long period. Regulatory uncertainty can weaken confidence amongst investors particularly if subsidies are reduced or withdrawn. In Europe, the reduction in the cost of solar power has made many governments rethink the financial commitment to high feed-in tariffs, and reducing such tariffs in response to reductions in the cost of the technology is inevitable. Similar cost reductions are expected in onshore wind power.

Feed in tariffs are typically discriminatory, favouring zero carbon technologies over fuel burning systems. In the USA, no financial instrument exists at a Federal level to promote biomass cofiring. In the Netherlands, the renewable targets require cofiring of 10.4 TWh, but subsidies cease in 2015. Whether or not there is certainty of a continuation of subsidies, the Dutch government recognise cofiring as a viable technology option for reducing CO_2. This is also mirrored in the UK, Denmark and Belgium where assistance to cofiring or 100% biomass is provided to varying degrees.

In most respects, pellets are superior to wood chips in terms of moisture content and heating value therefore requiring smaller vessels to transport the same amount of energy. Figure 10 shows dry bulk vessels, both roughly the same size in shipping terms, but one carries a high moisture content wood chip load and the other carries a lower moisture wood pellet cargo. The wood pellets cargo ensures that more energy (GJ) is shipped per tonne of cargo, so even if wood chips are carried in a larger vessel, the smaller vessel carrying wood pellets carries a higher energy payload.

Wood chips are traded in larger volumes than pellets, but most of the market is for the paper and pulp industries. Wood chip trade has increased considerably since 2001, with Japan being the largest importer in the world (11 Mt/y), and China the second largest (both countries accounting for 83% of wood chip trade). Trade in 2012 was 31 Mt, considerably larger than the trade in pellets (HDfestforest, 2013).

cargo hold capacity	110,000 m^3
deadweight (dwt)	53,600 tons

cargo hold capacity	60,000 m^3
deadweight (dwt)	53,500 tons

	density kg/m^3	net calorific value GJ/t	vessel type	load weight tons/shipment	energy transported GJ/shipment
wood chips	385	12.3*	woodchip carrier	42,300 tons	520,000 GJ
wood pellets	650	17.0**	dry bulk carrier	40,500 tons	689,000 GJ

* ~30% water content ** ~10% water content

Figure 10 Benefits of transporting wood pellets versus wood chips (Poyry, 2009)

In 2013, Vietnam overtook Australia as the largest exporter of wood chips accounting for 20% of global exports. Less than 10% of annual wood chip trade is for energy consumers, although the consumption figure is higher as these markets use locally sourced fuel. Obtaining reliable data on wood chip trade is challenging and further research is needed in this area (Lamers, 2012)

The International Standards Organisation (ISA) recognises wood pellets as a global commodity in its own right and in 2014 published a new set of standards relating to solid biofuels for a range of wood pellets, briquettes, chips, and torrified products (thermally treated and densified). The key standards relevant to cofiring fuels are as follows:

- ISO 17225-1 :2014 Solid biofuels – fuel specification and classes – Part 1: general requirements;
- ISO 17225-2 :2014 Solid biofuels – fuel specification and classes – Part 1: graded wood pellets;
- ISO 17225-6 :2014 Solid biofuels – fuel specification and classes – Part 1: graded non-woody pellets;
- ISO 17225-8 :2014 Solid biofuels – fuel specification and classes – Part 1: thermally treated and densified biomass fuels.

3 Current resource estimates – a review of published material

Slade (2011) surveyed a number of studies related to all biomass sources and showed that by 2030, the global potential for biomass production could reach 100–200 EJ/y (roughly 10–20% of future primary energy supply). These projections are based on the assumption that water supplies are adequate and that food agriculture yields will rise in the coming decades with advances in farming. This would make large amounts of arable land (perhaps 20–50%) available for biomass production. This is in broad agreement with more recent data published by IRENA (2014) which estimates that the global biomass supply in 2030 could be in the range of 97-147 EJ/y. Of this, wood residue could be 13–15 EJ/y, and harvesting residue could be 13-30 EJ/y. The largest potential for biomass production comes from energy crops, 33–39 EJ/y.

For comparison, the IEA Clean Coal Centre's own assessment suggests that wood residues could supply 9 EJ/y and (cereal) crop residues 4 EJ/y, falling well within the ranges published by Slade (2011) and IRENA (2014). These latter studies did not calculate the *total* biomass reserve in the world's (industrially) productive forest.

3.1 Data reporting

One of the most complex problems with understanding resources is the variety of fuel types, which for biomass is as diverse as the range of plant types that exist in the world. However, a similar complexity applies to coal where many ranks and qualities of coal make resource assessment more complex than say gas or oil. All fossil fuel resources can be reported in terms of mass or energy. Biomass is frequently reported in energy terms such as exajoules by most analysts. The order of scale for energy units in joules are as follows:

- Exa 10^{18}
- Peta 10^{15}
- Tera 10^{12}
- Giga 10^{9}
- Mega 10^{6}
- Kilo 10^{3}

Converting vast quantities of energy data into mass in tonnes of a particular commodity is made more complex due to the plethora of biomass types. Consequently, care must be taken when interpreting energy resource data. The findings from biomass resource studies concluded that under certain conditions where societal behaviour and land use remains unchanged, the world might contain 100–200 EJ (*see* Figure 11). The range is wide and subject to variation depending on the model assumptions. The world biomass resource is considerable given that the global supply of all fossil fuels, nuclear power, and renewable energy was 560 EJ (13.5 Gtoe) in 2012 (IEA, 2014).

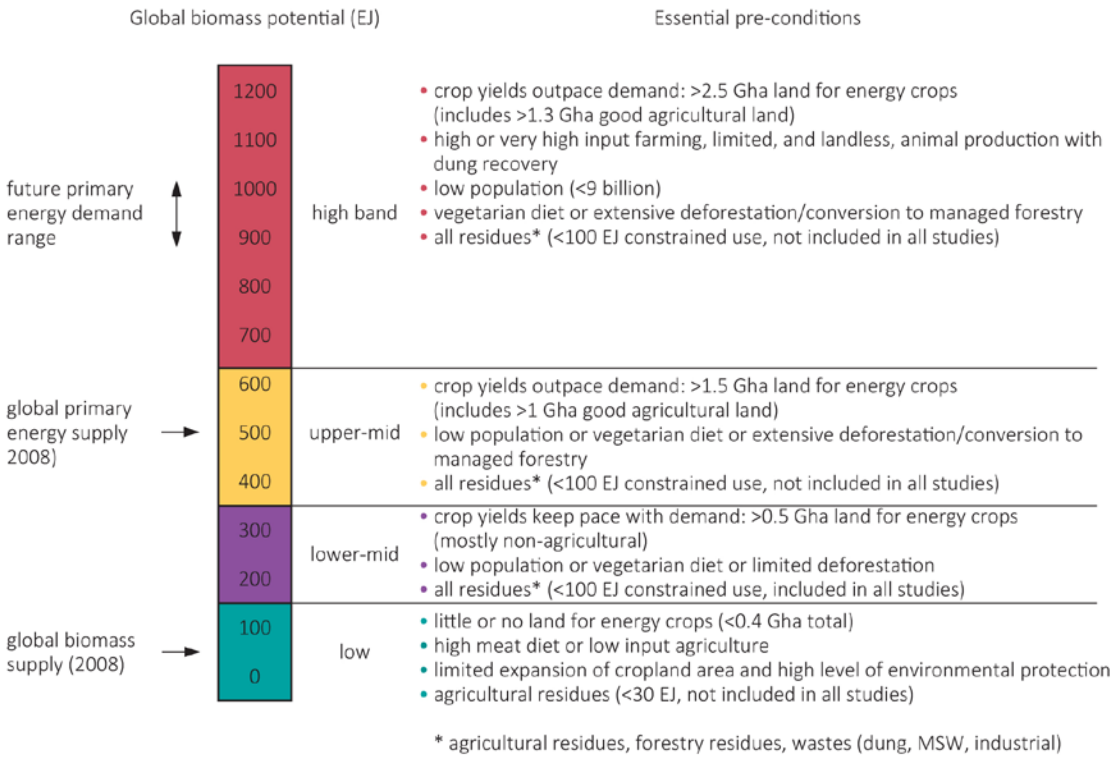


Figure 11 Global biomass potential and pre-conditions essential in exajoules EJ (Slade, 2011)

Converting this biomass resource to tonnes is easily done where the heating value of some biomass can average between 10–20 MJ/kg, but values can readily fall outside this range depending on the moisture content and type of biomass. *For illustrative purposes, if an average heating value of 15 MJ/kg is assumed, a biomass resource range of 100–200 EJ suggests there is 7–13 Gt of biomass available in the world.* The lower value of this range assumes a limited amount of land is available for growing crops specifically for energy use, thus preserving more land for agriculture.

Using a single conversion factor is fraught with uncertainty and justifies a great deal more research in this field of energy studies. In Slade (2011), 28 different scenarios from various authors and publications were assessed with forecast years of 2030, 2050 and even as far as 2100. Some projections assumed highly constraining conditions that come with population growth and more sustainable farming practices. These constraints included a high demand for food (especially meat), a limited intensification of food production, little expansion of agriculture into forested areas, grasslands and marginal land, and diets based on existing trends. A technically possible resource of up to 1200 EJ of biomass is available given immensely high crop yields, low population, very high intensity cattle farming on less land, a shift towards vegetarian diets to replace meat diets, and the utilisation of residues.

The most conservative estimate indicates a resource of no more than 100 EJ/y, with minimal energy crop cultivation, a high meat diet and low input agriculture, a static amount of cropland, but high levels of environmental protection and a modest level of agricultural and forest residue production. Similar conclusions were reached by Chum and others (2011) in a major report for the IPCC (where 2010 global primary energy consumption was 520 EJ). Only 100 EJ was considered economically viable. Doombosch and Steenblik (2008) also estimated bioenergy potential of a similar order (*see* Table 2).

Table 2 World bioenergy potential by feedstock, 2050 (Mills, 2013)

Feedstock type	Bioenergy potential, EJ
Agriculture, forest residues, and waste	40–170
Agriculture intensification	140
Surplus agriculture	120
Surplus forest	60–100
Degraded land	70
Total	100–600

Higher estimates are published elsewhere. The WEC Survey of Energy Resources estimates that bioenergy could theoretically provide 2900 EJ/y, but that technical and economic factors limit its current practical potential to just 270 EJ/y. Projections by the WEC, WEA and IPCC estimate that by 2050, bioenergy could supply between 250 and 450 EJ/y, representing around a quarter of global final energy demand (Mills, 2013).

Other published material suggests that forest residues could supply between 43 to 77 EJ and resources are large enough to meet a substantial share of the world's primary energy consumption by 2050 (Smeets and Faaij, 2007; Lauri, 2014). Demand for all woody biomass (household and power and CHP sectors) could account for 2–18% of world primary energy consumption in 2050. Using cost curves and the availability of wood at varying prices, global wood supply is estimated to be 0–23 Gm^3/y (0–165 EJ/y). These supplies varied depending on (energy) wood prices within the range of 0–30 \$/GJ (0–216 $\$/m^3$).

A summary of various assessments of global biomass resources and/or supply fall within the resource range indicated by Slade (2011), including the *World Bioenergy Association* (WBA) which estimates that forestry products could meet 70 EJ of primary energy per year. Data published by IRENA suggest that 35–39 EJ/y of forestry products could be used in the year 2030; by 2050, the biomass supply could range up to more than 200 EJ (*see* Figures 10, 11 and 23). These and more detailed assessments are discussed in more detail in the following section.

In contrast to these figures, IEA Clean Coal Centre findings suggest that residue resources for forestry activities are closer to 9 EJ/y, and cereal crop residues are 4 EJ/y, indicating the considerable constraints which might be faced by utilities if only waste by-products are to be permitted for use as a cofiring fuel. However, the published material also suggests there is a wealth of resource still available amongst energy crops, forestry and other waste streams that the IEA Clean Coal Centre has not considered and requires further research.

3.2 Implications for increasing biomass production on resources

Despite some variation in published resource projections, there appears to be a consensus that to minimise further impacts of energy related land use (from biomass or biofuel), water abstraction and general ***environmental issues will require the supply to remain at 100 EJ/y or less***. These resources will also include biofuels and other energy crops.

Bioenergy demand could rise to 250 EJ/y by 2050 supplying 20–30% of the world's primary energy needs, but not without a major doubling of biomass harvests (Bensen, 2012). A large-scale promotion of bioenergy could result in economic incentives to divert land from food production to biodiesel or other similar products. Increasing the yield of crops and increasing the use of residues compromise intensive farming practice, water demand, and soil conditioning. Issues of land use are discussed further in Chapter 6.

3.3 Assessing wood resources in-situ using (living) forestry data – a bottom up approach

Establishing world resources of biomass is straightforward as long as some basic concepts are clarified. Only a proportion of the world's forest is eligible for felling, only a fraction of that forest is felled in any year, and only a sub proportion of that produced as waste or residue.

The FAO (2010) data covering existing forest area and agricultural land provides the basis for resource calculations. The latest data published by the FAO are based on national submissions and surveys. Factors that result in changes of land use due to economic or environmental reasons and affect resource assessments will be discussed later in this report.

3.3.1 Forestry and Agricultural Organization (FAO) data

Forest resources can be measured in two main ways, by land area in hectares or by mass in tonnes. Every five years the UN FAO publishes data on the world's forests, and the latest report is due out in 2015, but at the time of preparation, this report refers to the data found in the 2010 edition. The data are presented in terms of area in hectares (ha) or multiples of hectares, while biomass and carbon resources are provided in tonnes. Different measures of forest are therefore used based on a unit of measurement that is appropriate.

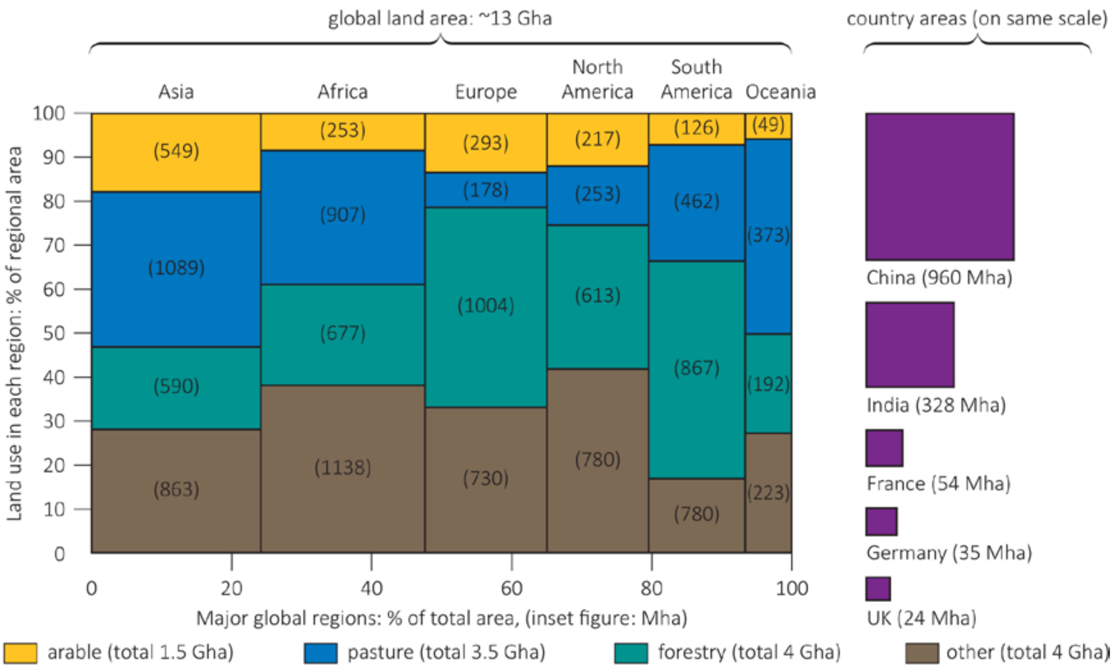
Firstly, the definition of forest has specific criteria as follows:

land spanning more than 0.5 hectares with trees higher than 5 metres and a canopy cover of more than 10 per cent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use.

Forestry land also includes: cleared forest land that will be regenerated (within five years) as a part of forest management or natural disasters; forest roads, national parks, areas of scientific and cultural interest, corridors of trees (more than 0.5 ha and width more than 20 metres), wind breaks, mangroves, plantations (rubber, cork, and Christmas trees), and bamboo and palms. *All of these must meet the criteria of being a minimum 0.5 ha, reach 5 metres in height and 10% span.* Exclusions are fruit tree plantations, oil palm and agroforestry when crops are grown under tree cover; these are qualified as agricultural land, not forestry.

3.3.2 Forest area and land use in world regions

While land area itself is not always a clear indication of the biomass in tonnes, area provides a useful indication of land usage. The world's land area is roughly 13 Gha, and can be split into four major categories which are arable, pasture, forestry, and other land (the latter includes all built-up areas, recreation, other wooded land and so on). Total forest area is just over 4 Gha (*see* Figure 12). Pasture accounts for 3.5 Gha for livestock grazing, while arable covers considerably less land at just 1.5 Gha (a great deal of which is devoted to growing crops to feed livestock).



source data: FAOSTAT 2009. Arable: area under temporary agricultural crops, (includes permanent crops eg coffee).
Pasture: permanent meadows and pastures either cultivated or growing wild (wild prairie or grazing land).
Forest: areas spanning more than 0.5 hectares with trees higher than 5 metres.
Other: land not classified as agricultural land and forest area, incudes built-up and related land, barren land, other wooded land etc. For full definitions see FAOSTAT.

Figure 12 Global land area in giga hectares (FAO, 2010)

Five countries account for more than half of the world's forest area. These countries are the Russian Federation, Brazil, Canada, the USA and China. Ten regions have no forest at all and an additional 54 have forest on less than 10% of their total land area. Forested land is most widespread in Europe which has 1004 Gha, the majority of which is in Russia. South America also has a great deal of land area covered in forest with 867 Gha. Asia, Africa and North America each has roughly 600–680 Gha of forested land. Figure 13 illustrates the geographical spread of forest land cover showing a clear localisation of forest in North America, South America, Russia, Central

Africa, and much of Asia. Regions lacking forest are vast, such as northern Africa, the Middle East, Central Asia, the Indian subcontinent and Australia.

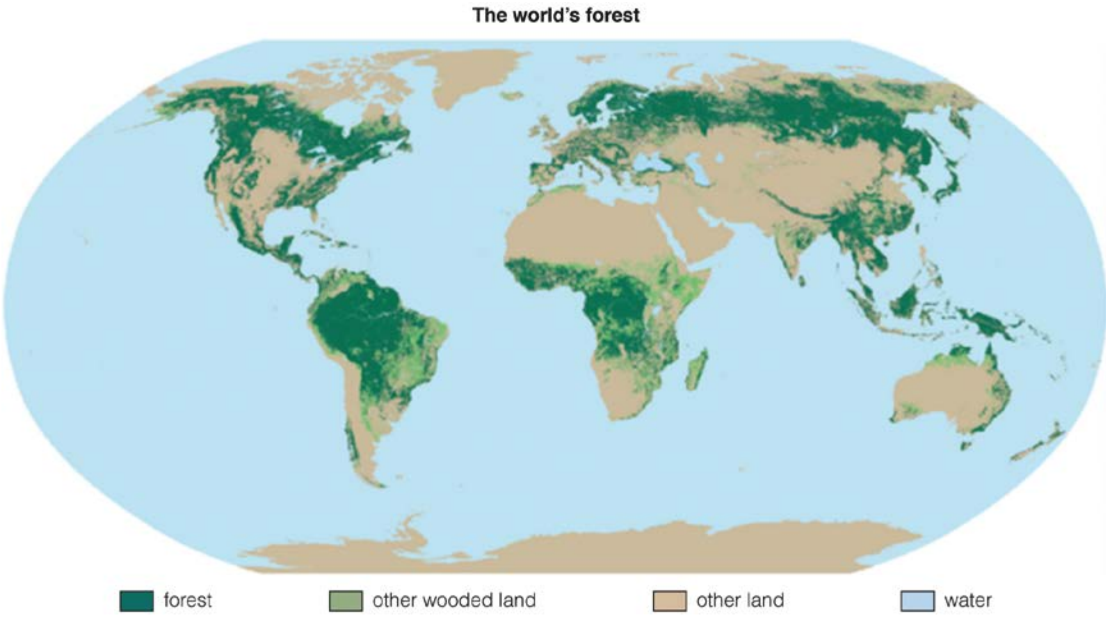


Figure 13 Map of the geographical spread of the world's forests (FAO, 2010)

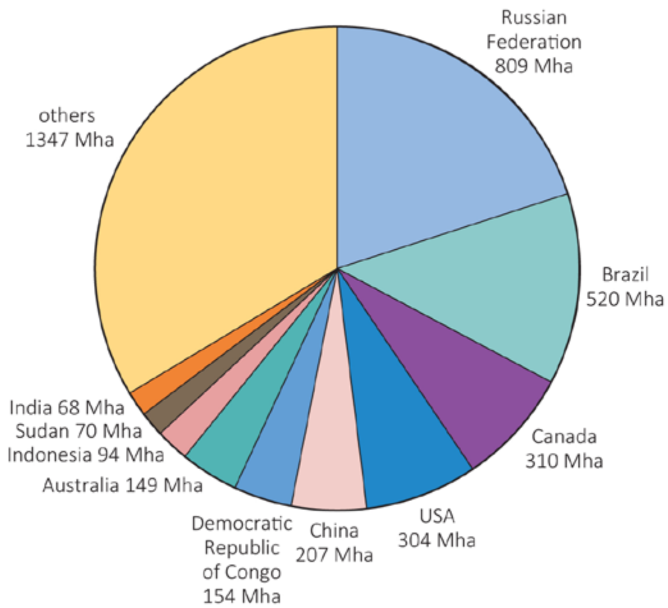


Figure 14 Ten countries with the largest forest area, 2010 (FAO, 2010)

The single largest area of forest is found in Russia with 809 Mha, while second is Brazil with 520 Mha (*see* Figure 14). When ranked in order of *carbon stock* in living forest biomass, Brazil is by far the richest country, almost double that of Russia. Many countries which apparently have less land area covered in forest appear in Table 3 among the top ten largest stock of living biomass in forest.

Table 3 Ten largest forested countries by carbon stock in Mt (FAO, 2010)

	1990	2000	2005	2010	% change 1990-2010
Brazil	68119	65304	63679	62607	−8
Russian Federation	32504	32157	32210	32500	0
Democratic Republic of Congo	20433	20036	19838	19639	−4
USA	16951	17998	18631	19308	14
Canada	14284	14317	14021	13908	−3
Indonesia	16335	15182	14299	13017	−20
Peru	8831	8713	8654	8560	−3
Colombia	7032	6918	6862	6805	−3
Australia	6724	6702	6641	6641*	−1
China	4414	5295	5802	6203	41
World forest carbon stock	285330	281669	280500	270265	−5

* estimate

4 Calculating residue resources in a nation's forest

Within the world's forest is a potential stock of cofiring fuel. That fuel can only be accessed once other forestry activities have been carried out, such as felling and sawmilling. However, like fossil fuels, the reserves of fuel can be vast, albeit not accessible at any one time due to the limitations of production capacity for a given year. Unlike fossil fuels, forest biomass can be extracted over time, but then must be replanted at a suitable rate to prevent resource depletion.

This report, does not consider the whole tree as an energy resource, only the residue is assumed to be available (chippings and dust from tree discards such as branches, bark, foliage and stumps). Wood residue is estimated as a percentage of the forest felling activity or biomass stock. The percentage can vary from 50-68% as described earlier, but a figure of 58% takes into account wood used for timber, various losses in sawmilling, and stumps (excluding roots). Two types of residue mass can be estimated:

- the potential waste or residue (at any time) as a fraction of entire forest biomass or carbon stock (Mt) to get the *total stock* of residue that is present in the world's forest regardless of production (Chapter 5); this approach is common with the assessment of fossil fuel reserves; OR
- as a fraction of the unused biomass produced by existing forest industries (timber and paper industries) giving the potential residue supply in any year (Chapter 6); this approach is common with most biomass resource studies.

From the forest mass data (in tonnes), the theoretical quantity of residue that exists within that mass can be easily calculated by using a residue factor. Deadwood is not included in this assessment calculation, but could boost these resources greatly.

Living forest is an immensely important resource for biodiversity, carbon sinks, soil/water protection and a home for some local communities. Therefore the entire forest mass cannot be eligible for felling as much of the forest may be protected or preserved. Also, geographical and topographical challenges may prevent easy access to much of the forest, especially where the land is mountainous. Steep relief may not preclude felling in all cases, but may make the recovery of residues from stumps problematic, but not impossible. As a result of all these various factors, only a certain proportion of any forest will be allowed to be felled for *industrial purposes* supplying the timber and paper industries. Worldwide, roughly 30% of all forest area is eligible to be accessed for industrial production (*see* Figure 15). The next largest area is designated for multiple uses, which will include forests suitable for productive use, but without firm data, this is excluded. The balance comprises forest that is managed for the purposes of habitat protection, soil and water protection, and so on.

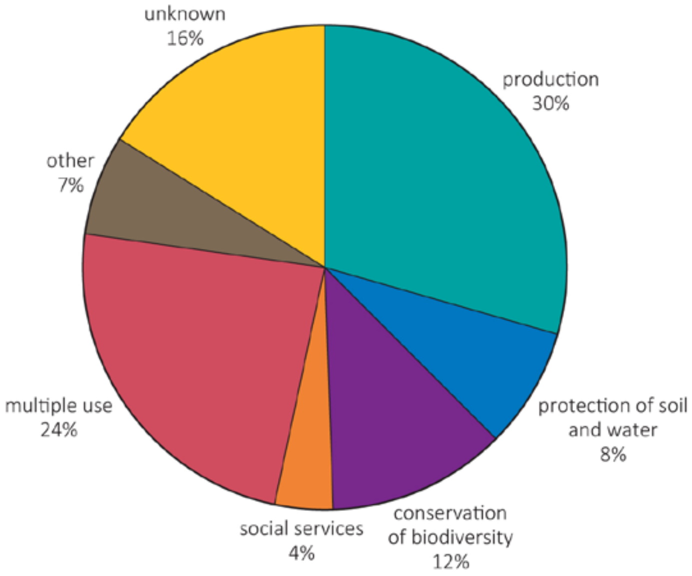


Figure 15 Designated functions of forests in 2010 (FAO, 2010)

Cofiring fuel is only currently supplied from a waste stream; sustainability criteria are immensely important to power station operators, especially those of coal-fired plants. As such, extraction and wood pellet production from primary wood is best avoided, unless the forest is being cleared to protect the forest from fire or similar intentions. A simple process of calculating world forest residues is summarised as follows using:

- global and national forest biomass data series from the FAO (Mt);
- adjust the data to include productive forests only (%);
- determine the typical residue that can be obtained per tree (%);
- multiply % residue per tree to the nation's productive forest (Mt).

Sections 4.1-4.4 examine each step of the process of deriving the resource figures from forestry data for a list of sample countries where the FAO data are available. While incomplete, they cover countries which possess a majority of the world's forest area.

4.1 Global and national forest biomass from the FAO (Mt)

The world's total biomass resource amounts to 600,066 Mt comprising of above- and below-ground biomass, plus 67,000 Mt of dead wood (FAO, 2010). Below ground biomass includes live roots, but not roots of less than 2 mm diameter. Assuming the roots of trees are left in the ground for soil stability, a root-to-shoot ratio is applied (ranging from 0.2 to 0.31) to obtain the biomass that is above ground.

Factors that affect the biomass stock of a country include species and climate which greatly impact the density of biomass per area of forest. Previous sections have already discussed how Brazil's biomass exceeds Russia, although Russia's forest covers the largest area.

Biomass is usually estimated by applying density conversion factors to growing stock, which is often expressed in volume terms (m^3). This conversion factor will differ depending on the dominant tree species so tropical tree species will differ from temperate species. As such, the tonnes of biomass per hectare in forests will differ depending on the forest type; Table 4 shows how the tonnes per hectare for tropical forests are significantly higher than for temperate regions (for example, South America 247.4 t/ha; tropical Africa 176 t/ha; Europe 90 t/ha). Arid African regions will see a negligible figure.

Table 4 Biomass and dead wood stock by region and subregion in 2010 (FAO, 2010)

Region/sub-region	Biomass		Dead wood	
	Mt	t/ha	Mt	t/ha
Eastern and southern Africa	33385	124.8	6888	25.7
Northern Africa	3711	47.1	1069	13.6
Western and Central Africa	81603	248.7	7747	23.6
Total Africa	**118700**	**176.0**	**15704**	**23.3**
East Asia	18429	72.4	2514	9.9
South and Southeast Asia	51933	176.4	5964	20.3
Western and Central Asia	3502	80.5	70	1.6
Total Asia	**73864**	**124.7**	**8548**	**14.4**
Europe (excluding Russian Fed)	25602	130.7	1434	7.3
Total Europe	**90602**	**90.2**	**15790**	**23.3**
Caribbean	1092	157.5	120	17.2
Central America	3715	190.5	419	21.5
North America	76929	113.3	8633	12.7
Total North and Central America	**81736**	**115.9**	**9172**	**13.0**
Total Oceania	**21302**	**111.3**	**3932**	**20.5**
Total South America	**213863**	**247.4**	**13834**	**16.0**
World	**600066**	**148.8**	**66980**	**16.6**

The most abundant biomass regions have vast areas of tropical forest, these include South America which possesses 213,863 Mt of biomass stock and Africa which has 118,700 Mt. The combination of large areas and immensely biomass dense forest is due to high rainfall and excellent growing conditions for tropical species of trees.

While these regions have the richest biomass compared with more temperate regions such as Europe and North America, Europe appears to have a large amount of dead wood at 15,790 Mt. Data on dead wood dry matter are weak and rely heavily on the IPCC improving new and better default values and conversion factors. However as a generality, it appears from Table 4 that deadwood is equivalent to just over 10% of the growing biomass.

4.2 Forest designated for industrial production

Roughly, 1.2 billion ha of forest are managed for the production of wood and non-wood forest products; this area accounts for 30% of the total forest area. The majority of the world's forests come under a plethora of categories that overlap and are further complicated by the ownership of the forest. It is not the intention of this report to review the sustainable practice of forest management, which is discussed in detail by Adams (2013), but stringent management of forest could further restrict the potential resource that can be exploited (for example, avoiding conflict with agricultural land, widening the status of forest that is designated for conservation and so on). In general, forestry activities do not conflict with land designated for agriculture, but in some Asian countries, felling occurs to grow crops and this must be managed carefully.

4.3 Residue from harvested trees

The FAO (2010) and Parikka (2003) state that it is common for 60% of total harvested trees to be left in a forest and/or non-commercial species to be subject to slash and burn, felled, or left to rot to make access for logging easier. In North America and parts of Europe, residue is reused wherever possible as a fuel for heat raising in forestry processes, while in developing Africa and Asia, this material may be gathered and used for residential use.

In the past, sawmills regarded wood waste as a troublesome by-product which was disposed of in landfill or incinerated. The waste would therefore either decompose producing CH_4 or be burned producing CO_2.

Different regions have different rates of residue recovery. Hassan (2005) published a comprehensive study on timber production, and stated that in the USA, 98% of the bark, saw dust, and wood trimmings from sawmill operations, and the black liquor produced in the pulping process, are currently used as fuel or to produce other fibre products (EIA 1994). Enters (2001) indicates that on average, only half the wood harvested in Asia is used and the rest is unused residue that goes to waste. Much of this waste may be collected for domestic heating and cooking purposes but verifying quantities of this requires a great deal more research.

A global economic recovery may well increase the demand for wood products in construction, furniture, and paper thus creating more waste by-products. These processes from which residues are generated may be divided into two broad sections of the wood supply chain (also *see* Table 5):

- residues from the harvest and extraction of logs; traditionally not economically viable for post processing, but have since become an important feed for pelletising;
- residues during timber manufacture, plywood, particleboard and so on.

Further downstream, waste wood products from transport pallets, construction timber and furniture can be recovered and is an area of further research.

Table 5 Types of residue FAO (1990)

Source	Type of residue
Forest operations	Branches, needles, leaves, stumps, roots, low-grade and decayed wood, slashings, and sawdust
Sawmilling	Bark, sawdust, trimmings, split wood, planer shavings, sander dust
Plywood production	Bark, core, sawdust, lillypads, veneer clippings and waste, panel trim, sander dust
Particle board production	Bark, screening fines, panel trim, sawdust sander dust

According to the FAO, less than two thirds of a typical harvested tree is taken from the forest for further processing. Any remainder is left, burned, or collected for local fuel wood. The forest industry therefore has access to a potential abundance of waste residue that has a useful purpose as a heat raising fuel. The residues are varied and the main types include bark and sawdust (Lutz, undated).

Bark is often removed from the log before it is sawn into lumber. Although bark can have a high moisture content, it is still combustible. Bark can also be mixed with other materials such as sawdust to produce wood pellets. However, pellets with bark added make more smoke than those without. Another common use for bark is as landscape mulch.

Sawdust is created as individual boards and sections are sawn from the log. The accumulation of residues in sawmills can become an obstacle to the production process, so they need to be removed quickly. Sawmills may use circular saws or band saws. Circular saw blades are thicker than band saw blades and thus create more sawdust with each cut. Sawdust is also occasionally used by pulp mills for autogeneration heat or power. Accumulated sawdust, whether in the forest or in sawmill yards, constitutes a reservoir for fungi (typically of the genera Fomes, Schyzophylum and Polyporus, among others) which leads to wood rot. Dry sawdust is also a major fire risk (Godoy, 2001).

The first major product that results from felling is (industrial) roundwood, the cylindrical section of trunk which may or may not have bark (*see* Figures 16, 17 and 18). In this form, the roundwood is easy to stack and transport. Most of the forest industries' cutting equipment is designed to handle and process roundwood.

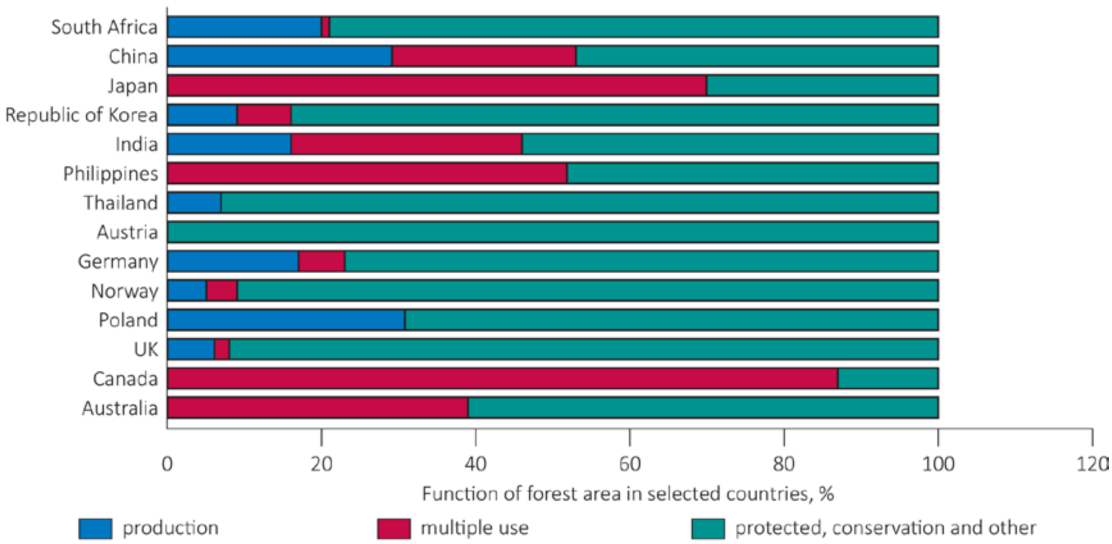


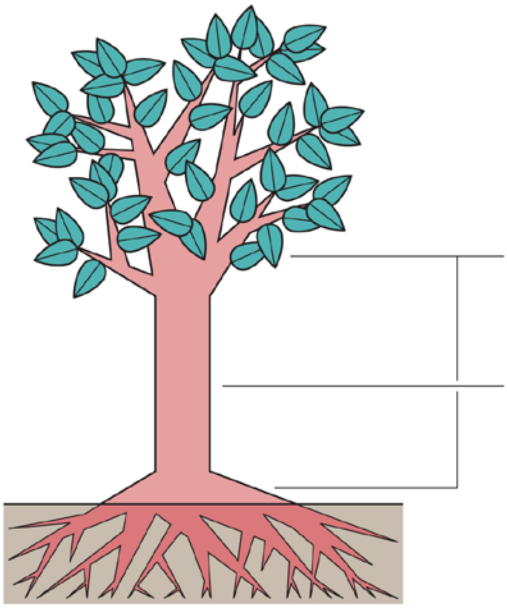
Figure 16 Function of forest in selected countries % (FAO, 2010)

Figure 17 An example of a stock of roundwood timber (Landreport, undated)

Figure 18 Roundwood handling (Pedwell, 2012)

During the lumber production process, just 28% of the tree is recovered for *sawn timber* products and a further 17% for smaller sections such as *slabs, edgings and offcuts*, the purposes for which the tree was originally intended. The sawn timber may undergo extra trimming and cutting to specified dimensions required by the next stage of the timber supply chain.

If 45% of the tree is assumed to be used for wood products (or pulp), *55% of the tree is residue or waste, not all of which will be recovered due to perhaps 4% of various losses*. The remaining unused parts of a tree that can technically be recovered include 23% branches and tops (including foliage), 10% stumps (above ground), 5% sawdust (forestry), 7.5% sawdust and fines (sawmill), and 5.5% bark *(see* Figure 19).



tree part or product	portion %
top, branches and foliage	23.0
stump (excluding roots)	10.0
sawdust	5.0
slabs, edgings and off-cuts	17.0
sawdust and fines	7.5
various losses	4.0
bark	5.5
sawn timber	28.0
total	100.0

Figure 19 Various parts of a tree and the potential residue (FAO, 1990)

This would reduce the overall potential material in the tree that is available for cofiring to 46%; if not utilised, this would be left to decompose or be incinerated. This residue proportion is a reasonable starting point from which the cofiring fuel stock will be produced. Twigs and foliage can cause problems further down the supply chain for wood chip sizing and pellet manufacture so further deductions should be made, but for simplicity, these are included as they will also be attached to the top and branches of a tree (comprising canopy) that contain valuable wood for fuel. Forestry sawdust can offer a valuable source of nutrients for the forest floor if left at the felling site, but is included for the purposes of this analysis.

Bark can be deducted for the production of pellets or as a raw cofiring fuel, although it is often included in the roundwood production data by the FAO, referred to as roundwood production 'over' bark. Bark nevertheless remains a potential low grade fuel with a modest heating value and is occasionally used as a fuel for wood drying and so is included in the resource figure. Overall, the breakdown of wood products and residues shown in Figure 19, acts as a useful proxy to determine the forest residue stock available for making wood chips and pellets for power station cofiring.

4.4 Scaling up residue estimates to national forest stock

Multiplying the percentage available residue in a single tree (46%) by the tonnes of biomass in a nation's productive forest will yield a reasonable estimate of the residue stock in a given forest mass.

Table 6 shows the results of the analysis, listing total residue reserves in productive forests for all the sample countries; ***the combined resource for all the 21 countries in this sample is 14,218 Mt***. In 2010, the production of wood pellets was a fraction of one per cent of the global potential. Russia is the largest resource of forest residues since it has a large biomass stock with more than 5718 Mt. The species that predominates in Russian forests include mainly coniferous types; in higher latitudes, regrowth can be slow compared with lower latitudes of the same species. Given this resource is for productive forest, the biomass should be accessible and within regions that are already designated for timber production.

Table 6 Top producers of forest residue, Mt (IEA CCC, 2014)

Country	Potential residue in the productive forest stock, 46% of total stock, Mt
Subtotal of sample countries	**14218**
Russian Federation	5718
Indonesia	2221
USA	2078
Brazil	1613
China	807
Sweden	316
France	308
Finland	246
India	232
Philippines	162
Poland	132
Norway	81
Austria	80
Republic of Korea	65
South Africa	52
Canada	50
Thailand	40
UK	15
Japan	0
Germany	0
Austria	0

The USA, Indonesia and Brazil are also large resources each possessing roughly more than 1600 Mt. The world's leading producer of wood pellets is the USA, so it is unsurprising the USA has more than 2078 Mt of residue resource available of mainly coniferous species. Forests in Indonesia and Brazil comprise entirely tropical species with a higher tonnage of biomass per hectare compared with Russia.

This resource assessment is extremely conservative. Countries such as Canada, the UK, Germany, and Australia all have an apparently small forest area allocated for productive use as forest can be categorised as *Multiple use* or *Other*.

Figure 16 on page 40 shows the amount of forest area that is designated for production (shown in blue). However, countries with large areas of forest are protected; in the case of Canada, Philippines and Australia, a large proportion is designated for *multiple uses*, some of which could be for industrial production. Canada for instance has 270 Mha of forest designated for multiple use, this covers 87% of the country's total forest, which is more than half the forest area of Brazil. Canada has more forest area than the USA, yet while the USA designates 20% of its forest to industrial production, in Canada only 1% is allocated.

In terms of productivity, output in the USA is approximately 2 t of industrial roundwood per hectare of designated forest. Actual tonnes of wood harvested per hectare are considerably more. Canada may have different criteria for allocating forests to the USA, but as a proxy, if the same assumption (of 2 t/ha) applies to Canada, it would suggest that the actual forest area designated for industrial production is closer to 45 Mha (versus the reported 3 Mha by the UN FAO).

Since, only forest designated for productive use is included in this report, the results in Table 6 could under estimate the resource for biomass in some important countries like Canada. Further research is clearly needed in these regions.

These resource figures are a cautious estimate of residues available in the world's major forests. The data exclude deadwood, which could add 10% to the resource, and there is also additional potential from the stock of reusable construction wood and municipal waste. These are complex sectors beyond the scope of this report. Forestry sawdust can offer a valuable source of nutrients for the forest floor and account for 5% of the total tree, and so could reduce these resource estimates by less than 5%.

5 Measuring the resource based on forest industry activity

As shown in the previous sections, the world's forest that is designated for 'productive' purposes contain a potential residue and waste stock of 14,218 Mt.

However, the amount of biomass residue that is actually available in any year is dependent on the output from the world's forest and wood processing industry. Part of this supply stream is already captured, stored and processed into pellets or fired as a chipped fuel. For the rest, neither the infrastructure nor the demand is in place to utilise the waste. This potential resource can be measured easily by applying the same methodology as in the previous chapter. However, annual production data are in volume terms (1000 m^3) and appropriate conversions to tonnes and EJ must be done.

5.1 Method of measuring residues from roundwood production

The potential supply of residue uses the latest data on industrial roundwood production from the FAO. Where forest biomass is reported in tonnes, roundwood production is reported in units of volume (1000 m^3). Residues from annual roundwood production can be estimated using the following approach:

- global and national roundwood production from the FAO in 1000 m^3 (2013);
- convert roundwood volume (1000 m^3) to mass (tonnes) using average densities as follows: 700 kg/m^3 for coniferous species and 756 kg/m^3 for non-coniferous species. Wood densities can vary widely, from as low as 150 kg/m^3 for balsa to more than 1000 kg/m^3 for ebony;
- determine the residue per tonne of roundwood (adding in residues that would have been produced during felling).

Roundwood production consists of a trimmed main section of trunk cut to a specific size and resembles a cylinder ($l \times \pi \times r^2$) where l is length of cut cylinder, r is radius. The volume of roundwood including bark (over bark) would be the largest dimensions including the diameter of the bark and the cut length of the trunk. However, the additional residue mass indicated in red in Figure 19 is not accounted for in roundwood data. These residues must therefore be appended to the annual industrial wood production data.

5.2 Results based on industrial roundwood production

According to the FAO (2011), industrial roundwood is used for any purpose other than energy. It comprises: pulpwood for paper; sawlogs and veneer logs for construction and furniture; and other industrial roundwood (for example, fence posts and telegraph poles). Industrial roundwood will be a product of the trunk section of trees and contains the source of most of the sawmilling residues. Residues from sawmills are easily derived from the blue section of the table in Figure 19, but as mentioned earlier, excludes waste left in the forest from initial felling and cutting (for example top, branches, foliage, sawdust and stumps). These materials can be easily calculated and added on a pro rata basis using the figures shown in red Figure 19.

Interpreting Table 7 is best done using an example country. In 2013, the largest producer of industrial roundwood was the USA which had an output of 210 Mt/y (293.582 million m^3). The cutting and shaping of roundwood gives an estimated level of residue and waste of 44 Mt/y. A great deal of residue is produced at the forest felling stage and could amount to 111.8 Mt/y (approximately 148 million m^3 by volume); the total combined residue from felling and sawmills amounts to 155.8 Mt/y.

Table 7 Industrial wood production and calculated residue mass (FAO, 2010, IEA CCC, 2014)

Country	Industrial roundwood production in 2013 (1000 m^3 over bark)	Industrial roundwood production*, Mt	Residue from forest felling and cutting, Mt	Residue from saw mills, Mt	Total residue potential from industrial wood production in 2013,** Mt
Subtotal of sample countries	**1325400**	**963**	**512.7**	**202.0**	**714.6**
USA	29358	210	111.8	44.0	155.8
Russian Federation	180378	129	68.5	27.0	95.5
Brazil	146804	111	59.1	23.3	82.3
Canada	148128	106	56.2	22.1	78.4
China	142574	104	5504	21.8	77.2
Indonesia	62605	47	25.2	9.9	35.1
Sweden	63000	45	23.8	9.4	33.2
India	49517	37	19.8	7.8	27.6
Finland	49331	35	18.7	7.4	26.0
Germany	42052	32	16.9	6.7	23.6
Poland	32908	23	12.5	4.9	17.4
France	24945	18	9.8	3.8	13.6
Australia	22847	17	9.2	3.6	12.8
Japan	18479	13	7.1	2.8	10.0
South Africa	15906	12	6.4	2.5	8.9
Austria	12432	9	4.7	1.9	6.6
Norway	9019	6	3.4	1.3	4.8
Philippines	3858	3	1.5	0.6	2.2
Republic of Korea	3858	3	1.5	0.6	2.1
UK	3020	2	1.2	0.5	1.7
Thailand	14.6	0.01	0.01	0.00	0.01

* derived from industrial roundwood production data (adjusted for coniferous/non-coniferous roundwood

** excludes losses, sawn timber, edgings, and forest sawdust

For the 21 sample countries, industrial roundwood production amounted to 1325.4 million m^3 (Table 7) (963 Mt when adjusted for average density). These countries account for almost 80% of world roundwood production.

The potential residue to be produced by these countries is 714.6 Mt/y. This means that with effective recovery, even with some losses, more than 700 Mt/y of wood residue and waste resulting from roundwood production could be used as a renewable combustible fuel.

Russia, Brazil, Canada and China each produce more than 100 Mt/y of roundwood, and residues production fell into the range of 77–96 Mt/y in 2013. These residues are therefore a potential resource that exists today in the current timber and wood product industry.

5.3 Limits to roundwood production – timber and paper industry outlook

Wood residues used for pellets or wood chips are highly dependent on forest industrial activity and demand for timber products and paper. Some analyses assume projected wood pellet production will increase in coming years, implying an increase in timber and paper production (although in parts of North America wood demand from the paper industry has decreased significantly). Wood pellet production in the USA is expected to grow from 7 Mt/y in 2013 to 10 Mt/y by 2017; the bulk of the growth will come from pellet mills in the southern States. These states could easily account for at least half of production expected in 2017. Some of the biggest producers include Green Circle, Georgia Biomass, Enviva, and Fram. Figure 20 shows the cost of pellet mills in 2012 in US$/t (short). Southern producers have a distinct advantage over other US producers. Eastern US producers tend to prefer the domestic market due to the cost of wood, energy and limited access to port capacity, although the East coast of the US has plenty of coal export capacity that could be used (Walker, 2012).

Canada could see production rise from just over 3 Mt/y to 5.5 Mt/y by 2017 driven chiefly from a rise in exports. At least half will come from British Columbia and the other from Eastern Canada. In recent years, timber production has been afflicted by beetle infestations in British Columbia, while in Eastern Canada the collapse of the forest industry has seen many communities suffer from the closure of hundreds of saw mills, and paper pulp capacity is down from 15 Mt/y in 2005 to 9.4/y Mt in 2011. This reduction in the timber industry could curtail growth in the production of residues and the material needed for pellet manufacture. However, tree plantations could feasibly be redirected from pulp markets to pellet production for power generation provided they meet suitable sustainability criteria. Canada's British Columbian producers can produce pellets at even lower costs, but once ocean freight rates are factored in, these North American producers can supply pellets to Europe for around 180 $/t. The wood costs about 60 $/t – the notion that the wood residue is free as it is waste is incorrect. Beneficiation, storage, auditing, transportation and quality control clearly cost the pellet industry (Walker, 2012).

Pellets are best suited for export or more distant transportation, while wood chips might be advantageous for local energy markets. However, voyage distances between North America and Asia might exceed the limits of current transport costs making trade between these regions less economic. A great deal more research is required to gain a better understanding of international biomass trading and transportation. Wood chips are still transported worldwide for the pulp industry.

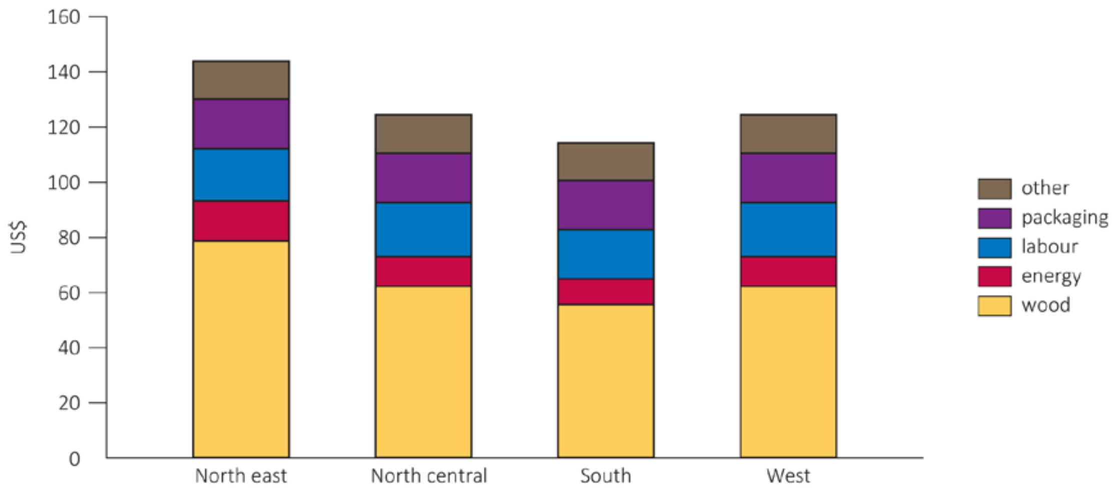


Figure 20 Average variable cost of domestic pellet mills in the USA for 2012 (Walker 2012)

5.4 Threats to forest biomass levels

Afforestation and reforestation have made a substantial impact on the development of forest resources since the late 1990s. Forest that is designated for conservation and biological diversity (as a primary function) accounts for 12% (480 million ha) of the global forest area. Since 1990, this preserved forest has increased by 95 million ha, with some of the biggest gains occurring in 2000-05 particularly in South America and Asia. Deforestation is still significant in certain parts of the world, but one positive outcome is that the area of planted forest is increasing and accounts for 7% of total forest area (264 Mha).

Large-scale planting of trees is significantly reducing the net loss of forest area globally Afforestation and natural expansion of forests in some countries and regions have reduced the net loss of forest area significantly at the global level. The net change in forest area in the period 2000–10 is estimated at –5.2 Mha per year (an area about the size of Costa Rica), down from –8.3 Mha per year in the period 1990–2000. China, Russia, USA, Japan and India lead the world in planting accounting for more than half of this new planted area.

Deforestation is mainly a result of converting tropical forest in Africa and South America to agricultural land. Cofiring in both OECD and non-OECD economies, if practiced sustainably, should not impact forests in an adverse way.

Food production is the largest category of 'non-wood' forest removal worldwide, arising from Asian demand for plants such as camellia, oil seeds, nuts and bamboo. Brazil and Indonesia have the highest net loss of forest since 1990, but Australia's drought and fires have also impacted forests in recent years. Asia has seen a net gain in forest of more than 2.2 Mha/y between 2000-10 due to efforts by China, despite a continued high rate of net loss in many countries in South and Southeast Asia.

Deforestation and afforestation are measured by examining forest area, but in terms of forest felling, wood utilisation is measured in volume terms. World wood removals increased between 2000 to 2005 amounting to 3.4 billion m^3/y; illegal felling will lead to a higher rate of removal. Biomass for domestic heating and cooking accounts for half of all wood removed, but interestingly, wood pellets generally come from the remaining half.

6 Agricultural crop residue

Many coal-fired power stations are located within easy reach of farmland, either by road or rail. Residue by-products from agriculture also offer a considerable source of fuel for cofiring. The type and quantity of residue depends on the crop, farm management and the degree of post-harvest processing. In this section, there is focus on two examples, cereal crop management in Denmark and the UK and palm oil residues in Malaysia; other countries are discussed where appropriate. Determining the amount of residue resource from the world's existing crop production requires an understanding of the proportion of a crop that is available sustainably. More details on the calculations and additional assumptions behind making these deductions are described in IRENA (2014).

Agricultural residues refer to the portion of plant material that remains after a crop has been harvested and separated. Primary residues are those that are the result of farm-level activities; they include items such as straw, stalks and leaves that are left over after harvest. The main residue is straw, which has a plethora of different purposes; reinstatement into the soil improves soil condition, while straw is also an essential and low cost food and bedding material for livestock. Straw is the most important agricultural residue in the EU; indeed, almost 23 Mt/y of dry biomass from straw could be available yearly. As a cofiring fuel, straw has been thoroughly tested in coal-fired power plants and its properties and performance in station boilers are well understood.

Secondary residues are those that result from processing, such as sugar beet pulps, cotton mill wastes, and peanut shells. For most crops, primary residues are produced in quantities approximately equal in weight to the actual crop production; the amount of secondary residues varies depending on the crop and processing methods used.

6.1 Agricultural residues for cofiring – straw

Straw is an immensely versatile material which is easy to handle, compress and transport in bale form; it can be processed further to produce dense pellets suitable for burning in industrial boilers and power stations. Denmark has rapidly developed large-scale conversions of coal-fired power stations which utilise many types of biomass, and make use of large quantities of straw that is produced locally. Denmark is already committed to a 30% renewable energy by 2020 through a national support scheme of an electricity subsidy of 2 euro cents per kW (for full or cofiring of biomass). Figure 21 shows a large outdoor storage area. Straw pellets are transported by road, while Figure 22 shows the size of each bale relative to the size of the truck transportation. There are 24 big bales in two layers on the truck and trailer, with a total weight of 12 tonnes (Nikolaisen, 2012).

Figure 21 Large outdoor storage of straw for energy purpose in Denmark (Nikolaisen, 2012)

Figure 22 Normal transport of straw for large-scale energy use (Nikolaisen, 2012)

6.2 Estimating agricultural crop residue resources

As a general rule, only a quarter of the straw generated for each crop is assumed to be recoverable (IRENA, 2014). The basic calculation for each crop is as follows:

$$Resource = Total\ crop \times\ harvet\ index \times\ recoverability - residues\ dedicated\ to\ other\ uses$$

The *harvest index* is an immensely important number as it quantifies the yield of a crop species versus the total amount of biomass that has been produced. Simply, the index is the fraction of the above ground biomass that is the primary crop. This primary crop can be grain, tuber or fruit.

Root systems are considered too complicated and uncertain to include unless land is being cleared completely when roots are included. The remainder that is not crop becomes the waste by-product of the growing process; here is the potential resource for biomass cofiring after factors such as recoverability and other non-energy residue demand are taken into account.

$$Total\ biomass\ production = \frac{cereal\ production}{harvest\ index}$$

$$\boldsymbol{Available\ straw\ as\ \%\ of\ total\ biomass}$$
$$= (Total\ biomass\ production)\ x\ (\%\ of\ which\ is\ straw)\ \ x\ (\%\ suitable\ for\ collection\ and\ bailing)$$

Based on UK figures for grain/seed production in 2011, 25% of the total biomass is available as straw (*see* Table 8). This figure agrees with recent straw yield ratios published by IRENA (2014). Other EU wide analysis suggests that the straw resource for the EU-15 countries in 2002 was around 9 Mt (Pastre, 2002), wheat production in the same year for these countries amounted to 104 Mt (FAOSTAT, 2014).

Table 8 Cereal and straw production in the UK in 2011 (Stoddard and Watts, 2012)

	Grain/seed production (000 t)	Harvest index for grain/seed (%)	Total biomass production (Mt)	Proportion of total biomass as straw (%)	Straw biomass (000 t)	Straw available for collection & bailing (%)	Available straw (000 t)	Available straw as a % of total of biomass
Wheat	15257	51	29916	43	12864	60	7718	25.8
Barley (Winter)	2200	51	4314	43	1855	60	1113	25.8
Barley (Spring)	3294	51	6459	43	2777	60	1666	25.8
Oats	613	47	1304	47	613	60	368	28.2
Oilseed rape	2758	35	7880	35	2758	50	1379	17.5
Total	24122		49872		20867		12244	24.9

This would suggest that the total biomass (wheat + dry straw) is 113 Mt, and the ratio of straw to biomass is more like 9% (versus the 25% assumed by IRENA) due to the much lower assumptions on availability coefficients.

This average straw ratio is based on a series of steps starting with crop production data, and then adjusting for harvest and availability. Wheat and barley generally yields 25–26% of straw from the total (above ground) biomass, while oats can be higher and oilseed rape much less. The largest single crop in the UK in 2011 was 15.3 Mt of wheat production.. The harvest index is 51% of the total wheat based biomass that is grown. The proportion of total biomass that is straw is 43%. Of this, 60% is considered to be available for collection and bailing, providing an ultimate (wheat based) straw resource of 7.7 Mt. Other analysis suggests UK straw resources are closer to 1.5 Mt (Stoddard and Watts, 2012).

Since 2011, wheat production has fallen year on year to 13 Mt in 2012 and 12 Mt in 2013. Weather related problems affected agriculture, with a wet autumn in 2012 and a cold spring in 2013. UK production was hit badly leading to a greater need for imports. Logically, straw production will also decline. This does not however affect the ultimate long-term resource which is determined by land use (and ideal conditions), which is assumed to remain unchanged, but the data clearly show that seasonal variations and weather related aberrations can seriously affect the short-term availability of straw in any given country (FAO, 2014).

6.2.1 Estimating the global resource of agricultural straw residues

The world's agricultural economy produces around 230 EJ/y worth of biomass for food, livestock feed (including grazing), fibre and bioenergy (most of which is derived from residue and waste flows). For comparison, the world's primary energy in 2012 was around 560 EJ/y.

For four decades, rising food demand encouraged a 30% increase in cropland and intensified agricultural practices. The largest producer in the world is the USA which produced 411.7 Mt of wheat and maize in 2013. The global resource for usable residue from cereal crops amounts to a possible 517.4 Mt. At a conservative heating value of 14 MJ/kg of yellow straw (versus the higher value grey straw), the current world resource of straw is equivalent to 7 EJ. Grey straw contains a higher heating value as a result of leaching from rainfall which removes some of the potentially corrosive alkalis; when dried, grey straw is a more desirable energy product for cofiring.

Table 9 lists the world's 30 largest producers of cereal crops and consequently straw based biomass. An extremely interesting outcome is how Denmark does not feature in the list of the top 30 countries that produce cereal crops, yet the country is a major developer in biomass conversion and cofiring in coal-fired power stations. Nevertheless, straw resources in Denmark are considerable. According to IEA CCC calculations, the country has 15 PJ of straw residue that is available from its annual cereal production; this agrees with analysis by Skott (2011). However, Skott suggests there is an unexploited potential of 40 PJ (based on then 2008 land use). It is possible that the list in Table 9 grossly underestimates the potential of global biomass available from cereal production.

Table 9 World cereal production and estimated straw residue in 2013 (FAO, 2014; IEA CCC, 2014)

Country	Wheat, Mt	Maize, Mt	Estimated straw residue (equal to mass to wheat and maize), Mt	Recoverable and usable straw residue (25% of estimated straw residue), Mt
1 USA	58.0	353.7	411.7	102.9
2 China	121.7	217.8	339.6	84.9
3 India	93.5	23.3	116.8	29.2
4 Brazil	5.7	80.5	86.3	21.6
5 Russian Federation	52.1	11.6	63.7	15.9
6 Ukraine	22.8	30.9	53.7	13.4
7 France	38.6	15.1	53.7	13.4
8 Canada	37.5	14.2	51.7	12.9
9 Argentina	8.0	32.1	40.1	10.0
10 Germany	25.0	4.4	29.4	7.4
11 Pakistan	24.2	4.8	29.0	7.3
12 Turkey	22.1	5.9	28.0	7.0
13 Mexico	3.4	22.7	26.0	6.5
14 Australia	22.9	0.5	23.4	5.8
15 Romania	7.3	11.3	18.6	4.7
16 Indonesia	0.0	18.5	18.5	4.6
17 Iran (Islamic Republic of)	14.0	2.5	16.5	4.1
18 Egypt	9.5	6.5	16.0	4.0
19 Kazakhstan	13.9	0.6	14.5	3.6
20 South Africa	1.8	12.4	14.1	3.5
21 Italy	7.0	6.5	13.5	3.4
22 Poland	9.5	4.0	13.5	3.4
23 Spain	7.6	4.9	12.5	3.1
24 UK	11.9	0.0	11.9	3.0
25 Hungary	5.1	6.7	11.8	3.0
26 Ethiopia	4.0	6.7	10.7	2.7
27 Nigeria	0.1	10.4	10.5	2.6
28 Serbia	2.7	5.9	8.6	2.1
29 Bulgaria	5.1	2.3	7.4	1.8
30 Philippines	0.0	7.4	7.4	1.8
Rest of the world	**200.0**	**310.4**	**510.4**	**127.6**
World Total, Mt	**834.9**	**1234.6**	**2069.5**	**517.4**
World Total, EJ (at 14 MJ/kg)	**11.7**	**17.3**	**29.0**	**7.2**

Table 9 shows the resource for the year 2013, earlier years would show how weather and climate affects crop output. Some of the latest findings suggest that the potential for crop residues can be expanded depending on the capacity for the world's agricultural industry. IRENA (2014) estimated that total biomass supply worldwide could range from 97–147 EJ/y by 2030 (in primary energy terms). About 38–45% of the total supply is estimated to originate from agricultural residues and waste (37–66 EJ/y).

The remaining supply potential (60–81 EJ/y) is shared between energy crops (33–39 EJ/y) and forest products, including forestry residues (27–43 EJ/y). By 2050, the demand for all biomass could increase, but agricultural residues will remain a larger proportion of the total biomass supply providing up to 550 EJ/y *(see* Figure 23). Part of this outcome is due to the favourable economics offered by agricultural residues and waste. Sourcing low cost residue can be important since the process of pelletising straw and wood (chip) residue adds further cost to the final biomass product.

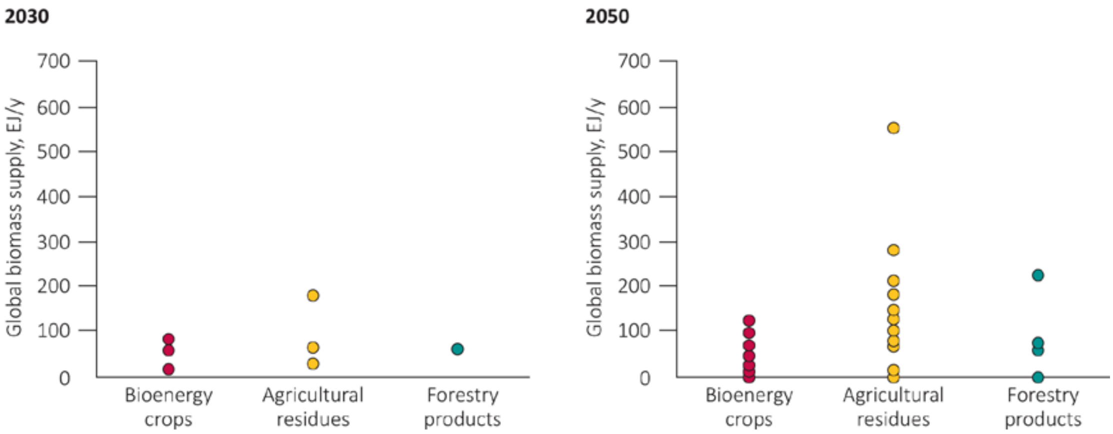


Figure 23 Literature review of global biomass energy supply potential estimates in 2030 and 2050 (Slade, 2011)

A key observation is the spread of results arising from years of research studies that examine resources differently depending on the prevailing regulatory and policy circumstances at the time of the analysis. Much of the variation is less to do with assessments of agricultural practices, but more on how land use is assessed. There are many issues regarding land conservation and sustainable use, but one of the key debates that arise continually is the impact of pasture dairy and cattle farming, and the vast land, agricultural, energy and water resources needed to supply the rising demand for meat across the world.

6.3 Surplus land – potential to boost long-term biomass supplies from agriculture

Competition between different forms of land use can be critical, and is intensifying between use for human food, animal food, and dedicated energy crops. Regulatory forces often act as an external lever that can steer land use in a particular direction, whether for agriculture or for conservation. During the early 1990s, around 6–7 Mha (10%) of arable land in the EU was removed from production to limit agricultural surpluses under the set-aside scheme. In the UK, land that was surplus for food production requirements led to discussions on an agricultural land set-aside scheme, which motivated the development of energy crops (Slade and others, 2011).

Other types of land might be converted to energy crop use in the future. These areas include marginal and degraded land, deforested and forested areas, and extensive grasslands such as the African savannah and Brazilian cerrado. But these lands may include areas that are high in biodiversity, remote from any infrastructure, used for seasonal grazing or otherwise unavailable for a myriad of reasons. Moreover, they may suffer from poor soils, have limited water availability, be unsuitable for mechanised agriculture or be otherwise poorly yielding or uncultivable.

6.3.1 Land use scenarios

Scenarios that study the impact on arable land of dairy and cattle farming are useful, but they need to examine the impact on land dedicated to energy crops. These crops include those chiefly for biodiesel and biogasoline. It is not clear whether these include miscanthus and grasses, but for the purposes of this report, only agricultural crop residue is considered.

Figure 24 illustrates the current distribution of land use and the potential land use that is suitable for biofuels. This illustration is a good example of how more land could be converted from pasture to crop production provided the right economic and market incentives exist.

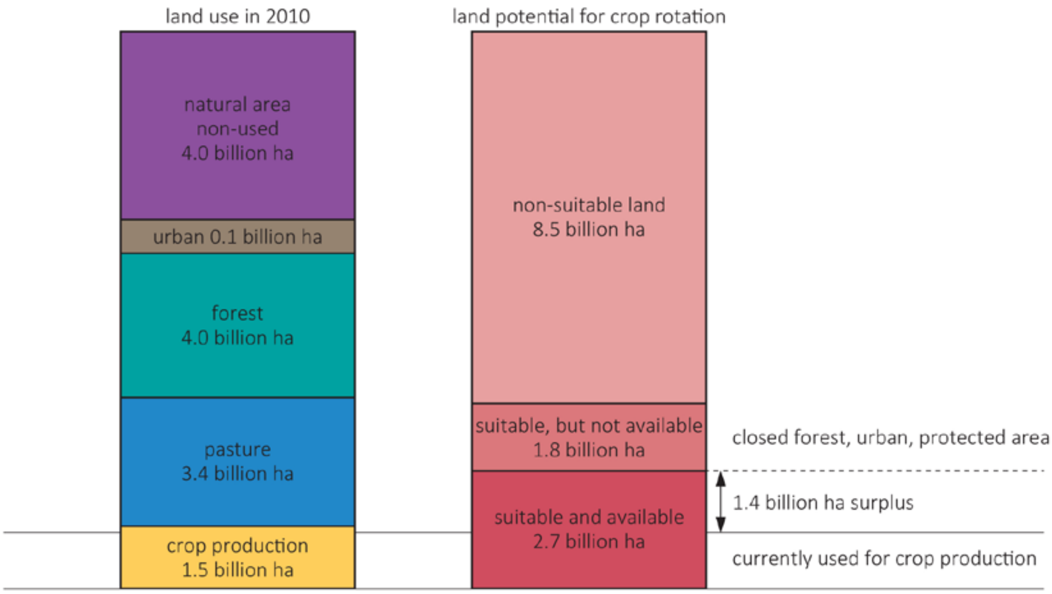


Figure 24 Land use for crop, pasture, forest and other uses in 2010 and future potential for bioenergy crops (IRENA, 2014)

Global land area covers 13 Gha, of which 8.5 Gha is unsuitable, leaving 4.5 Gha suitable for crop production, but only 2.7 Gha is available. The remaining 1.8 Gha is used for non-agricultural purposes.

The current production of food crops utilises some 1.5 Gha of land, of which 1.3 Gha falls under this category of 'suitable land' (for bioenergy crops). ***As a result, about 1.4 Gha of additional land is suitable but unused to date and thus could potentially be allocated for bioenergy supply in future (IRENA, 2014)***.

Figure 24 illustrates how land conversion is feasible, but there are still constraints on land that can be cultivated for crops.

In this report, resource analysis by the IEA Clean Coal Centre assumes only residues and waste from cereal crops are used, but if the plant type were to alter to another type of cereal, residues of some kind may still be available for cofiring.

Meat demand has an impact on the area available for energy crops (Hoogwijk and others, 2005). Assuming the trends for meat consumption remain the same or increase, the demand for pasture land and cropland devoted to cereal-based animal feed will affect the crops designated for human consumption. As a means of illustrating the high impact of dairy and cattle farming, a European scenario indicates that high population growth and high meat consumption would require three times the land area (for food production) than that needed in a low population growth and low meat consumption scenario (scenario B1) (Hoogwijk and others, 2005). On a global scale Yamamoto (2000) finds that high demand for meat reduces the global energy crop potential from 150 EJ/y (reference case) to 78 EJ/y (high demand for animal food case), whereas the potential from food biomass residues increase from 160 to 186 EJ/y, presumably due to the increase in crops grown for livestock feed, from which residues will be produced, suitable for cofiring in power stations. Analyses of future land use scenarios are found in IRENA (2014); the study concludes that 1.4 Gha of surplus land will exist in 2030, down from the 1.5 Gha that existed in 2010. Population growth will lead to a 30% rise in food demand, while supplies of cereal could be more modest at just 15% growth between 2010 and 2030. Less land might be suitable in the future than has been seen in the past.

In some parts of the world, the land designated unsuitable for crops or agriculture is less well defined. In many cases, forest areas should not be used for agricultural production, but in the tropics, climatic conditions are perfect for some crops and expansion and encroachment into forest is common. Crop resources in tropical regions might include palm oil, rice, and, rubber wood; despite a loss of forest, a multitude of residues are available from these crops. Global palm oil production is dominated by two countries, Malaysia and Indonesia, both of which have a rich rain forest and a wealth of biodiversity. Human activity is threatening vast tracts of land and forest dwelling species of animal.

A deforestation policy is being adopted by some of the major consumers of palm oil to minimise the impact of their activities.

World palm oil production in 2008 reached 17.7 Mt; Malaysia is the second largest producer of oil palm after Indonesia. Projections for 2016-20 suggest that Malaysian palm oil production could reach 15.4 Mt. (Abdullah and Sulaiman, undated). Palm oil has changed Malaysia's agricultural economy. Crude palm oil mills use large quantities of water and energy, and the manufacturing process produces large quantities of solid waste, wastewater and air pollution. Solid waste materials include empty fruit bunches (EFB), palm pressed fibre (PPF), shell and palm oil mill effluent (POME). Table 10 shows the breakdown of product or waste from each bunch of fresh fruit (FFB).

Table 10 Oil Palm wastes in Malaysia (Abdullah and Sulaiman, undated)

Products/wastes	Percentage by weight FFB (dry basis)
Palm oil	21
Palm kernel	7
Fibre	15
Shell	6
Empty fruit bunches	23
POME	28
Total	**100**

Few data exist for oil palm dry matter production; most estimates refer to palm oil, palm kernel, and fresh fruit bunches (FFB). As an approximation, for each kg of palm oil, another 4 kg of dry biomass is produced, a third of which is found in the fruit bunches, and two thirds in trunk and frond material.

A small fraction of this dry waste matter is used; open burning can still occur and is a major cause of air pollution in South East Asia. Empty fruit bunches can be utilised to make paper while the trunk can be used for saw wood and ply wood or lumber. Wood chips can be used for fibre board.

In Malaysia, effort is being put into understanding and utilising the large amounts of residue from the country's agri-businesses. Palm oil residues are particularly interesting with a potential to provide enough fuel to power 6 GWe of generating capacity. While the fleet consists of mainly subcritical plants operating at around 30% efficiency, there is greater potential in cofiring in newer power stations firing coal at a higher efficiency closer to 40%.

In Malaysia, more than half of the residues come directly from agricultural and forest activities, the rest comes from mills and other processes. Residues available for cofiring are estimated to be about 12 Mt/y, of which oil palm provides the largest potential (77%), followed by rice (9.1%) and forestry residues (8.2%). Remaining residues come from wood based municipal waste, rubber, cocoa, and coconut residues (the last two being negligible) (Griffin and others, 2014). Palm oil and palm accounts for almost all the other residues available to Malaysian power generators combined.

The availability of agricultural residues in some of Malaysia's regions is good, but accessibility is a different matter. Biomass palm oil resources are located in the south of the country while the major power stations are located around the western regions closer to Kuala Lumpur. Road networks link the palm oil regions with the market, but truck is expensive. Rail is cheaper to operate, but expensive to install.

6.3.2 Cofiring experience with palm oil

Other biomass types such as husks and shells from non-cereal crops also offer a growing supply source; olive pit and palm oil husks and fibre can be abundant in certain regions of the world.

Quantities of agricultural residues given in this section therefore greatly underestimate the overall potential from other fuels, and further research is required in understanding the resources of non-cereal residues.

In Malaysia, cofiring biomass in 330 MWe units can reduce annual electricity generating costs by $20 million compared to current coal-fired generation and reduce CO_2 emissions by 1.9 Mt. The capacity could be increased to 1000 MWe, resulting in cost savings of $35 million every year and a reduction in emissions. This would exceed the entire renewables target of 975 MW of capacity (Griffin, 2014). There is some cofiring experience of burning pelletised fuel in large power stations such as the 700 MWe Jimah plant. Typical challenges regarding handling and storage of the fuel as well as increased slagging were experienced. The cofiring was injected at a concentration of roughly 2% of fuel by weight (Rahman, undated).

The abundance of residue from the palm oil industry is similar to that of wheat straw, where a small percentage of the plant is used. Fruit bunches, mesocarp fibre and palm kernel shell waste could also provide large amounts of biomass. Rice husks and wood fuel also result from agricultural activities, whether from land clearance or crop production. The heating value of these husks and shells range from 14.6–19 MJ/kg and so are comparable with wood pellets. The processing of tropical crops and wood can greatly improve the quality of the cofiring fuel. Pelletising and torrefaction have been researched for these local Malaysian fuels, the latter process being done at a bench scale showing that heating values can be increased slightly for nearly all torrified fuels.

6.3.3 Summary of tropical residues

Further research is required to firmly establish the potential resource of agricultural residues for cofiring. Major obstacles include the conflict with forestation and deforestation policies, and also the limited low cost infrastructure linking the agricultural areas with the demand centres which are chiefly in the Peninsular Malaysia region around Kuala Lumpur. Large-scale cofiring at rates of perhaps 5–10% is possible, provided the usual challenges of fuel storage and boiler slagging can be overcome or managed. The effects of weather and climate means uncovered fuel storage will limit the life of the fuels.

7 Conclusions

Compared with the wealth of fossil fuel resources and reserves data available worldwide, there is a dearth of equivalent data for biomass. Yet, biomass accounts for 10% of global primary energy supply (56 EJ of in 2012). Surprisingly, biomass is equivalent to 300% of all other renewable energy production, combined. The role of biomass in the world's economy is as a heating and cooking fuel in agrarian communities, but it is becoming an extremely important power station fuel in a long-term strategy to reduce greenhouse gas emissions from coal-fired power stations.

The world currently has 60 GWe of power capacity that is designed for biomass and waste; solid fuels account for almost two thirds of this. Large-scale conversions from coal-fired units of around 600 MWe to 100% biomass units are being undertaken in Denmark and the UK.

The potential to partially or fully convert units amongst the world's coal-fired fleet is substantial. Coal power exceeds 1800 GWe, of which half is in China, and 36 GWe uses solid biomass as a secondary fuel. This figure could increase substantially in an effort to help curb CO_2 emissions from fossil-fuelled plants across the world. However, there is little indication that there is enough biomass in the world to supply such a scale of consumption.

Published research suggests that the world biomass supply could reach 100–200 EJ/y but optimistic estimates can be as high as 1200 EJ depending on the wide variety of assumptions on sustainable practice, land use and dietary trends of the world's population. At the lower estimate of 100 EJ/y this is equivalent to 5800 Mt/y of biomass (wood equivalent). These estimates comprise all solid and gaseous biomass from both primary and industrial waste sources, but more critically, include a considerable resource aimed at energy crops supplying bio transport fuels.

However, cofiring large amounts of biomass with coal requires careful selection to ensure that any adverse effects on boiler performance are minimised, but also that the sourcing is as sustainable as possible. One such source will be waste residue from existing forestry, sawmilling, and agricultural activities; and utilising biomass that would otherwise be left to decompose or used as landfill (leading to the emission of greenhouse gases).

Wood and agricultural crop residues such as straw have provided an important resource for cofiring in modern power stations. Recent research from IRENA suggests that forest residues could supply 21 EJ/y of biomass, and agricultural residues supply 13 EJ/y. These alone account for a third of the future world biomass supply.

Simple analysis carried out in this report suggests there is 14,218 Mt of wood residue within forest that is already designated and available for industrial wood production (*see* Table 11). The primary products for wood production are chiefly timber and paper and pulp. Residues arising from the felling, trimming and cutting of the wood give rise to a substantial resource of residue suitable for processing into cofiring pellet fuel.

Table 11 Total potential residue contained in forests designated for productive use (IEA CCC, 2014)

	Mt	EJ
South America	1612.8	20.2
North America	2128.2	26.6
Russia	5718.4	71.5
Europe (ex Russia)	1178.5	14.7
Asia-Pacific	3528.0	44.1
Africa and ME	52.2	0.7
Subtotal of sample countries	**14218.0**	**177.7**

Those forests designated for productive use contain 14,218 Mt of potential residue in the form of offcuts and chipping resulting from the separation of branches, bark, tree stumps, foliage and so on from the primary wood product (usually timber and paper chips). This amounts to around 177 EJ of imputed energy contained in these residues. The majority is contained in Russia which has the largest land area covered in both productive and total forest. North America is the largest producer and exporter of wood pellets; resources in Canada could be underestimated.

While the global resource for residue is abundant in the world's forests, the amount that is produced and available in any year is in direct correlation with the actual output from the forestry and milling industries.

The conservative calculations carried out in this report suggest that the potential residue produced from current industrial roundwood and cereal crop production could give rise to a potential 1090 Mt/y of residue (14.2 EJ/y in wood pellet equivalent). This residue resource is almost three times current demand for primary biomass in the power and heat sector, and more than double the total biomass demand worldwide.

By 2030, IRENA estimates that 37–66 EJ/y of agricultural residues and waste and 27–43 EJ/y of forest products and forestry residues could be available. With a current supply of 8.9 EJ/y of wood residues and 5.4 EJ/y from agricultural residues, there is a great deal more unexploited potential yet to be realised through improved harvesting, crop yield performance and land use and forestry management.

A 5% cofiring scenario for the world's fleet could create a biomass demand from subcritical coal plants operating at midload to baseload of 235 Mt/y. This is around a fifth of the annual residue resource from roundwood and straw, and a fraction of the 14,219 Mt/y of residues present in the world's productive forest as calculated by the IEA CCC.

The 14.2 EJ/y of forest residue and straw calculated in this report also underestimates the deadwood available in forests which can be as much as 10% of the forest mass.

Other sources of residue will include the millions of hectares of forest that are not clearly designated for productive use which were not included in this assessment. Municipal and industrial wood waste could also provide a significant proportion of the world's biomass and is an area requiring further research

Agricultural residue potential is substantial, but heavily dependent on infrastructure to collect, bale and transport the material, but more fundamentally, the current land use could be used differently. Switching land from livestock farming to arable farming is possible, especially for unused land, and could greatly enhance the potential for supplying agricultural crop residues.

Clearly, there is an abundance of biomass resources worldwide. The cautious approach to calculating residues in this report has indeed shown a residue potential below estimates of other published analyses, yet still far above the potential demand that could be created through cofiring 5–10% of fuel used in the world's coal-fired power fleet.

Europe's power market has already demonstrated that biomass sources need not be restricted to local suppliers, but in a dense pelletised form, these fuels can be transported from North America.

The potential for waste and residue from the global forestry and agricultural sectors to supply the world's coal-fired power stations is considerable. If these sectors are practiced sustainably, a proportion of the world's coal can be replaced with carbon neutral biomass, therefore making considerable saving in CO_2 without causing any detrimental effect to the operation of the power stations.

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