IRENA
International Renewable Energy Agency

Global Bioenergy

SUPPLY AND DEMAND PROJECTIONS

A working paper for REmap 2030

September 2014

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international cooperation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. www.irena.org/remap

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KEY FINDINGS

- **The global energy picture is changing rapidly in favor of renewable energy**. According to IRENA's global renewable energy roadmap – REmap 2030 – if the realisable potential of all renewable energy technologies beyond the business as usual are implemented, renewable energy could account for 36% of the global energy mix in 2030. This would be equal to a doubling of the global renewable energy share compared to 2010 levels.
- **Biomass has an auspicious future.** By 2030, biomass could account for 60% of total final renewable energy use and **biomass has potential in all sectors.**
- **Most biomass demand today is its traditional uses for cooking and heating.** In 2010, more than 60% of the total global biomass demand of 53 exajoules (EJ) was used in the residential and commercial buildings sectors. Much of this was related to traditional uses of biomass for cooking and heating. Biomass demand in the manufacturing industry (15%), transport (9%) and the power and district heating (8%) sectors accounted for about one-third.
- **Biomass applications could change over time.** Global biomass demand could double to 108 EJ by 2030 if all its potential beyond the business as usual is implemented. Nearly a third of this total would be consumed to produce power and district heat generation. About 30% would be utilised in biofuels production for the transport sector. The remainder would be halved between heating applications in the manufacturing industry and building sectors. Biomass use in combined heat and power (CHP) generation will be key to raise its share in the manufacturing industry and power sectors.
- Estimated **global biomass demand,** according to REmap 2030, in the **United States, China, India, Brazil and Indonesia** together account for 56% of the total.
- **Global biomass supply** in 2030 is estimated to range from 97 EJ to 147 EJ per year. Approximately 40% of this total would originate from agricultural residues and waste (37-66 EJ). The remaining supply potential is shared between energy crops (33-39 EJ) and forest products, including forest residues (24-43 EJ). The **largest supply potential** exists in Asia and Europe (including Russia) (43-77 EJ).
- **International trade of biomass** would play an important role in meeting the increasing global demand. Trade could account for between 20% and 40% of the total global demand by 2030. **Domestic supply costs of biomass** is estimated to range from as low as USD 3 for agricultural residues to as high as USD 17 per GJ for energy crops.
- There are many **challenges to be address in biomass demand and supply, its international trade as well as the substitution of its traditional uses** in realising such high growth rates. Moreover, with bioenergy demand estimated to double between 2010 and 2030, ensuring the **sustainability of biomass will gain even more importance** including environmental, economic and societal aspects.
- For a **sustainable and affordable bioenergy system**, existing national and international initiatives/partnerships as well as energy and resource policies need to be expanded to address the challenges across the biomass use and supply chain.
- While biomass represents an important stepping stone in doubling the global renewable energy share, potential of other renewables should be expanded further with policy support to **ensure the deployment of a broader portfolio of technologies** and **reduce dependency on biomass resources**.

1 INTRODUCTION

The International Renewable Energy Agency (IRENA) has developed a Global Renewable Energy Roadmap – called REmap 2030 – to double the share of renewables in the global energy mix by 2030. This ambitious target is derived from the Sustainable Energy for All (SE4All) initiative, which is currently chaired by the United Nations Secretary-General and the World Bank President. REmap 2030 projects that existing and future renewable energy expansion, as currently planned, will result in a 21% share of renewables globally (IRENA, 2014a). This leaves a nine percentage-point gap to achieve a 30% renewable energy target in 2030, or a 15 percentage-point gap to achieve the 36% target, as indicated in the SE4All Global Tracking Report (Banerjee *et al.,* 2013).

The REmap 2030 analysis (IRENA, 2014a) indicates that biomass would become the single most important renewable resource if all additional renewable technology options in the 26 REmap countries[1] were to be implemented worldwide by 2030. Biomass would then account for 60% of global renewable energy use and would dominate all end-use sectors. Biomass would then comprise 20% of the global primary energy supply, doubling its share from 10% in 2010.

In 2010, Africa and developing countries in Asia each accounted for a quarter of global biomass use (IEA, 2013a) while China accounted for another sixth. Developing countries use biomass mainly for cooking, industrial applications and electricity generation. The industrialised countries of the Organisation for Economic Co-operation and Development (OECD), which accounted for a fifth of global biomass consumption in 2010, use biomass mainly for heating and electricity generation in efficient boilers and combined heat and power (CHP) plants. The trend towards modern and industrial uses of biomass is growing rapidly. However, the demand often occurs in locations geographically distant from the supply source. This results in increasingly complex production systems (*e.g.*, feedstock supply and conversion combinations) (Searcy *et al.*, 2013).

REmap 2030 shows that biomass use worldwide could grow by 3.7% per year from 2010 to 2030 – twice as fast as it did from 1990 to 2010 (IEA, 2013a) – if cost-effective applications are put in place. Global biomass demand would then double from 53 exajoules (EJ) in 2010 to 108 EJ by 2030 (IRENA, 2014a).

Biomass applications will change. In 2010, about two-thirds of all biomass use was in building (residential and commercial building sectors), of which more than three-quarters (half of total biomass use) was for traditional applications, such as wood-burning fires and cook stoves. By 2030, as traditional uses decline, less than a fifth of biomass use may be in buildings.

Electricity generation from biomass, often combined with district heating, would grow by 10% per year to account for nearly a third of global biomass demand by 2030 – roughly triple its share in 2010.

Liquid biofuels for transport would grow nearly as fast to 28% of biomass use – also tripling their 2010 share. Total demand for cooking and heating in industry and buildings would decline to 40% by 2030, compared to its 80% share in 2010 due to growth in the transport and power sectors and substitution of traditional uses.

Other recent studies also arrive at similar estimates for biomass' share of the global renewable energy demand in 2030 (*e.g.*, see review in IPCC, 2011). Therefore, biomass would be the single most important resource to mitigate climate change (*e.g.*, IPCC, 2011; EUWID, 2014a). However, affordability, supply security and sustainable sourcing are major concerns.

In view of the increasing importance of biomass use, estimates of its supply potential have been the focus of many studies. Different studies quantify the potential of biomass at global, regional and country level for the short- to long term. Studies take into account such factors as differing land use, water and resource availability estimates, as well as varying levels of population and

1 The 26 REmap countries which together account for 75% of the global total final energy consumption (TFEC) in 2010 are: Australia, Brazil, Canada, China, Denmark, Ecuador, France, Germany, India, Indonesia, Italy, Japan, Malaysia, Mexico, Morocco, Nigeria, Russia, Saudi Arabia, South Africa, South Korea, Tonga, Turkey, Ukraine, the United Arab Emirates (UAE), the United Kingdom (UK) and the United States (US).

Table 1: Global biomass demand growth by application in REmap 2030, 2010-2030

	2010 (EJ/yr)	2030 (EJ/yr)	Growth (%/yr)	Growth (EJ/yr)
Buildings, traditional	27	12	-4.1	-0.8
Buildings modern	8	13	2.6%	0.3
Manufacturing industry	8	21	4.9%	0.7
Transport liquids production	5	31	9.7%	1.3
Power and district heat generation	5	31	10.0%	1.3
Total	**53**	**108**	**3.7%**	**2.8**

Note: All data are expressed in primary energy terms. To estimate raw biomass required for the production of liquid biofuels, a conversion efficiency of 50% is assumed to convert the final energy content of liquid biofuels to primary energy. Raw biomass refers to net input, thereby excluding biomass that goes back to the food chain, such as protein meal, dried distillers grains with solubles (DDGS), etc. and subtracting fossil energy required to produce, transfer and convert to final energy.

economic growth to arrive at the biomass supply potential. Due to the large variation in these parameters and the different constraints assumed for the availability of resources, estimated biomass supply potentials for the year 2050 range from as low as 50 EJ/yr to technically challenging potentials as high as 1,500 EJ/yr. Considering this wide range, formulating appropriate bioenergy policies for specific countries is extremely complex.

The objective of this working paper is not to add yet another data input to this already complicated prognosis. Rather, it addresses itself to a number of crucial questions in view of biomass' large demand potential in 2030 (IRENA, 2014a), as well as the uncertainties concerning supply in a sustainable, affordable way and how this might be ensured. These questions are presented below, with the related sections where these questions are answered indicated in brackets:

- How much biomass is available / recoverable by 2030, taking sustainability concerns into account? (Section 4.3)
- What will be the supply cost and future price of biomass? (Section 4.3.3)
- How fast can biomass' supply expand? (Section 8.2)
- What is the optimal use of biomass? (Sections 4.1 and 4.2)
- What are the key uncertainties for biomass prospects? (Sections 5, 6 and 7)
- What can governments do to strengthen biomass deployment? (Section 9)

This working paper starts by describing the methodology IRENA applied to estimate the biomass supply potential and costs (Section 2). It continues by presenting the current bioenergy market situation (Section 3). Section 4 compares the total biomass demand estimates according to REmap 2030 with these supply estimates. Section 5 discusses the uncertainties in realising the demand and biomass supply growth estimates between now and 2030. Section 6 discusses the biomass supply cost estimates. Section 7 outlines the sustainability issues around biomass. In view of the uncertainties in bioenergy growth and sustainability, Sections 8 and 9 identify the technology options and hedging strategies, as well as policy needs, needed to strengthen bioenergy use and supply growth. The working paper concludes with Section 10, which outlines the next steps for improving expanding the bioenergy work of IRENA based on the findings of this paper.

2 METHODOLOGY

Section 2.1 explains the analytical framework. Sections 2.2 and 2.3 explain how biomass supply and costs are estimated by country and biomass source. Section 2.4 focuses on the methodology of trade volume estimates.

2.1 Overview of the biomass demand and supply framework

In 2013 IRENA carried out a detailed analysis to estimate the supply potential of biomass based on data from the Food and Agriculture Organization of the United Nations (FAO) for 118 countries (including the 26 REmap countries) covering two-thirds of the total global potential.

The potentials of four main types of biomass are estimated for each country:

(i) Energy crops, including food crops;
(ii) Forest products (fuelwood, residues and processing, and post-consumer waste);
(iii) Agricultural residues (harvesting residue, processing residue and food waste); and
(iv) Animal manure.

Biomass production potential from algae is excluded from the scope of this study since the technologies are still developing and the potential yields are still speculative (Sikes, van Walwijk and McGill, 2010; Biddy *et al.*, 2013). Since the algal potential could ultimately prove quite substantial, the overall estimates of biomass production potential in this paper may therefore be considered conservative.

The bioenergy assessment framework is illustrated in Figure 1, which illustrates that biomass energy comes from two different sources. One is *primary* bioenergy, which uses farmland or forests to produce biomass< the other is biomass *residue*, which is generated as a by-product of food or wood products throughout their supply-consumption chain.

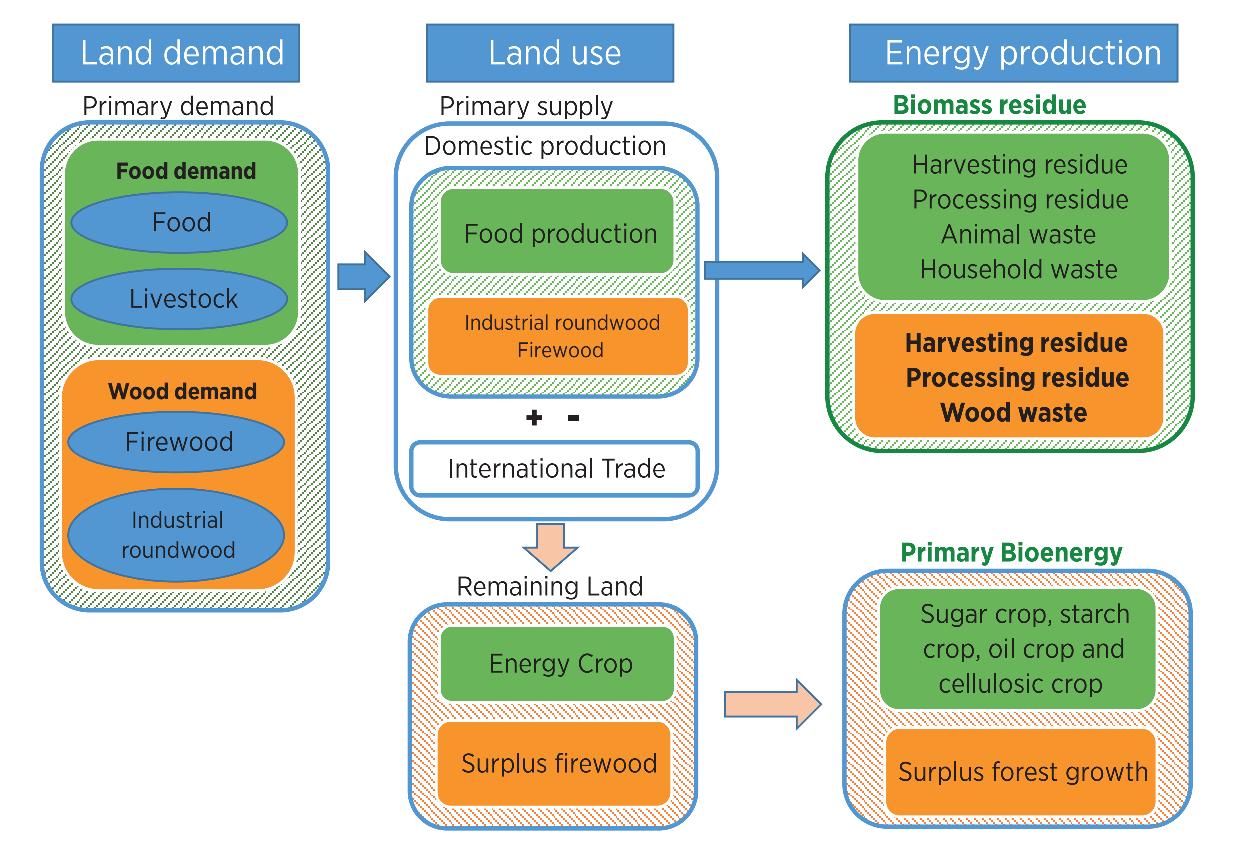
Production of *primary bioenergy* from agricultural resources is closely related to food demand and supply because both energy and food crops are produced using the same agricultural land resources. The total volume of agricultural *residue* generated is primarily a function of crop production, which is related to the amount of land cultivated (in hectares), the mix of crops raised and crop yields per hectare. Demand for food and energy is determined by developments in a given country's population and economy (indicated by gross domestic product, GDP). Population and economic growth data to estimate food demand are collected and published by from United Nations (United Nations, 2009) and the World Bank (World Bank Development Prospects Group – cited from FAO 2012a), respectively.

For energy demand estimation, national plans from the 26 Remap countries were used. Together, they account for three-quarters of the TFEC[2]. The assumptions for population and economic growth in these 26 countries may deviate from source projections used to estimate food demand, but are adequate for the purpose of this working paper.

The food and energy demand-supply cycles send signals to the markets to increase or decrease their prices accordingly. Food and energy prices, in turn, affect the prices of agricultural commodities as raw materials for energy and food. Expansion of agricultural production requires additional expenditure for the deployment of unused or underutilised agricultural land or application of modern technology and management techniques to increase crop yields on cultivated land. Land allocation is determined dynamically based on these factors. However, not all countries have sufficient land resources to meet their food and energy demands. Therefore, in this assessment, *food production* is prioritised. Energy crops are cultivated only when resources are available once the food demand is satisfied. Still, this assumption may not reflect the market reality of globally traded food commodities.

2 Total final energy consumption (TFEC) is the sum of consumption by the different end-use sectors. TFEC is broken down into energy demand in the following sectors: industry, transport, other, non-energy use, and non-specified. (IEA 2008)

Figure 1: Supply and demand framework of bioenergy



If bioenergy demand cannot be met through domestic resources, it may be imported from other countries. For example, if a country has excess land after meeting all its domestic food and bioenergy demands, it is assumed that its remaining resources could be utilised to produce bioenergy crops for export (see Section 2.4 for the trade volume estimation methodology).

Agricultural and forestry residues do not compete with food for land because they originate from non-utilised portions of the existing commodity production. Thus, estimation of the future food supply is the most important factor to assess the potential for agricultural residues. For forestry residues, the most important factor is the production of wood products. Usage of wood products is concentrated in OECD countries because of the large pulp and paper industry sector in these countries. Therefore, the related biomass potential is also located there.

In this assessment, the basic dataset to estimate the supply potentials of bioenergy crops and agricultural residues is based on the FAO report (FAO, 2012a) and database (FAOSTAT, 2014). This database includes current and future land use, land areas classified by agricultural productivity, current and future yield of agricultural commodities and the current and future production of food. These data were combined with a number of factors to estimate the bioenergy supply potential, such as the residue generation factor, recoverable fraction, animal manure generation coefficient, methane emission factor from manure, etc.

Demand for bioenergy is estimated based on two steps according to the REmap 2030 methodology (IRENA, 2014a). First, the national plans of the 26 REmap countries covering the period 2010-2030 were collected. These national plans highlight TFEC[3] developments for each end-use sector, namely industry, buildings, trans-

3 TFEC includes the total combustible and non-combustible energy use from all energy carriers as fuel (for the transport sector) and to generate heat (for industry and building sectors) as well as electricity and district heat. It excludes nonenergy use, which is the use of energy carriers as feedstocks to produce chemicals and polymers. In this study, assessment of the energy use of end-use sectors other than industry, buildings and transport is excluded. Excluded sectors account for less than 10% of the global TFEC.

port, according to policies in place and under consideration (referred to as the "Reference Case" throughout this report). The growth in energy demand is based on the given country's own population and economic growth projections, which could digress from food demand projections.

In dialogue with country experts and based on various literature and its own technology, resource and cost databases, IRENA's experts have identified the "REmap Options", which are the realisable renewable energy technology potentials, in addition to each country's the Reference Case. Amongst the diverse renewable energy technologies, bioenergy represents a readily available and adaptable resource that can be used both for power and heat generation, as well as for motor fuel.

In REmap 2030, bioenergy has a dual potential:

- First, *modern* bioenergy use offers the potential to substitute for fossil fuel use in all end-use sectors and in power and district heat generation.
- Second, modern bioenergy can also substitute for *traditional* uses of biomass. The International Energy Agency (IEA, 2012) defines traditional use of biomass as: *"...the use of wood, charcoal, agricultural residues and animal dung for cooking and heating in the residential sector"* and notes that "it tends to have very low conversion efficiency (10% to 20%) and often relies on unsustainable biomass supply". Today about two-thirds of global bioenergy use is in traditional form. Given the projected growth in energy demand of developing countries in the next two decades, the traditional use of biomass will grow even further in the absence of a transition to modern energy access.

In order to estimate global biomass demand in 2030, REmap Options in the 26 REmap countries are identified for all sectors. These Options are then added to total bioenergy demand in the Reference Case, excluding the total traditional use of biomass volume for which modern uses substitute. The total of the 26 REmap countries is scaled to the global level, assuming that they represent three-quarters of the global TFEC. Detailed technology, sector and country results can be found in the REmap 2030 report (IRENA, 2014a) and the REmap project webpage[4].

4 *www.irena.org/remap*

In REmap 2030, the levelised cost of heat/electricity production costs of each renewable energy technology option is estimated. In order to estimate the cost-effectiveness of renewable energy technologies, their costs are compared to the substituted conventional energy technology which delivers the same energy service. The cost assessment was done from the perspective of both government and business:

- From the government perspective, energy prices exclude taxes and subsidies, and a standard 10% discount rate is applied. This approach shows the costs of renewable energy technologies as governments would calculate them.
- From the business perspective, the process was repeated to include domestic prices (including, for example, energy tax subsidies and the cost of capital), which result in localised cost assessments of the REmap Options.

REmap Options represent the realisable potential beyond the Reference Case; what can be realistically planned and funded, resource availability, policy frameworks, etc. Therefore, projected costs should *not* be viewed as a limiting factor to the deployment of REmap Options. Costs, however, are as such not a limiting factor to the deployment of REmap Options.

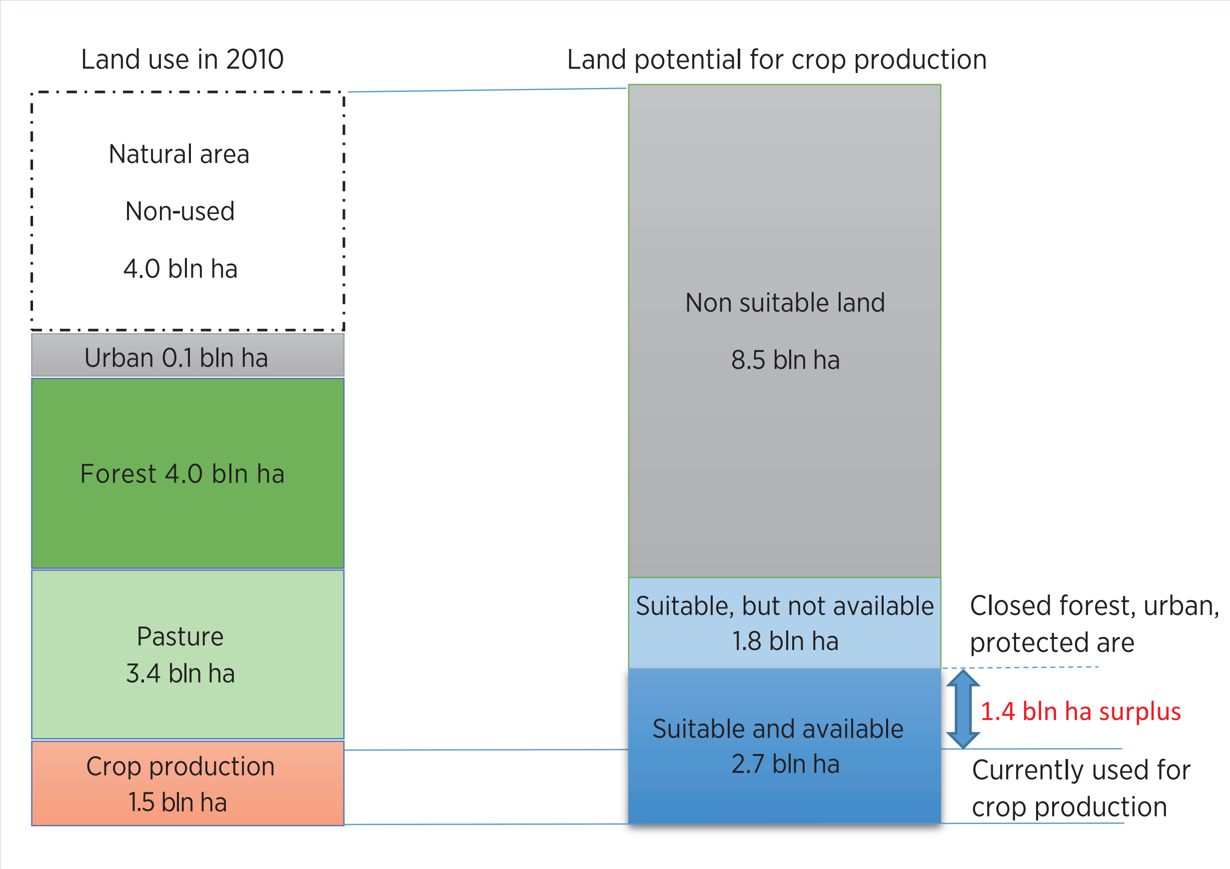
All biomass supply and demand data provided in this report are in terms of primary energy unless otherwise stated[5] and expressed in lower heating values (LHV).

2.2 Biomass supply

In this study, a *low* and a *high* range of potential bioenergy supply is estimated for a total of six regions: Africa, Asia, Europe (including Russia), North America, Latin America and the OECD Pacific. The rest of this section explains the details of the methodology for each bioenergy commodity.

5 Biomass use for heat and power generation is expressed in primary energy terms. Liquid biofuels used in transport as motor fuel are expressed in final energy terms. In order to convert liquid biofuels (in final energy) to raw biomass (in primary energy), a conversion efficiency of 50% is assumed. This method differs from the IEA energy statistics methodology (see Box 2).

Figure 2: Current land use and suitable area for agriculture



Source: FAO/IIASA (2000); FAOSTAT (2014)

Bioenergy crops

According to the FAO, worldwide there are approximately 13 billion hectares (ha) of land available, of which 4.5 billion ha are suitable for crop production (see Figure 2). Out of this 4.5 billion ha, 1.8 billion ha is not available for crop production as they are used for non-agricultural purpose (*e.g.*, urban and protected areas) or needs to be protected for environmental protection (closed forests[6]). Thus, the total amount of suitable land available for crop production is estimated at approximately 2.7 billion ha. The current production of food crops utilises some 1.5 billion ha of land, of which 1.3 billion ha falls under this category of "suitable land". As a result, about 1.4 billion ha additional land is suitable but unused to date and thus could be allocated for bioenergy supply in future.

The bioenergy crop potential is estimated by multiplying the bioenergy crop yields (in tonnes per hectare per year, t/ha/yr) by the available surplus land (ha). Available surplus land is calculated by subtracting land demand for non-energy uses from potentially available land. *Future land demand* is based on FAO estimates, and data for *potentially available land* are drawn from the Global Agro-ecological Zone Assessment (AEZ) model (FAO/IIASA, 2000) (see Table 2).

Improvements in agricultural yields are based on the FAO estimates for cereal[7] which are roughly 0.7% per year over the 20-year projection period (resulting in an aggregate compound increase in production of some 15% over this period, while global population and food demand are projected to increase by up to 30% in the

6 In this study, closed and protected forests are excluded from the potential production area.

7 Share of coarse grain for global bio-ethanol production was more than 50% in 2010 (the majority of coarse grain in the United States is maize).

Table 2: Suitable land, land in use and surplus land

Region	Unit	Suitable land	Of which, land in use			Surplus land		
			2010	2020	2030	2010	2020	2030
Africa	million ha	806	239	265	290	567	541	516
Asia	million ha	529	391	392	392	137	137	137
Europe	million ha	448	254	255	255	195	194	193
L. America	million ha	540	173	197	221	367	343	319
N. America	million ha	352	187	188	188	165	165	164
Oceania	million ha	113	41	40	40	72	73	74
World	million ha	2 789	1 286	1 336	1 386	1 503	1 453	1 403

Source: FAO/IIASA (2000) and FAO (2012a)

Note: "suitable land" is the sum of "very suitable", "suitable", "moderately suitable", and "marginally suitable" (high range of supply)

same period). The global average land use for cereal in 2010 was 0.28 ha/t/yr. In this assessment, "cereal" is defined as potential energy crop with a LHV[8] of 15 gigajoules (GJ) per tonne (air dry: 12-14% water content).

In this assessment, the Global AEZ model (FAO/IIASA, 2000) was used to theoretically extract "suitable land" under different land categories, including how extensively the land is used (*e.g.*, marginally suitable land, moderately suitable land, etc.), or land with environmental limitations (*e.g.*, deployment of protected areas, forest areas). Data for suitable land were then combined with future projections of "land in use" by FAO (FAO, 2012a).

In the assessment of the *high range of supply*, (i) very suitable, (ii) suitable, (iii) moderately suitable, and (iv) marginally suitable land was selected. Closed forests, highly protected areas and land reserved for infrastructure and housing were excluded. For the *low range of supply*, marginally suitable land was excluded from the analysis. In this assessment, only "cereal" is assumed as the potential energy crop, which results in a conservative supply potential. Including the assessment of sugar and oil crops, permanent grass, algae and other suitable resources could increase the bioenergy supply potentials[9].

8 LHV is net amount of heat released during combustion per mass unit of fuel. Biomass usually contain certain amount of water (10-60%) and energy used during drying phase of combustion is accounted as net loss and subtracted from the total amount of generated heat.

9 These include soy beans (2.6 t/ha/yr), wheat (3 t/ha/yr), sugarcane (71.8 t/ha/yr) or cassava (12.4 t/ha/yr), which have similar or even higher yields than cereal (FAOSTAT, 2014).

Agricultural residues

Each agricultural commodity has a specific residue generation rate based on its morphological characteristics, farm management and the post-harvest process. The supply potential of agricultural residues is calculated by multiplying the residue coefficients (percentage of amount of residue in total harvest) with the commodity production volumes (in tonnes per year).

In reality, most residues are *not* utilised for energy because they are difficult to collect or used for specific purposes, such as land conservation, manure and straw incorporation in the field to maintain soil organic matter. This is accounted for in the residue recovery rates. The historical and projected annual crop production growth by region and the residue coefficients are provided in Annex A. About a quarter of the residue generated for each crop is assumed to be recoverable, reflecting an assessment that half the residue could be collected sustainably and half of that amount could be collected economically.

After the recoverable fraction of residues is estimated, the amount of residue used for animal feed is calculated separately. This is deducted from the total residue volume.

The amount of residue used for animal feed is calculated in two steps. First, the "amount of meat / milk production" and "feed conversion rate" are multiplied together to estimate the "total amount of feed demand". Second, this product is further multiplied by the "fraction of animal feed supplied from residue". The fraction of residue use is dependent upon the animal type and feeding system. Data on "meat and milk production" are based on FAO estimates (FAO, 2012a). Data for the "feed conversion rate" and the "fraction of animal feed supplied from residue" by animal type and by feeding system are based on Bouwman *et al*. (2005).

Residue generation factors could differ depending on the location. These differences were not taken into account in this assessment due to the unavailability of data. As for the recoverable fraction for the high range of supply, it is assumed that 25% of the harvesting residue (*e.g.*, Smeets, Faaij and Lewandowski. 2004), and 90% of the processing residue could be recovered. A higher fraction for processing residues is assumed because it is much easier to collect the generated residues inside processing plants. For the *low range of supply*, the recoverable fraction for harvesting residue is also 25% while the recoverable fraction for processing residues is estimated at 25-90%. This significant span is due to the fact that some tropical commodities are assumed to be produced and processed on a small scale and in a less mechanised way, thus with a lower recovery rate. As for harvesting residue, the residue coefficient was collected from the literature; then the lower and higher ranges of the coefficients were used to estimate the low and high ranges of supply, respectively.

Post-consumer waste

As for post-consumer waste (PCW), food waste in urban areas and wood-based waste (*e.g.*, waste paper, discarded furniture, demolition waste) was covered in this assessment. To estimate the supply potential of bioenergy from household food waste, region-specific data for per capita municipal solid waste (MSW) generation were used from the Intergovernmental Panel on Climate Change (IPCC) guidelines (tonnes per capita per year, t/cap/yr). The share of the eight major components in MSW are provided in Annex B. A LHV of 15 GJ/t (air dry) was used to convert physical quantities into primary energy terms.

In order to estimate the recovery rates, it is assumed that waste could be collected only from urban areas where population density is high and waste collection and treatment systems are relatively well-organised. Utilisation of food waste in small-scale biogas systems, together with animal waste, could be an option in rural areas, but this is not included in this assessment since country-level statistics for the installation of biogas digesters was not available. Also, it is assumed that wastes currently treated for "solid waste disposal systems" and "incinerated" are the only collectable fraction. For household food waste, no distinction was made between low and high range of supply.

As for the post-consumer waste for wood products, estimates from Smeets and Faaij (2007) were used; they apply residue a generation factor and recovery rate to the volume of industrial roundwood consumption (see Section 2.2.5).

Animal waste

Generation of methane (CH_4) from animal manure depends on animal type, feed and grazing management and is location-specific. In principle, it is estimated as the difference between livestock energy needs (life maintenance, pregnancy, milk production, animal labour, etc.) and feed energy (amount of energy contained in the feed). Subsequently, the remaining amount (indigestible fraction) is excreted as manure. A share of this manure generates methane based on its chemical composition and the environmental conditions (temperature and humidity).

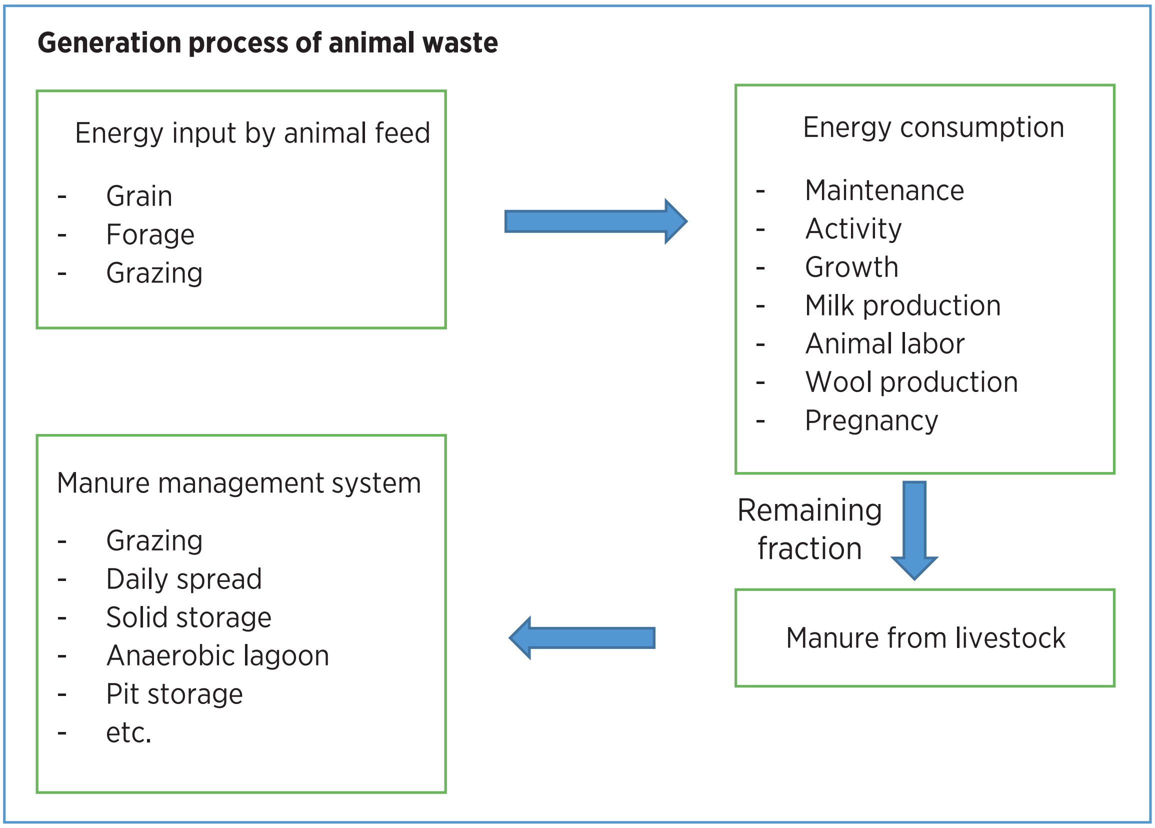
All these processes are location- and animal-specific. IPCC carbon accounting methodology collects and summarises these by regions (IPCC, 2006a). These coefficients are used to assess the biogas generation potential from livestock manure. The number of animals in 2030 is based on FAO estimates (FAO, 2012a) (see Annex C).

As for all other residues, recovery is critical to utilising animal wastes. The recovery rates depend on the manure management system. In this assessment, the manure management system is classified in nine categories (see Figure 3) based on the IPCC guidelines (IPCC, 2006a). The recovery rate is assumed to be 100% when the manure management system collects all animal manure in one place and no specific utilisation other than digestion is mentioned. For animal waste, no distinction was made between low and high range of supply.

Forest products

To estimate the supply potential of forest products, the assessment according to Smeets and Faaij (2007) was used. In this assessment, forest products' potential are

Figure 3: Animal waste



classified into four categories, "surplus forest growth" (surplus forest products after meeting the demand of industrial roundwood and woodfuel), "logging residue", "wood processing residue", and "discarded wood-based products" (*e.g.*, waste paper, discarded furniture, demolition waste; this is covered under post-consumer waste in our assessment). Surplus forest growth is estimated by subtracting the demand for industrial roundwood and woodfuel from forest productivity growth. Logging residue, processing residue and wood waste are estimated by multiplying industrial roundwood production and residue generation ratio and recovery fraction. Although the residue generation rate and the recoverable fraction of wood waste could differ by type of wood products (*e.g.*, paper, demolition waste, etc.), only a single coefficient is used in this assessment. It is assumed that 25% of the total wood logging residue and 75% of the total wood processing residue and wood waste can be recovered in sustainable fashion.

For the high range of supply, the economic potential of 43 EJ according to the same study was used. According to the study, this is equivalent to the total potential that can be produced at economically profitable levels in the areas of available supply, which satisfy two conditions: productivity (gross annual increment) above profitable level[10] and proper accessibility (physical accessibility and distance from road infrastructure). The forest areas, however, exclude all protected areas, estimated as 10% of each country's total forest area. More recent estimates of the global market-environment potential of woody biomass (*e.g.*, Lauri *et al.,* 2014) point to higher values reaching 77 EJ worldwide.

For the low range of supply, the ecological-economical potential of 24 EJ according to Smeets and Faaij (2007) was used. According to the definition, under ecological-economical potential, wood production and utilisation are limited to the forest stock in disturbed areas only (forest that are currently under commercial operation)

10 The global average growth rate of commercial forests was about 2.1 m^3/ha/yr in 1998 which is a more or less static value that does not change over time (FAO, 1998).

in order to protect biodiversity in undisturbed old-grown forest.

2.3 Biomass supply cost

The price for primary biomass is determined by three factors: (i) the supply side factor (technically achievable biomass supply volume with associated cost), (ii) the demand side factor (energy demand, land demand associated with food and feed production/energy crop production/and other usages, the price of competing usage (*i.e.*, fossil fuel price, food price)), and (iii) the policy factor (*i.e.*, tax incentives, blending mandate). All three factors are dynamically interlinked and require economic models for detailed assessment. To avoid an overly complex procedure, actual market prices of primary biomass in 2010 were used in this analysis as a proxy for the prices in 2030. For the residue and waste, price estimates from the literature were used and global averages were assumed in regions for where there were no reliable statistics.

The supply cost of each biomass type was estimated for each region analysed. For this purpose, a bottom-up approach was applied to estimate the total cost based on 2010.

Table 3 shows the cost component of each type of biomass assessed in this study where no changes were assumed in the costs between today and 2030. The following assumptions were made for each biomass type.

For bioenergy crops (see Section 2.2.1), the current "farm gate" price of cereal is used as a proxy for the supply cost of energy crop (FAOSTAT, 2014). For wood products, the current trade values of wood fuel and wood residue were used as a proxy for supply costs (FAOSTAT, 2014) (see Section 2.2.5). The lower value between the export and import price is assumed to be the domestic supply cost.

For harvesting residue (see Section 2.2.2), there are no price statistics in most regions. However, corn stalk (stover) is a representative commodity for harvesting residues and price estimates are available for the US (Sarah and Tyner, 2008). The price ranges from USD 2.2-3.5 per GJ depending on the transport distance. Collection and transportation costs are the main cost components for utilising biomass residues, which would otherwise be left in place. Therefore, the estimated transportation costs are adjusted by country, based on transport fuel prices. The costs of supplemental fertiliser application to maintain soil fertility are also added.

The collection cost is assumed to be included in the supply cost of "harvesting residue", in addition to its transportation costs to the processing plant. For "processing residue", "animal waste" and "household food waste", neither collection nor production costs are assumed (see Sections 2.2.2–2.2.4). The only cost component is the transportation cost for this biomass type.

For all the biomass supply costs, USD 2 per GJ of primary biomass delivered costs is added to the final consumer.

For biomass which can exported, an international transportation cost is set for each region and added to the supply cost for each type of residue. For example, the export price from Latin America is calculated by adding representative transfer costs based on the distance to Europe multiplied by the unit price of vessel transfer. In addition to international transportation costs, USD 1 per GJ of primary biomass is added for international trade to represent transaction costs, such as tariffs or any kind of policy measures to promote domestic supply.

2.4 Biomass trade

The domestic bioenergy supply can be utilised locally or traded. The volume of domestic bioenergy supply and its interregional trade is estimated using the following five steps:

(i) Estimate bioenergy demand in REmap 2030;
(ii) Set reference energy (for conventional fuels) price in REmap 2030;
(iii) Estimate supply potential and supply cost in REmap 2030;
(iv) Estimate the total bioenergy demand which could be met by domestic supply; and
(v) Estimate the total surplus / deficit biomass which could be met by imports.

By comparing bioenergy supply costs and reference energy (conventional fuels) prices, the possible volume of fossil fuel substitution is estimated. Bioenergy is as-

Table 3: Breakdown of biomass supply costs and their ranges by biomass type, 2030

<table>
<tr><th></th><th>Production
(USD/GJ)</th><th>Collection
(USD/GJ)</th><th>Transport to processor
(USD/GJ)</th><th>Transport to end user
(USD/GJ)</th><th>Total cost
(USD/GJ)</th><th>Literature
(USD/GJ)</th></tr>
<tr><td>Bioenergy crop</td><td colspan="3">2-78</td><td rowspan="7">2</td><td>4-80</td><td>6 – 60</td></tr>
<tr><td>Harvesting residue</td><td>1.1</td><td>1.1</td><td rowspan="3">0.01-1.3</td><td>4.2-5.5</td><td>3 – 8</td></tr>
<tr><td>Processing residue</td><td>0</td><td>0</td><td>2-3.3</td><td></td></tr>
<tr><td>Biogas</td><td>0</td><td>0</td><td>2-3.3</td><td>0 – 4</td></tr>
<tr><td>Fuel wood</td><td colspan="3">8-35</td><td>10-37</td><td>2 – 22</td></tr>
<tr><td>Logging residue</td><td colspan="3">3-18</td><td>5-20</td><td>1 – 11</td></tr>
<tr><td>Wood waste</td><td colspan="3">3-18</td><td>5-20</td><td>1 – 11</td></tr>
</table>

Energy crop: cereal farm gate price (FAOSTAT, 2014)
Fuel wood: trade value / trade volume (FAOSTAT, 2014)
Logging residue and wood waste: trade value / trade volume (FAOSTAT, 2014)
Harvesting residue: The base price is the US corn stover collection cost, transportation cost and supplemental fertiliser cost. The transportation cost is adjusted based on the local gasoline price.
Processing residue and biogas: The base price is the US corn stover transportation cost. The transportation cost is adjusted based on the local gasoline price. Biogas relates to production from landfill and waste only.
Estimates are compared to the output from EU project "Biomass Futures", which estimates the supply price of different bioenergy feedstock in 2030.

sumed to be available if the supply cost is lower than reference price (= fossil fuel price).

(i) The bioenergy demand in 2030 is estimated based on the results of the 26 REmap countries. Demand can be distinguished between fuel use for heat and power generation and as motor fuel for transportation.

(ii) To determine whether demand could be met within a feasible price range, the reference price of conventional fuels for each country is set for "transportation fuel" and "non-transportation fuel", based on projections to 2030 (IRENA, 2014a). Also, reference prices in various countries are aggregated to produce a "global reference price" using weighted averages by the volume of fuel consumption. This "global reference price" is used to determine whether biomass resources could be competitive in international markets.

(iii) The supply potential and cost is estimated for each biomass type in each country by the method explained in Sections 2.2 and 2.3.

(iv) For each biomass type, domestic demand and supply are estimated using the supply potential, biomass supply costs and reference prices. Demand is satisfied with domestic supply only if the supply cost is less than the reference price. As a result, for each biomass type in each country, three categories of numbers are estimated: (i) bioenergy demand; (ii) domestic supply available to meet this demand; and (iii) the surplus / deficit of domestic biomass resources.

(v) Each country's surplus domestic biomass resource is considered as *potential exportable biomass*. To this volume, international transportation and additional transaction costs are added, on top of the supply costs (depending on the type

Table 4: Bioenergy reference price estimates for 2030

	Liquid biofuel reference price (USD/GJ)	Other biomass reference price (USD/GJ)
Africa	36	10
Asia	40	7
Europe	58	18
N. America	34	15
OECD Pacific	61	15
L. America	59	12
World	42	11

Note: The above prices refer to the average price of the fossil fuel mix in the six world regions, as well as the world as a whole in year 2030 based on the Reference Case (IRENA, 2014a). Liquid biofuel reference prices refer to the average of gasoline and diesel prices. Other biomass reference prices refer to the weighted average of natural gas, coal and oil products based on the fuel mix in that region. For fossil fuel prices, since a single value is used in the REmap analysis, this table also provides single data.

of biomass), which yields the export cost of biomass (Table 5). This is compared with global reference conventional fuel prices. If the shares of volume with export costs less than the global reference price, it is considered as exportable biomass in the global bioenergy market. The deficit of domestic biomass resources is assumed to be filled through imports.

Table 5: International transportation costs of biomass

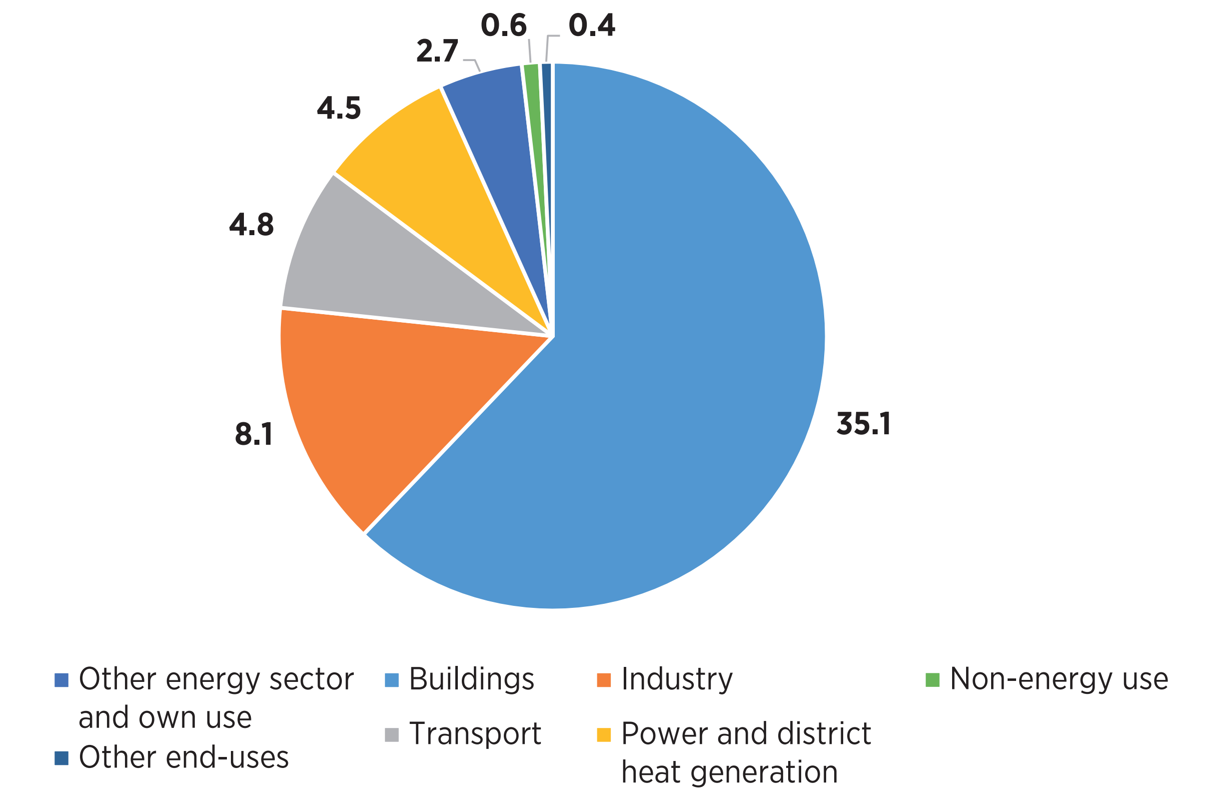
	(USD/GJ)	Route
Africa	3.6 – 5.3	Nigeria to South Africa
Asia	1.2 – 1.3	South East Asia to China/Japan
Europe	~0.6	Russia to Europe
N. America	1.1 – 4.2	USA to Europe
OECD Pacific	0.9 – 3.6	Australia to Japan
L. America	0.9 – 3.6	Brazil to USA

3 CURRENT BIOENERGY MARKET SITUATION AND SHORT-TERM PROSPECTS BY SECTOR

Biomass has potential areas of application in all sectors. In 2010, biomass use reached 56 EJ (see Figure 4). Of this total, 62% is used in residential and commercial buildings sector. Industry (15%), transport (9%) and the power and district heating (8%) sector are the other large bioenergy users. Bioenergy demand in these four sectors account for more than 90% of its total consumption worldwide. There is also a relatively new market for biomass: its use as a feedstock for the production of chemicals and polymers (represented by non-energy use in the figure below). Today around 600 petajoules (PJ) of biomass is used as raw material for this purpose, in Brazil, South East Asia, the US and Europe (Saygin *et al.,* 2014). Bioenergy potential assessment for non-energy use is excluded from the rest of this study as REmap looks at energy only.

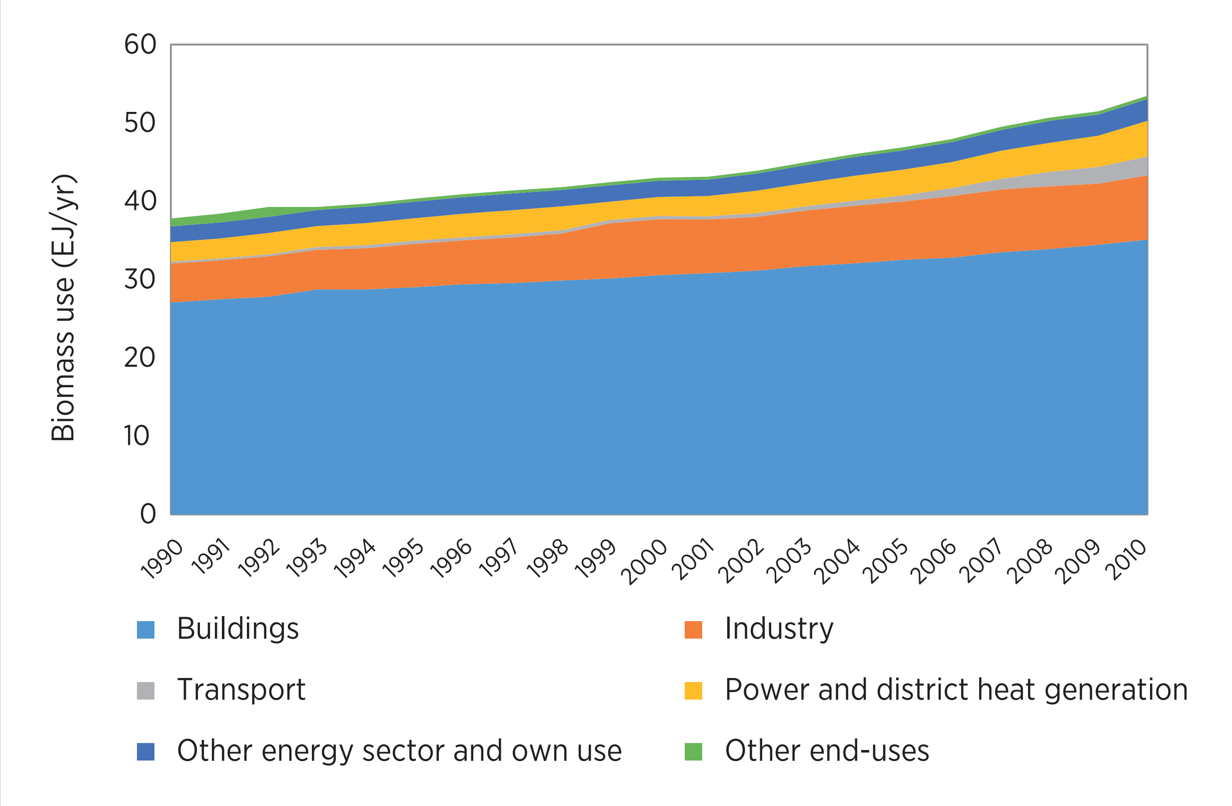
The breakdown of bioenergy markets has seen only modest changes between 1990 and 2010. Its use as fuel (mainly traditional) for heating in the buildings and industry sectors continues to account for a large share of its global demand (see Figure 5).

Figure 4: Breakdown of current bioenergy use by sector, 2010 (in EJ/yr)



Source: IEA (2013a); Saygin *et al.* (2014)

Figure 5: Development of global biomass use by sector, 1990-2010



Source: IEA (2013a)

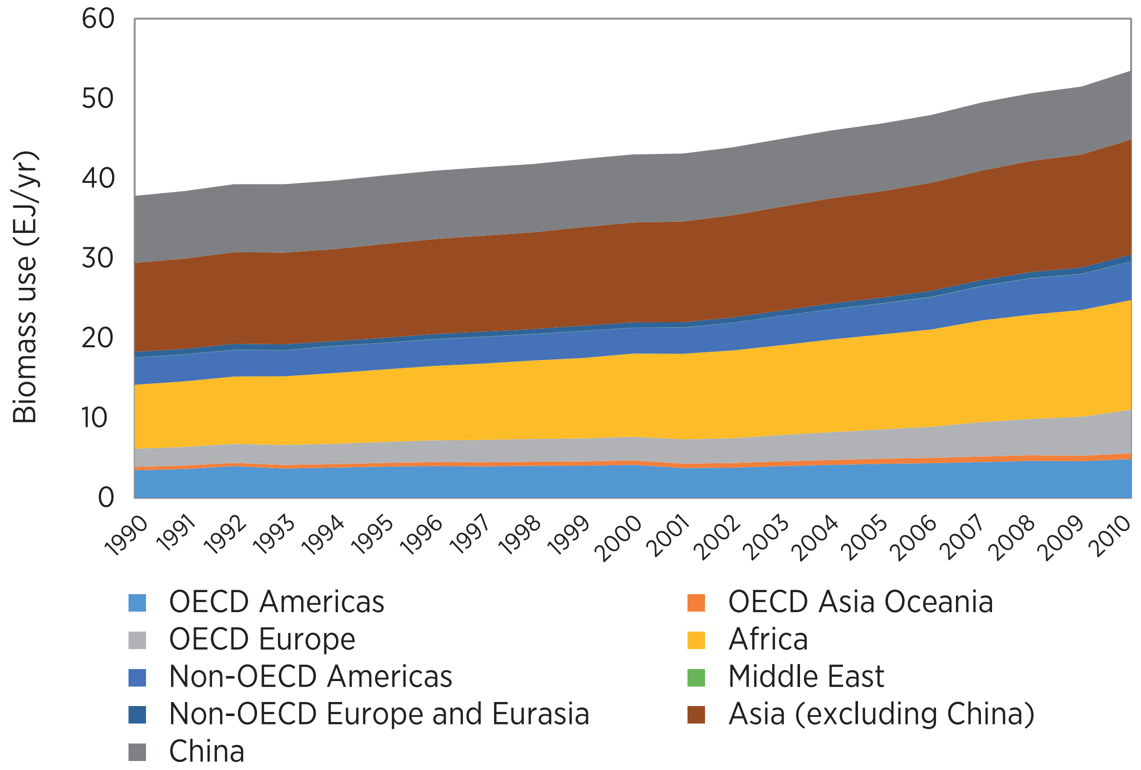
With respect to the rate of growth of markets, however, there *are* differences. The use of liquid biofuels in the transport sector experienced the largest growth among all the sectors, reaching an annual growth rate of 5.4% in 1990-2000 and even a higher annual rate of 19.2% over the period 2000-2010. It is followed by a 3.7%/yr growth in the industry sector from 1990-2000 and 6.5%/yr in the power and district heat sectors from 2000-2010.

Today, Asia (excl. China) and Africa together account for more than half of global bioenergy demand. This has not changed between 1990 and 2010. OECD Europe has increased its share of the global bioenergy demand from 6% to 10% at the expense of China whose share decreased from 22% to 16% (Figure 6). All other regions taken together account for about 20% of the total global bioenergy demand.

Among the different types of biomass, wood fuel (*i.e.*, pellets, fuel wood and charcoal), palm oil, bioethanol and biodiesel are the most widely traded commodities. Although there are no official statistics, the volume of direct and indirect (*i.e.*, including wood products used as energy) trade reached more than 1 EJ in 2011, which represents 2% of the total use of biomass energy worldwide (Vakkilainen, Kuparine and Heinimoe, 2013). International biomass trade increased steadily from 2004 to 2008 but has since remained stable at approximately 1 EJ worldwide (Vakkilainen, Kuparine and Heinimoe, 2013). The largest trade of biomass products involves wood pellets (130 PJ), equivalent to half of the 310 PJ of global wood pellet production in 2011, mainly based on sawdust and wood residues as feedstock. If global demand for wood pellets continues to increase, it can still be met with the existing capacity for a certain time as the 2008-2011 capacity utilisation rates were only between 50-60% (Cocchi *et al.*, 2011; Vakkilainen, Kuparine and Heinimoe, 2013).

Bioethanol is exported from many countries: Brazil (48% of global exports), the US (6%) and France (6%) together account for more than half of the global total. Most global production of biodiesel is concentrated in Europe (*i.e.*, Germany, France, Spain, Italy and the Netherlands

Figure 6: Development of global biomass use by main world regions, 1990-2010



Source: IEA (2013a)

account for one third of global production from a variety of feedstocks) and Latin America (Brazil and Argentina) account for a quarter.

African regions also have a high potential of land resources and could become a large exporter of bioenergy. For example, after Brazil (139 PJ), Nigeria, Congo, Ethiopia, Ghana and Tanzania produced 285 PJ of charcoal collectively in 2011. Yet current productivity in African regions is significantly lower than those of exporting countries. The recent IRENA (2013a) study on biomass supply potential in Africa showed a large range from 0 EJ to as high as 25 EJ in 2020. More than half of the high end (13.9 EJ) originates from energy crops, compared to 5.4 EJ of forestry biomass and 5.3 EJ of residues. The low end of energy crop supply is explained by 1) the significant population growth and concurrent increase in per capita food consumption, which has limited the available energy-related biomass potential and 2) the gap between potentially achievable yields and current actual yields (yield gap). The low end for residues is explained by the competing use of materials.

The agricultural yield gap is analysed in many studies. Regional comparisons show that the largest gap is in Africa. For example, the ratio of actual to potential yields is as low as 24% in sub-Saharan Africa, compared to a 64-68% potential yield in the Americas and Western and Central Europe (OECD-FAO, 2012). Modern technology and farming infrastructure will be required to fill this gap. An important driver to encourage farmers to adopt modern technology is the rising prices of agricultural commodities. However, where land is available, it is easier to expand the cultivation area than to increase yields (FAO, 2012a).

Trade in other types of biomass (*e.g.*, agricultural residue and wastes) is limited today. Compared to wood fuel or biofuels, the supply chain of residues and waste is not yet well-developed internationally or domestically. The international trade of agricultural residue and waste is generally limited to a few types of feedstocks, such as palm kernels from Malaysia to Europe, because global trading is generally not cost-effective. In many cases, the energy density of residue and waste is low compared to primary biomass (1-4 GJ/m^3 for residue, 6-17 GJ/m^3 for primary biomass). Thus, it is appropriate to consider applications suited to energy utilisation in small to mid-size distribution systems, rather than in international trade.

3.1 Power generation sector

In 2012, installed biomass power generation capacity reached 83 gigawatt-electric (GW_e), equivalent to 1.5% of global power generation capacity. Solid biomass (including "black liquor" which is a by-product of the pulp manufacturing) and MSW accounted for nearly 80% of the total capacity, with the remaining 20% being mainly biogas. Increasing amounts of pellets are co-fired in coal plants (RE Focus, 2013).

Supported by strong policy, installed biomass power capacity in Europe has increased over the last decade. It currently accounts for about half of all global installed capacity. Capacity additions in the Asia Pacific and Latin American regions through 2020 are expected to reduce the Europe's share in global production capacity. Growth in North America is contingent upon the anticipated rollout of bio-refineries for advanced biofuels.

Production from MSW has increased by about 6%/yr over the past decade. Today's installed capacity is mainly in the European Union (EU), the US and Japan, but developing countries and economies in transition are catching up. Biogas power capacity growth is even higher, at about 10% per year. China and India together have nearly 900 megawatt-electric (MW_e) biogas capacity while Germany has the largest capacity in the EU (3 GW_e). Italy is one of the fastest growing biogas countries in Europe (RE Focus, 2013; EUWID, 2014b).

3.2 Building sector

Traditionally, biomass has been used for heating in open fireplaces or stoves. Today there are also modern biomass uses in efficient boilers and furnaces. The share of modern use is lower compared to traditional uses of biomass in developing countries. The majority of biomass for heating is solid fuels, including wood logs and twigs, wood chips and saw mill residues, and pellets. In some countries, especially in rural areas, agricultural residues, such as straw, are also used.

In 2012, Europe accounted for about 60% of the global pellet demand, equivalent to 10 megatonnes (Mt) of solid biomass. Biomass-based heating demand in Europe alone is projected to increase to more than 20 Mt by 2020, more than double the current use of biomass (Wood Markets, 2013). Production for export to the EU is anticipated to reach 16-32 Mt/yr by 2020 (Goh *et al.*, 2013a).

In industrialised and developed countries outside of Europe, demand for modern forms of bioenergy is also increasing. Projections show that the total demand for wood pellets in North America, Japan and South Korea could reach more than 20 Mt by 2020 (Wood Markets, 2013). As a result of increasing energy demand—and in view of the fact that traditional biomass is one of the main sources of energy in the construction sectors of most developing countries—the demand for traditional biomass uses is also projected to increase at rates similar to those observed in the past. For example, China's wood pellet demand is projected to reach approximately 10 Mt per year by 2030 (Wood Markets, 2013).

3.3 Manufacturing industry sector

Today almost all renewable energy use in the industry sector is biomass and waste (~7.8 EJ) used mainly in the pulp-and-paper and food sectors where residues are available for free. Brazil, whose biomass demand reached 1.4 EJ in 2010, uses different forms of solid biofuels. For example, around 175 PJ of charcoal are used per year for iron-making in small blast furnaces where the mechanical strength of the reducing agent is not an issue. In the production of bricks, tiles and other ceramics, different forms of biomass are used in Asian countries. Coconut shells, rice husk, biomass briquettes, etc. are combusted either for steam generation or direct heat. In Europe, waste fuels are used in cement kilns and to an extent in lime production, but the shares are generally low, though some kilns run at 100%. Wood chips and wood pellets have also gained market share in other industry sectors of Europe. They are combusted in efficient boiler systems, which can attain the efficiencies of their fossil fuel-based equivalents.

"Business as usual" developments project no, or very limited, growth in the share of industrial biomass use. However, it has significant potential to substitute fossil

Box 1: Growth of biomass-based district heating in Denmark and Sweden

District heating is a widespread method used to supply space- and water-heating in many of the Northern and Baltic countries. The total population share served by district heating now stands at over 90% in Iceland. In Denmark, the share was as high as 61% in 2011 and in Sweden 48%. These two countries are particularly interesting because biomass plays an important role in the fuel mix of their district heating sectors.

A number of financial policy instruments have promoted the development of CHP and district heating in Sweden. In 1991, a carbon dioxide (CO_2) tax was introduced on heating and motor fuels (higher for buildings, lower for industry). There was also an investment subsidy scheme, started in the same year, for CHP plants, which required at least 70% bioenergy use in the first five years of the investment. There were also investment subsidies related to R&D of biomass usage. The electric certificate system between 2003 and 2005 helped to increase renewables use for power generation in Sweden. Between 2006 and 2010, subsidies for conversion from oil and electric heating helped to increase new capacity investments. Many climate change/environmental grants to district heating plants increased investments further. Given also the country's large forest industry (security of supply, well-established logistics), biomass is the key feedstock for heat and power generation. Moreover, Sweden is today the biggest investor in R&D for district heating in Europe.

CHP and district heating have substantially contributed to Denmark's improving energy efficiency. Today more than 60% of private residential heating (including water heating) comes from district heat plants. Denmark has a long history of district heating which started with the first heat supply law in 1979. This law has been followed by a number of successful policies similar to those in Sweden, such as subsidies (only until the 1990s), and the substitution of individual oil heaters in houses. As a result, most of the growth in these countries' district heating sector took place in the 1980s and 1990s. Most district heat in Denmark today is from small-scale CHP plants from a total of nearly 700 centralised and decentralised plants. The base load is supplied by a mix of natural gas and biomass (*e.g.*, straw, wood chips, MSW). The share of renewable energy and waste has increased from about 30% in the beginning of 1990s to more than 50% in 2010. The country aims to increase its district heat capacity further with renewables as part of its long-term goal of 100% renewable energy by 2050.

fuels for process heat generation via direct heat and steam. As in Brazil today, charcoal can be used in other countries to substitute coke input and coal injection in blast furnaces and sinter ovens. Technically, all fossil fuel use in cement kilns can be substituted with biomass.

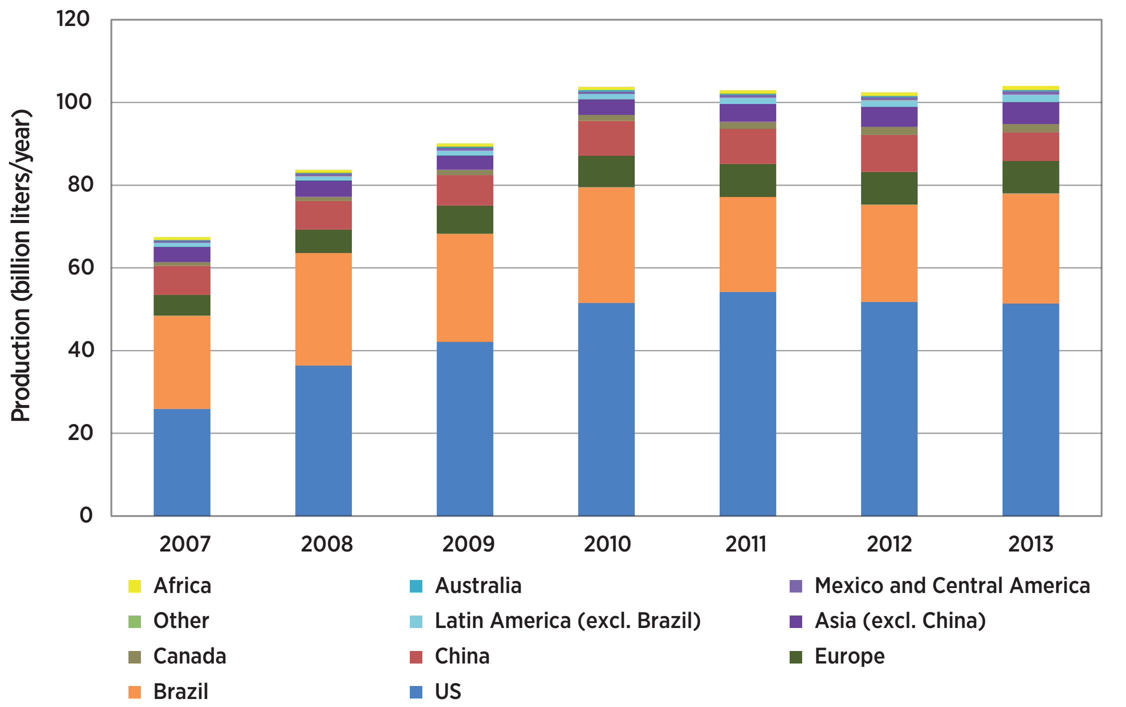
Biomass-based steam generation is particularly interesting for the chemical and petrochemical sectors, food and textile sectors, where most production processes operate with steam. Low and medium temperature process steam used in the production processes of these sectors can be provided by boilers or CHP plants. Combusting biogas in CHP plants is another option already pursued in northern European countries, especially in the food sector, where food waste and process residues can be digested anaerobically to produce biogas.

A recent IRENA analysis (2014b) estimated that three-quarters of the renewable energy potential in the industry sector is related to biomass-based process heat from CHP plants and boilers. Hence, biomass is the most important technology to increase industrial renewable energy use.

3.4 Transport sector

Biofuel consumption for road transport grew substantially from around 417 PJ in 2000 to 2,410 PJ in 2010. Bioethanol consumption grew from 272 PJ in 2000 to 1,426 PJ in 2010, an annual growth rate of 18%. The growth in biodiesel was even faster in percentage terms, from just 18 PJ in 2000 to 616 PJ in 2010, an increase of 42% per year.

Figure 7: Global ethanol production by country and region, 2007-2013



Source: F.O. Lichts (2013a)

Note: Data for 2012 for Africa, Australia, Mexico and Central America, and "Other" are not available and includes both fuel and non-fuel ethanol.

In 2010, some 84 million tonnes of conventional biofuels based on crops containing starch, sugar or vegetable oil were delivered, representing some 104 billion litres (85 billion litres of fuel ethanol and 19 billion litres of biodiesel) – enough to cover 2.7% of the global transportation fuel demand. Production grew from 290 million litres per day (l/d) in 2010 to 297 l/d in 2011 and 2012. Based on the total liquid biofuels outlook for 2013, production can grow to 321 l/d (IEA, 2013b). Finally, biogas is starting to be more widely deployed in countries such as Germany, Finland and Sweden, with a few hundred refuelling stations to date.

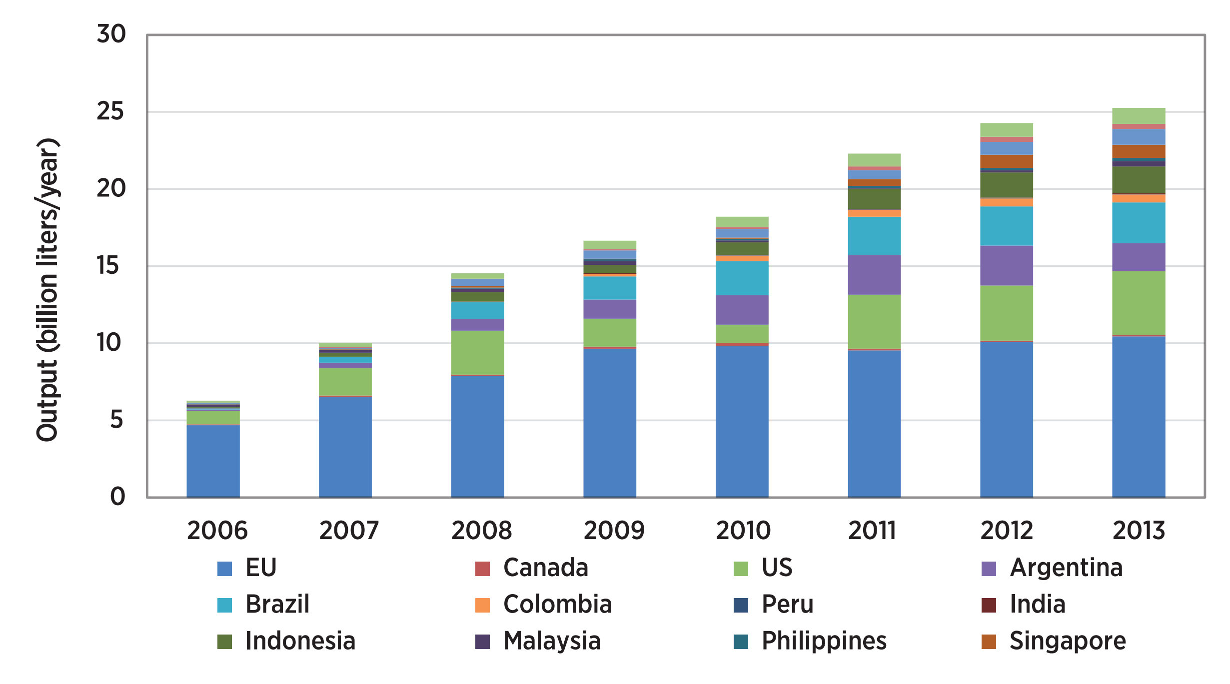
The largest producers of ethanol are the US and Brazil (Figure 7). The US produced around 60% of the global total in 2012, with Brazil accounting for around a quarter. Production of ethanol in the US is based almost exclusively on corn as a feedstock, while in Brazil sugar cane is used.

Global biodiesel production grew 47-fold between 2000 and 2013. Europe, where biodiesel production grew from 17 PJ to 378 PJ (around 10 Mt) in the same period, has led the growth. The rapid growth in biodiesel has been driven by the biofuels mandate; also, the large share of light-duty diesel vehicles in Europe means that any mandate for biofuels requires a greater proportion to be biodiesel. Brazil increased production of biodiesel from zero in 2005 to 2.5 Mt in 2013 to become the second largest biodiesel producer in the world, thanks to a mandate that sales of diesel should include 5% biodiesel.

Biodiesel production in Europe, around 327 PJ in 2011, was 5% lower than in 2010, with production facilities running at only around 39% of capacity in 2011 (Figure 8) (IEA, 2013a; EBB, 2013). Likewise, biodiesel production in North America fell by around 39% in 2010 compared to 2009 after the expiration of the biodiesel tax credit (IEA, 2013a; US EIA, 2012). In 2013, tax credits reached record high after their retroactive re-introduction.

Rapeseed is the feedstock for more than half of global biodiesel production in the EU. Argentina and Brazil also produce significant quantities of biodiesel, predomi-

Figure 8: Global biodiesel production by country and region, 2006-2013.



Source: F.O. Lichts (2013b)

nantly from soybeans. In the US, biodiesel production in 2012 was primarily based on soybean oil, although significant quantities of canola oil, corn oil, tallow, white and yellow grease were also used (US EIA, 2013). The EU also produces biodiesel, including biodiesel based on feedstocks imported from Malaysia and Indonesia. Thailand, Malaysia, Colombia, Indonesia and Singapore all produce biodiesel from palm oil.

Advanced biofuels based on lignocellulosic crops (wood and straw) produce ethanol and diesel substitutes from the woody parts of existing food crops (*i.e.*, the non-edible parts) and from other crops that thrive on land that is unsuitable for food crops (*e.g.*, switchgrass, jatropha). Prior to establishing any farming system, their potential for productivity within a fragile environment should be assessed first. For example, it is observed that jatropha could survive under severe environmental conditions without additional input, but is not as productive as if it performed on suitable land with appropriate input.

Production of advanced biofuels is just taking off, with only a few plants in operation worldwide. Around 0.2% of total biofuel production was advanced in 2012. As of late 2012, 230 million litres of cellulosic biofuels capacity were available worldwide, more than twice as much as in the previous year. In the EU, the lignocellulosic ethanol production capacity was around 30,000 tonnes per year in 2013 (EUWID, 2014c). The US has a capacity of 25 million litres. Total planned capacity is about 320 million litres across six facilities (Janssen *et al.*, 2013). By the end of 2012, Europe had five lingocellulosic ethanol demonstration plants in operation with a total production capacity of 82 million litres. Four new plants are planned with a total production capacity of 100 million litres (Janssen *et al.*, 2013). At present, the investment costs for a cellulosic ethanol plant are more than three times greater than for a corn-based plant. While feedstock costs are lower, the cost of cellulosic ethanol is still considerably higher than for first-generation ethanol (IRENA, 2013b).

Advanced biodiesel could be produced from a variety of feedstocks, including wood and waste, through a combination of gasification and biomass-to-liquid (BtL) routes. Another possible route for biodiesel production is the hydro treatment (or refining) of non-food oils, but also including animal fats and used cooking oil. Another liquid biofuel which has potential for both diesel and petrol engines is biomass-based dimethyl ether (DME). The first bio-DME plant in the world running with black liquor gasification located in Sweden has a total production capacity of 1.5 kilo tonnes per year. Since 2010, there is also a bio-methanol plant in the Netherlands based on crude glycerine as feedstock with a total production capacity of 200 kilo tonnes per year.

4 RESULTS

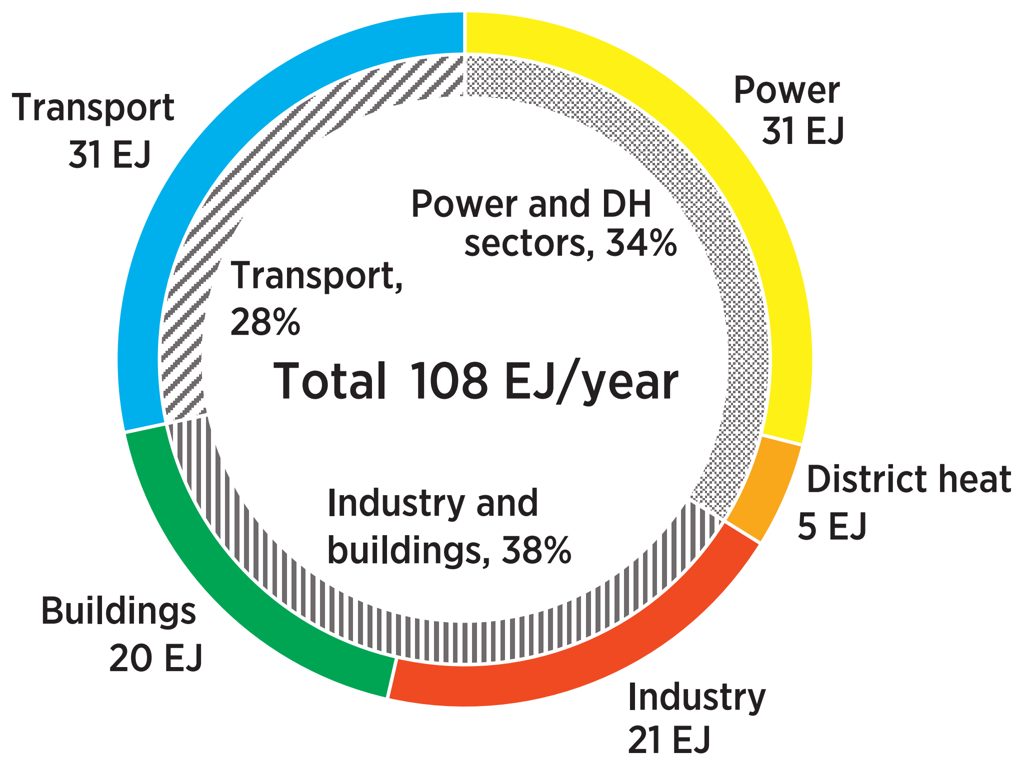
This section starts by presenting the global bioenergy demand estimates according to REmap 2030 (Sections 4.1 and 4.2). Section 4.3 presents the 2030 biomass supply potential and the costs. Section 4.4 compares the demand and supply estimates and discusses the potential impacts of increased bioenergy use on its international trade.

4.1 Sector-level bioenergy demand estimates in 2030

IRENA (2014a) shows that the national plans of the 26 REmap countries project an increase in bioenergy demand for both the end-use and power / district heat sectors between today and 2030. In the Reference Case of the 26 Remap countries, total bioenergy demand will increase from 36 EJ to more than 50 EJ in 2030. If the bioenergy demand of countries excluded from the REmap analysis is assumed to grow at the same rate, global biomass demand in the Reference Case is estimated at 70 EJ by 2030 – nearly 50% growth (or 1.6%/yr). If all REmap Options are deployed, biomass use in *primary energy terms* could reach 108 EJ in REmap 2030 (including nine EJ of unreplaced traditional biomass). Biomass is estimated to account for 60% of total final renewable energy use in REmap 2030, and approximately 20% of the global total primary energy supply.

Depending on the sector and application, the type of biomass used would differ. Figure 9 shows the breakdown of global bioenergy demand if all REmap Options

Figure 9: Breakdown of global biomass demand by sector in REmap 2030



are deployed in addition to the Reference Case. 78 EJ of the total demand will be used for heat and power generation. Biomass for heat generation will be shared between industry, buildings and the district heat sector. Modern and traditional uses of biomass for space and water heating will account for 20 EJ worldwide. Unlike the increasing demand for primary solid biomass in modern renewable energy applications, traditional biomass demand for space heating and cooking is expected to decrease from 21 EJ in the Reference Case to 6 EJ in REmap 2030, marking an important transition towards the more efficient use of biomass in households.

In industry, demand is estimated to reach 21 EJ in the REmap 2030, up to three-quarters of which (15 EJ) will be in industrial CHP plants to generate low- and medium-temperature process heat (about two-thirds of the total CHP output). CHP is an efficient way of utilising biomass as it yields heat and electricity as useful products, not just power. In addition, CHP is an alternative for a wide range of production processes as the temperature and pressure of delivered steam can be adjusted to the specific requirements of industrial processes. There are other renewable alternatives for process heat generation (*e.g.*, solar thermal, heat pumps or geothermal technologies). These are, however, either more costly or their deployment is constrained by the maximum temperature of the steam they can deliver. Therefore, biomass CHP plays a critical role for the manufacturing industry to raise its renewable energy share[11].

In addition to typical CHP users (*e.g.*, pulp and paper or chemical and petrochemical production), sectors, such as food and textile production, have additional potential for biomass CHP in REmap 2030. Other sectors with potential are wood, palm-oil or natural rubber production sectors in rapidly developing countries like Malaysia or Indonesia where by-products are combusted in rather inefficient boilers or only in power producing plants.

The remaining biomass demand is projected to be shared between stand-alone steam boilers and direct heat applications (6 EJ). As a result, installed thermal CHP capacity would reach about 920 gigawatt-thermal (GW_{th}). In addition, 105 GW_{th} of stand-alone biomass boilers and gasifiers for process heat generation would be installed worldwide. This is a growth of more than 70% in industrial biomass-based process heat generation capacity compared to the Reference Case in 2030. No additional demand beyond the Reference Case is estimated for charcoal use for iron production. Almost all renewable energy use will be from biomass and its products in the industry sector. Biomass demand for district heating will reach approximately 5 EJ by 2030.

The power sector, including fuel demand for on-site electricity generation in buildings and on-site CHP plants at industry sites, will require approximately another 31 EJ for power generation (resulting in the production of nearly 3,000 terawatt-hours (TWh) per year in 2030) (IRENA, 2014a). Although there is very little additional co-firing capacity in the REmap Options, in total up to two-thirds of the total biomass use in the power sector could be co-firing with coal to generate power. Steam cycle plants will account for the majority of the remaining biomass demand for power generation. The share of biomass use in gasifiers and anaerobic digesters is less than 5% of the total demand. The total installed biomass power generation capacity in REmap 2030 reaches 390 GW_e. Of this total, around 178 GW_e is the power generation capacity component of CHPs installed in the industry and DH sectors. Around 112 GW_e is co-firing and another 100 GW_e is power-alone plants. In comparison, the total installed coal capacity decreases from 1,800 GW_e in 2012 to 1,300 GW_e in REmap 2030.

Another 31 EJ (expressed in *primary energy terms*) is used for the production of liquid biofuels for the transport sector resulting in the production of approximately 650 billion liters liquid biofuel per year in 2030 (IRENA, 2014a). The transport sector is projected to use in total 16 EJ of liquid biofuels worldwide (expressed in *final energy terms*). About 63% of the total demand is estimated to be for conventional biofuels; the remaining 37% is for advanced biofuels.

4.2 Country-level bioenergy demand estimates in 2030

As shown in the previous section, total biomass demand increased by 36% between 1990 and 2010, equivalent to

11 According to IRENA's manufacturing industry roadmap (IRENA, 2014b), biomass is the main renewable energy resource which would account for three-quarters of the sector's total techno-economic renewable energy potential for process heat generation. Other major resources are solar thermal (including concentrated solar power), geothermal and heat pumps next to niche applications, such as wind for cement factories or solar for remote mines.

Box 2: Bioenergy accounting

In REmap 2030, biomass demand is estimated based on *primary energy terms*. This means that all values refer to quantities before the first conversion of raw biomass to any commercial biomass product (*e.g.*, wood pellets, liquid biofuels). For example, biomass demand related to the power sector is the total biomass used for power generation, and *not* the total amount of power consumed in final energy terms. In the transport sector, demand is equivalent to the total amount of raw biomass used for the production of liquid biofuels, and not the total bioethanol or biodiesel amount. Expressing biomass demand in this way ensures a consistent comparison with biomass supply estimates, which are also expressed in primary energy terms.

With regard to the transport sector, the accounting method applied by REmap 2030 to express demand is different than IEA's method. IEA considers the total energy content of liquid biofuels (*e.g.*, bioethanol) as *primary energy* instead of the amount of raw biomass used to produce this amount. Many other studies also follow this approach. In order for REmap 2030 results to be comparable with IEA and other studies, when necessary, a conversion efficiency of 50% (on an energy basis) is used to convert raw biomass to liquid biofuels.

Another important accounting issue concerns biomass use for heat and power production in CHP plants. Part of the total biomass input to the CHP plant is used for heat and another for power generation. Substituting fossil fuel use with biomass-fired CHP plant at an industrial site for heat generation as an example would raise biomass demand in the industry sector and, thereby, the sector's renewable energy share. The amount of biomass for power generation in the same CHP plant is demand related to the power sector. In REmap 2030, this approach was followed. For every GW_e of additional biomass-fired CHP capacity, the related fuel demand was estimated for power and heat production and subsequently allocated to power and heating sectors.

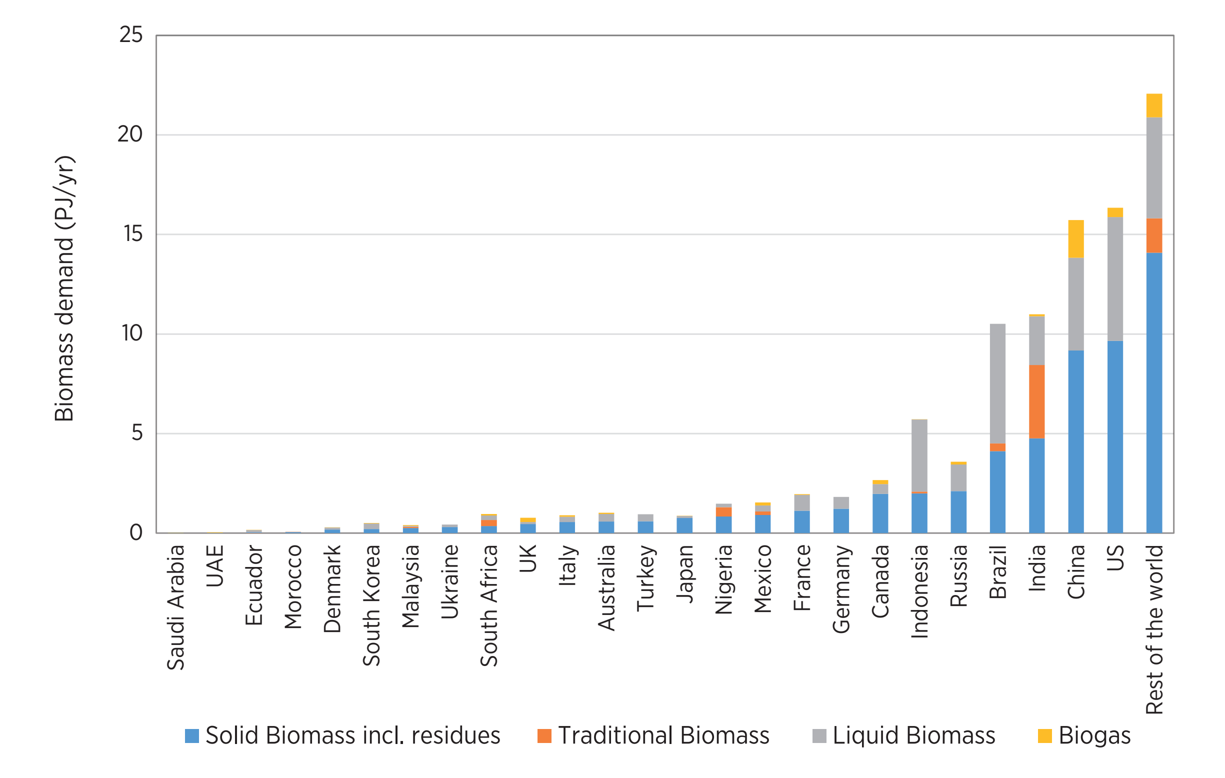
In contrast, many potential assessment studies do not follow this approach. It is often only the biomass for power generation which is reported, and the amount for heat generation is not fully accounted for. However, as this study also shows, a considerable share of the power generation capacity will be related to CHPs. Incorrect accounting and reporting of the related biomass use results in an under-estimation of its total demand, as well as the renewable energy use in the industry or building sectors.

1.6%/yr growth (IEA, 2012a). Although biomass statistics are uncertain, the trend is indicative of the growing importance of biomass. Reference Case projections for the 26 REmap countries show this trend continuing at a slightly lower rate until 2030 (1.3 %/yr). In comparison, if all REmap Options are deployed, a higher growth rate of 2.6%/yr in the same period would be realised. Considering that biomass has potential in a diverse set of applications in the heating and power sector, this growth seems reasonable.

Figure 10 shows the biomass demand in REmap 2030 of the 26 REmap countries, as well as the demand in all other countries of the world (bar on the far right) with a breakdown by biomass type. The US, China, India, Brazil and Indonesia would account for 56% of the total global demand in REmap 2030. One-third of the total global demand would be from the Asian countries analysed in REmap 2030 (35 EJ). Another 20% would be from North American countries, including Mexico (20.5 EJ). Modern uses of solid biomass for heating, cooking and power generation would be approximately half of the total global demand (56 EJ). Primary biomass for liquid biofuels production to be used in the transport sector and for other purposes (31 EJ) would account for about 36% of the total.

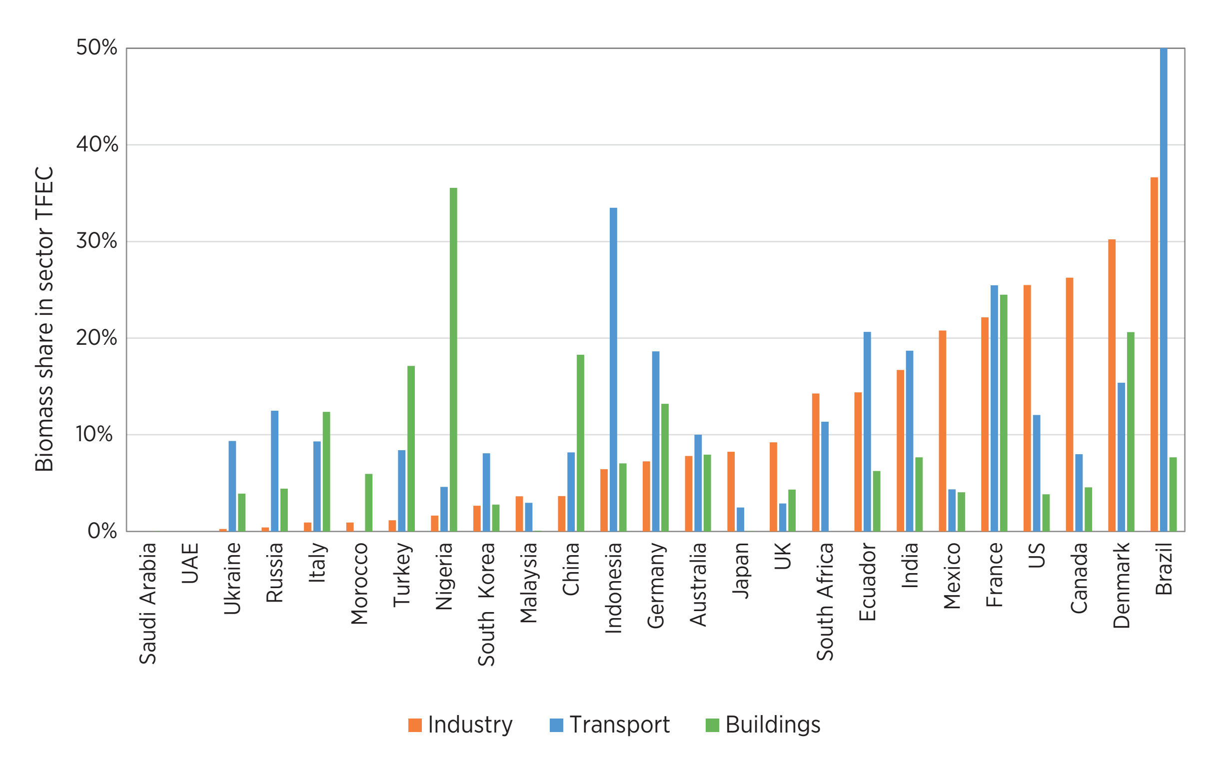
Figure 11 shows the modern biomass use share in the sector TFEC of the 26 REmap countries (ranked in increasing order from left to right based on the industry sector share). For the total of all REmap countries, biomass share in the TFEC (not shown in figure) reaches 17.5%. This is more than half of the total renewable energy share estimated in the TFEC of 27% according

Figure 10: Breakdown of biomass demand of REmap countries in REmap 2030



Note: Liquid biomass refers to the energy content of the total amount of raw biomass required for the production of liquid biofuels.

Figure 11: Modern biomass use share in sector TFEC of REmap countries



to REmap 2030. At the sectoral level, the contribution of biomass to total energy ranges between 7% (power) and 14% (transport) for the total of all REmap countries.

The highest share of biomass use is estimated in Brazil (39%), followed by France (26%) and Denmark (22%). Saudi Arabia has only 1% biomass share in its TFEC and UAE has less than 0.5%.

In the total of all REmap countries, the highest biomass share at sectoral level is estimated in the transport sector at 14% (orange bars in Figure 11). More than half of Brazil's transport sector has biomass, one-third in Indonesia and one-quarter in France. The share of biomass use in the sector's TFEC reaches more than 10% in a number of other countries, such as in Germany, India, Denmark and Russia.

The total of all REmap countries has a modern biomass use share of 11% in the industry sector. The share of modern biomass use in the industry sectors of Brazil, Denmark, Canada and Mexico would be more than 20% in REmap 2030. In most other countries, the biomass use share of the industry sector does not exceed 10%. In the building sector, the share of biomass use is 9% in the total of all REmap countries. Nigeria (36%), France (24%) and Denmark (21%) have the highest modern biomass use shares in their building sectors. In Nigeria, increased use of modern cooking equipment to substitute for inefficient cook stoves raises the share of modern biomass use.

Biomass-based power generation accounts for 7% of the total power generation of all REmap countries. Biomass contributes 16% of the total power generation in Brazil. In Canada, Indonesia, Malaysia, Mexico, Ecuador and the UK, biomass-based power generation contributes between 10 and 13%.

4.3 Biomass supply potential and costs in 2030

IRENA estimated that total biomass supply worldwide could range from 97-147 EJ/yr 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/yr). The remaining supply potential (60-81 EJ/yr) is shared between energy crops (33-39 EJ/yr) and forest products, including forestry residues (27-43 EJ/yr) (see Figure 12).

Agricultural residues and waste have the highest potential, but forest residues are also important. Bioenergy

Figure 12: Breakdown of biomass supply potential estimates by type, 2030

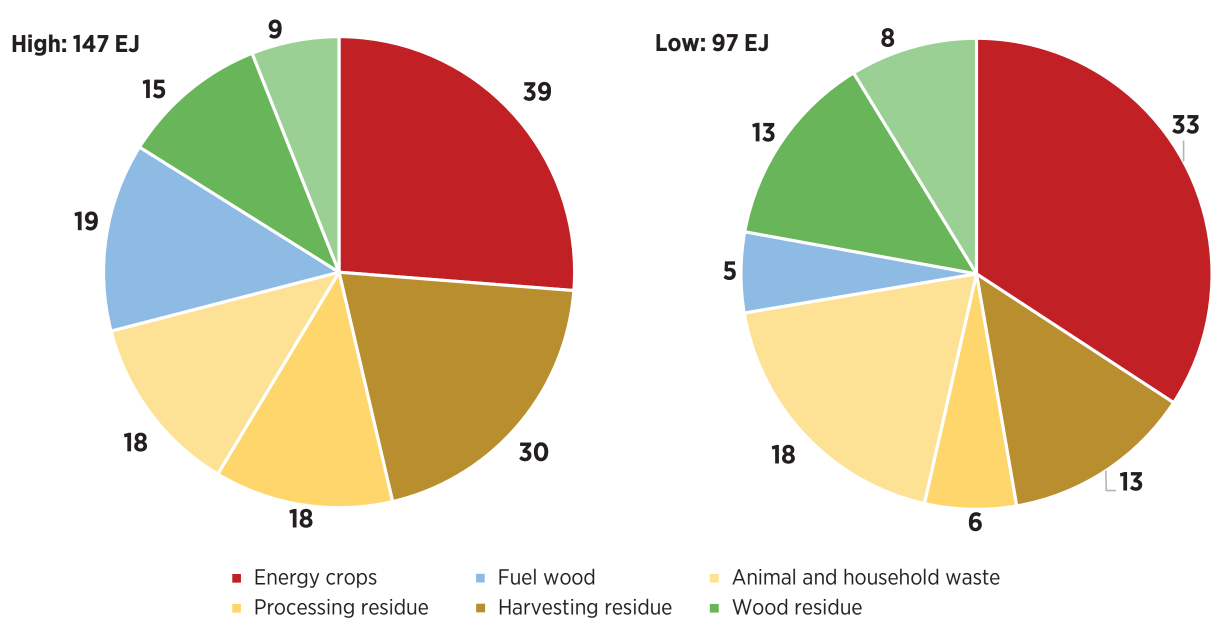
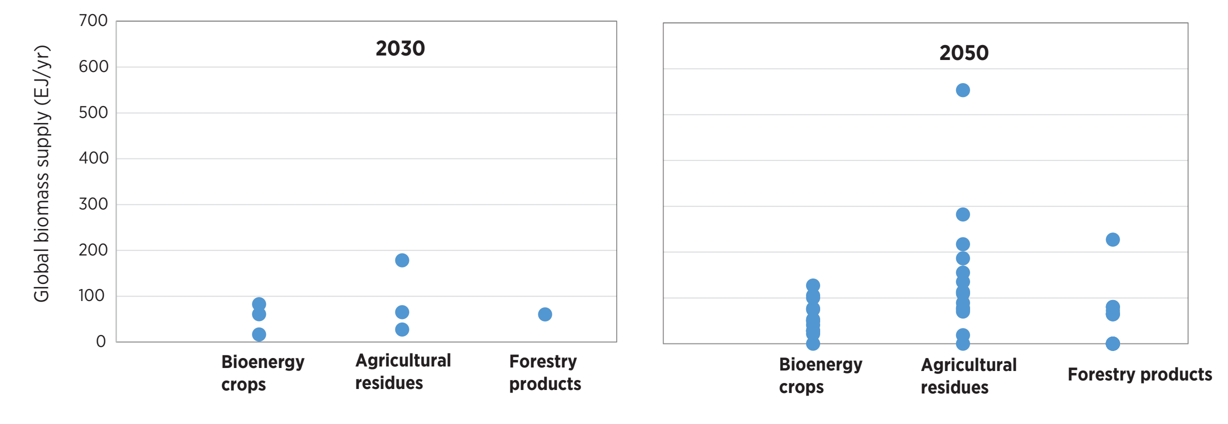


Figure 13: Literature review of global biomass energy supply potential estimates in 2030 and 2050



Note: In this comparison, differences in the way the heating value of biomass was expressed across studies (*e.g.*, REmap 2030 in LHV, most others in higher heating value) were not taken into account.

Sources: Fischer and Schrattenholzer (2001), Berndes *et al.* (2003); Hoogwijk *et al.* (2003); Smeets and Faaij (2007), Smeets *et al.* (2007); Field, Campbell and Lobell (2009); Hoogwijk and Graus (2008); Dornburg *et al.* (2008;2010); WBGU (2008); Erb *et al.* (2009); Hakala, Konturi and Pahkala (2009); Gregg *et al.* (2010); Haberl *et al.* (2010;2011); Beringer *et al.* (2011); and Lauri *et al.* (2014)

crops account for 26-34% of the total supply potential. This is an important finding as studies typically identify most bioenergy potential related to bioenergy crops.

Comparison of other studies

The total supply estimates match quite well with the recent estimate of 150 EJ/yr by the World Bioenergy Association (WBA) for 2030 (Kopetz, 2013). The WBA estimates a total of 62 EJ/yr of agricultural residues and food waste, close to IRENA's estimate of 42-69 EJ/yr. The potentials of forestry products according to the WBA is 70 EJ/yr, higher than IRENA's range of 27-43 EJ/yr. In comparison, IRENA estimates a higher potential for energy crops of about 35-39 EJ/yr compared to the WBA's estimate of 18 EJ/yr, mainly explained by the difference in land availability assumed (230 million hectares versus up to 900 million hectares).

Figure 13 provides a snapshot of the biomass supply potential estimates according to the literature for the years 2030 and 2050. The potential of energy crops is found to range between 16 EJ and 83 EJ/yr in 2030 and between 28 EJ and 127 EJ/yr in 2050 (only taking into account studies that provide an estimate). While the estimates of this study (35-39 EJ/yr) fall in the middle of the range found for 2030, they are much lower relative to 2050 estimates. A similar relationship between the estimates of this study and the ranges found in the literature exists for agricultural residues, waste and forest products; the estimates of this study are closer to the findings of studies published after 2010. This is an expected outcome of the fact that recent studies take into account sustainability issues and resource limitations regarding bioenergy supply in more detail, as well as improved data availability and quality (*e.g.*, about land).

Box 3: Utilisation of biomass residues in China and relevant support policies

Promotion of bioenergy in China

China's bioenergy utilisation has shown significant growth in last ten years, especially after China's Renewable Energy Law (MOFCOM, 2005) was enacted. In 2010, production of bioethanol was 2.1 billion litres. China was the world's third largest producer. Production of biogas in the same year was 15.5 billion m^3, which accounts for about 1.2% of China's total energy use, largely replacing biomass and fossil fuels for cooking in rural households (Regina Gregory, 2010). The number of household biogas digester installations exceeded 40 million in 2010, the world's largest. Biomass power generation capacity is 5,550 MW_e (2010). This development is supported by various kinds of policy measures, including long-term targets and planning, price subsidies, preferential taxes, low-interest loans, mandatory consumption of liquid biofuels, and support for research and development.

Table 6: Development of bioenergy use in China

	1998-2000	2010	2020 target
Bioethanol	-	2.1 billion liter	12.5 billion liter
Biogas digester	8 million	41 million	80 million
Biomass power	0.43 GW_e	5.5 GW_e	30 GW_e

China launched its Ethanol Promotion Programme in 2002. The steady growth of bioethanol production has been supported by government-controlled, subsidised prices (USD 584-730 per tonne), production under state owned enterprises and blending mandates. However, this policy led to the expansion of feedstock production areas, which caused land use competition with food production and rising food prices. The government decided to stop the construction of new maize-based ethanol plants and promulgate policies to encourage the production of biofuels from non-grain feedstock grown on marginal land. Still, there is concern in expanding production on marginal land from the perspective of its environmental impact and lower productivity. Ligno-cellulosic ethanol will be a promising technology to resolve this situation but still requires some time to improve the technology and make significant investments in logistics systems development.

Because of the nature of biomass feedstock, which has a lower energy density (*i.e.*, 15-20 GJ per tonne of biomass) compared with conventional fossil fuels (*i.e.*, from about 25 GJ per tonne for coal to 44 GJ per tonne for oil products), large-scale application is not suitable because of increasing transportation costs. Small-scale energy applications tend to have lower efficiency and be economically less competitive. The widespread dissemination of biogas digesters in China has been able to take advantage of its rural situation as follows:

1) **Lack of access to modern energy technologies:** In 2011, 446 million people in China (one-third of the total population) still relied on traditional biomass stoves for cooking. They lack access to modern energy (*e.g.*, LPG, kerosene, electricity) at affordable prices. Therefore, there is little competition among other types of modern fuel in disseminating biogas. Additionally, a significant positive health impact achieved by reducing the amount of soot and smoke from inefficient traditional biomass stoves, reduced labour/expense to collect/purchase biomass feedstock could be expected.

2) **Small-scale, mixed crop-livestock farming system:** Although Chinese livestock farming sector is in transition stage from small-scale backyard farming to medium/large-scale specialised grower, there is still a significant number of small-scale farmers who grow various crops together with a small number of livestock, such as swine or poultry. Most of the time, livestock are raised in a small pen next to farmer's house. This makes collection and utilisation easier. With minimum labour, animal waste can generate biogas.

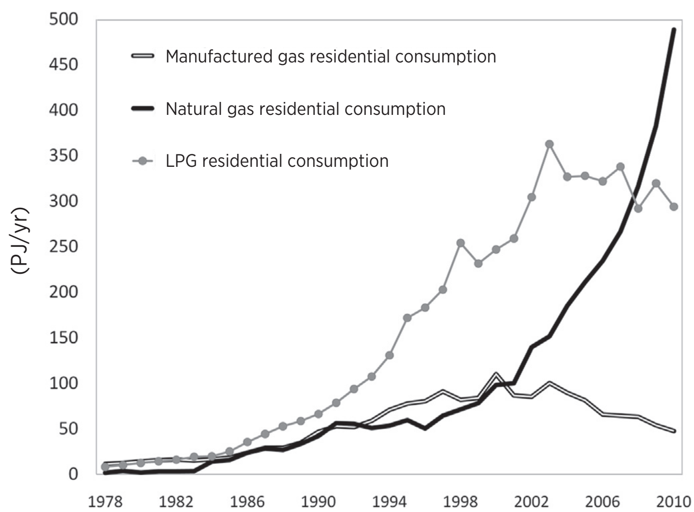
A series of policy measures, designed and implemented on a long-term basis, include national long term strategies, preferential loans, tax reductions, research and development (R&D), technology standardisation, technology demonstration thorough pilot plants, training and local technical support. Over ten years' support has been continuously implemented, including financial support which increased from USD 47 million in 2002 to USD 760 million in 2011. These levels of funding enabled large-scale dissemination and "cutting edge" technology.

Recent Change in China

China experienced a rapid shift in its energy use in keeping with its economic growth. As shown in the figure above, residential consumption of fuel gas increased from less than 200 PJ in 1990 to over 800 PJ in 2010. Liquefied petroleum gas (LPG) usage increased rapidly from 1990 to 2000, followed by increased natural gas use after the discovery and deployment of China's largest offshore natural gas reserve in the South China Sea. Although most of this change occurred in urban area, it is expected that as a result of conversion of LPG to liquefied natural gas (LNG) in many coastal cities, a reduced demand for LPG will likely be forthcoming in rural areas (Chi-Jen Yang *et al*., 2014).

Lack of access to modern energy technology has been one of the driving forces to disseminate small scale biogas in rural areas. As the situation changes, small-scale biogas systems will have to compete with other types of fuels, including fossil fuels and other renewable energies.

Figure 14: Rural household energy use in China

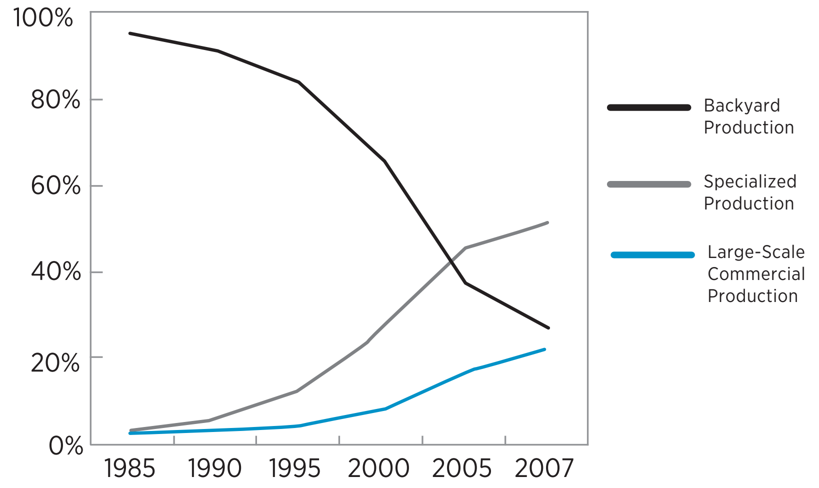


Source: Chi-Jen Yang *et al*. (2014)

Another change is occurring in Chinese livestock farming systems. Since the late 1990s, traditional backyard livestock farming has been gradually replaced by specialised household production and industrial-scale production systems. This also indicates another advantage of small-scale biogas systems in rural China (energy generation with minimal family labour and no collection/transportation costs) is diminishing.

Examining these two changes above, it is clear that small-scale biogas systems will face competition with other modern energy technologies in the near future and household level feedstock collection will become more difficult because of replacement of backyard farming by specialised or industrial-scale farming. Biomass digester system need to adapt to this change by shifting small-scale distribution systems into medium- to large-scale energy systems, which may produce different kinds of energy (*e.g.*, electricity). As for biomass power generation, China has a mature technology. Total installed capacity amounts to 2 GW, including the world's largest biomass power plant with 1200 MW_e capacity. 75% of the feedstock comes from agricultural residue. Farmer-based collection systems for agricultural residue is now established for biomass power generation (DCleantech, 2012). However, the collection of feedstock still poses the largest barrier since ag-

Figure 15: Decreasing share of backyard hog farming in China



Source: ILRI (2012)

ricultural production is mostly small-scale and geographically scattered. Because of logistics limitations, the economically feasible transport range is limited to a 50 km radius from power plant. Short-term harvest periods (*e.g.*,rice and straw, about six weeks) presents yet another limitation for stable feedstock supply (van Sambeek *et al.*, 2012).

Implication for other countries

In general, biomass resources in the Asian region (*e.g.*, India) share several common characteristics:

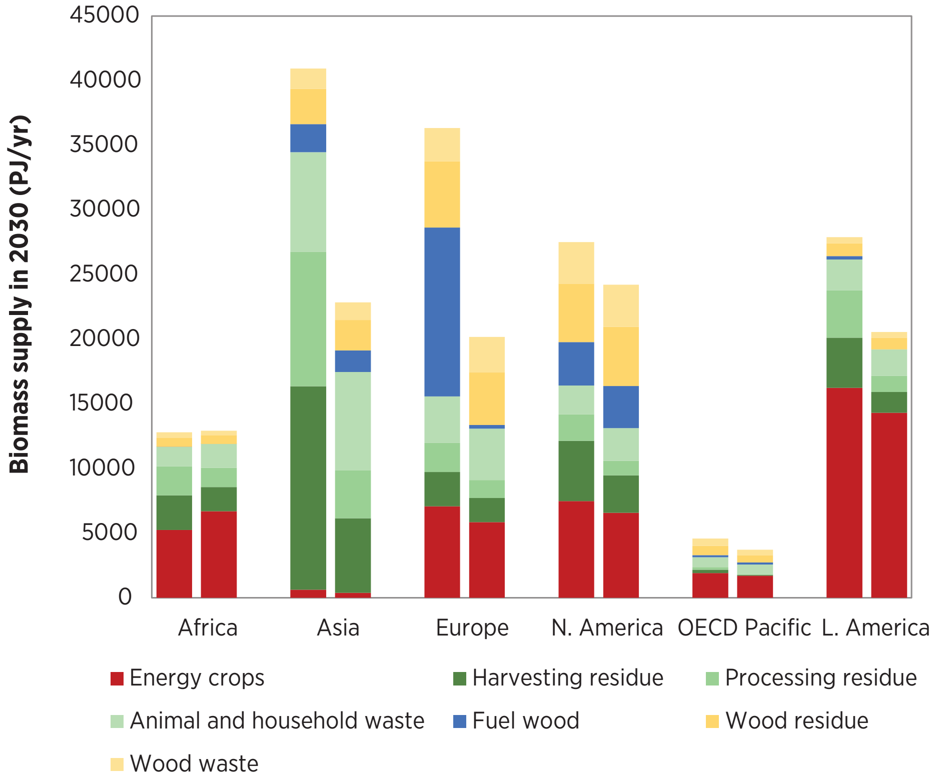
- High population density, limited land availability for agriculture;
- Potential competition between food and bioenergy;
- Limited access to modern energy technologies in rural areas (for power and cooking heat17%; and 51% of the population does not have access to modern energy); and
- Small-scale farming systems into which a small number of livestock are integrated, can be observed in rural areas.

These are some features that enable wide dissemination of biomass digesters in rural China. Therefore, with appropriate policy measures, the promotion of small-scale biomass digesters could contribute to the improvement of energy access, together with health and environmental benefits.

But in the long run, the energy demand/supply situation may lose its comparative advantage. Other technologies (*e.g.*, industry-scale biogas systems, agricultural residue gasification systems, lingo cellulosic bioethanol and biomass-based power plants) could be alternative targets depending on the stage of transition.

Figure 16 provides a comparison of the bioenergy supply potential throughout the six world regions. The largest supply potential—43-77 EJ/yr —exists in Asia and Europe (including Russia). North and Latin America together account for another 45-55 EJ/yr of the total supply. Harvesting residues in Asia (6-16 EJ/yr), energy crops in South America (~16 EJ/yr) and fuel wood in Europe (0.3-13 EJ/yr) and North America (~3 EJ/yr)

Figure 16: Breakdown of biomass supply by regions, 2030



account for a large share of the total global biomass supply. Energy crops in North America (~7 EJ/yr), Africa (5-7 EJ) and Europe (~7 EJ/yr), as well as processing residues (4-10 EJ/yr) and waste (~8 EJ/yr) in Asia are also important.

Europe includes Russia and for that reason, Europe has the second largest supply potential worldwide. More than one-third of the region's supply potential is from fuel wood originating from Russia. There is also large gap between the lower (7 EJ/yr) and higher (21 EJ/yr) estimates of European forest biomass resource potential. As mentioned in Section 2.2.5, the lower estimate applies severe environmental restrictions and assumes only the utilisation of forest resources currently under commercial operation to avoid a negative impact on biodiversity by developing forest plantation in pristine (*i.e.*, non-disturbed) areas. Russia has large area of undisturbed forest and thus its potential is significantly reduced in this scenario. More detailed environmental criteria for sustainable forest management, combined with GIS-based forest resource assessments, may provide better estimates of deployable forest resources while maintaining biodiversity.

Comparison of the estimated supply and demand for different bioenergy applications

The analysis suggests that the biomass resource potential in 2030 is adequate, but the analysis also assumes very rapid market growth for bioenergy applications. There are also uncertainties around both and demand.

Table 7 shows the estimated demand growth for different biomass applications between 2010 and 2030. Modern biomass use for heating in the building and industry sectors would grow in total by 0.9 EJ/yr if all bioenergy-related REmap Options are implemented by 2030, and the substitution of biomass for traditional uses would decrease by the same amount. The biomass which is freed up from the substitution of its traditional uses with modern forms could, in theory, be used to meet the increasing demand for heating. However, in reality the traditional use of biomass is located mainly in Africa and Asia and is often sourced unsustainably. In 2030, modern uses of biomass will exist in all different countries and regions. Biomass as motor fuel and for power and district heat generation will grow by nearly 2.8 EJ/yr.

Table 7: Biomass demand and supply growth between 2010 and 2030

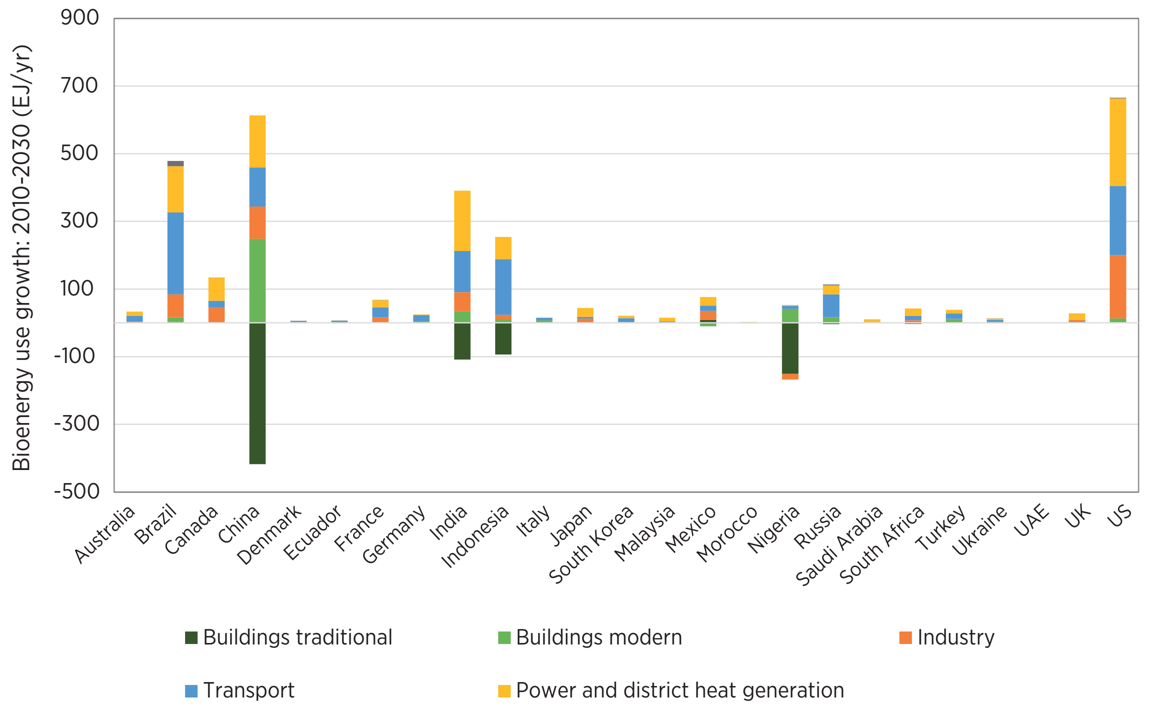
		2010 (EJ/yr)	REmap 2030 (EJ/yr)	Growth (%/yr)	Growth (EJ/yr)
Buildings traditional		27	12	-4.1%	-0.8
Buildings modern		8	13	2.6%	0.3
Industry		8	21	4.9%	0.7
Transport		5	31	9.7%	1.3
Power and DH generation		5	31	10.0%	1.3
Total demand		53	108	3.7%	2.8
Total supply	Low	56	97	2.8%	2.1
	High		147	4.9%	4.6

Note: REmap 2030 represents the total biomass demand from REmap Options in addition to the Reference Case.

In comparison to demand growth, bioenergy supply is estimated to grow by between 2.1 EJ and 4.6 EJ/yr over the entire period. The low end of supply growth is sufficient to meet the growth of all modern bioenergy demand for power and heat generation. Meeting demand in the growth of primary biomass for liquid biofuels will require additional supply growth.

Figure 17 shows the annual growth in bioenergy demand for the 26 REmap countries which account for three-quarters of the total global demand, with a breakdown by application. Total net biomass demand (accounting for the decrease in traditional use of biomass) will increase by between 100 PJ and 200 PJ/yr in Brazil, China, India, Indonesia and Russia. The growth in the US in

Figure 17: Annual biomass demand growth estimates between 2010 and REmap 2030



comparison would be about 465 PJ/yr if all bioenergy-related REmap Options are implemented by 2030. The largest annual growth would be in the transport sector (indicated with yellow bars below), estimated between 115 PJ and 240 PJ/yr in countries with the largest total growth.

Biomass supply cost estimates

Biomass supply costs depend on collection, feedstock production costs, processing and transportation distances (from source to processing plant to the use site). Figure 18 shows the supply cost of biomass as a function of the total global biomass supply in the year 2030. The supply potentials of each region are broken into two components: (i) the domestic supply cost (in USD/GJ) and the domestic supply potential (in EJ/yr) (indicated with blue horizontal brackets); and (ii) the related supply cost and the exportable volume (=surplus) (indicated with orange horizontal brackets) if a region has export potential.

Domestic biomass sources can be classified into three supply cost groups: (i) < USD 5 per GJ (low); (ii) USD 5-8 per GJ (medium); and (iii) > USD 8 per GJ (high). The low-cost group consists of processing residues and biogas (*e.g.*, bagasse, corn cobs, rice husk, wood processing residue, animal waste). The medium-cost group consists of harvesting residues (*e.g.*, cereal straw, corn stalk or other crop residues collected from the field); and the high-cost group consists mainly of energy crops and fuel wood.

Residues could be supplied at very low cost if supply chains are efficient. Utilisation is mostly limited to short distances since the transportation/collection cost is the biggest cost item. Logistics are critical, especially in the case of residue utilisation. For primary biomass, logistics are relatively well-developed to supply agricultural commodities as food/feed.

Figure 18 shows the estimated cumulative supply potential of biomass resources worldwide (on the x-axis) relative to supply costs (on the y-axis) for 2030. The

Figure 18: Global supply curve for primary biomass, 2030

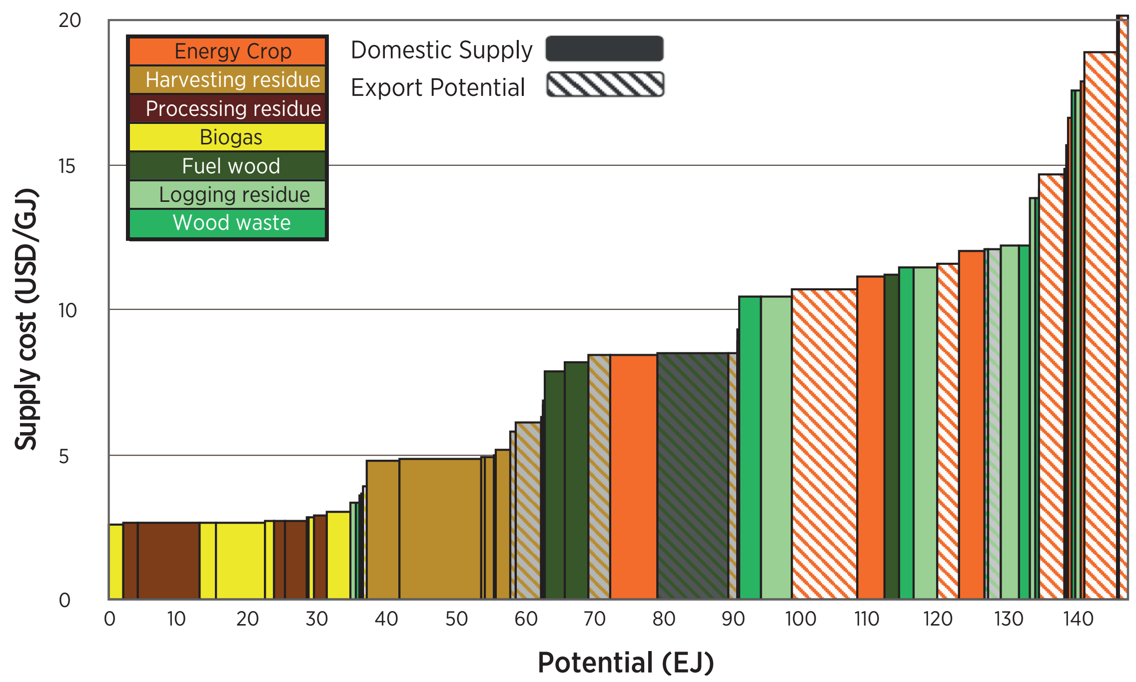
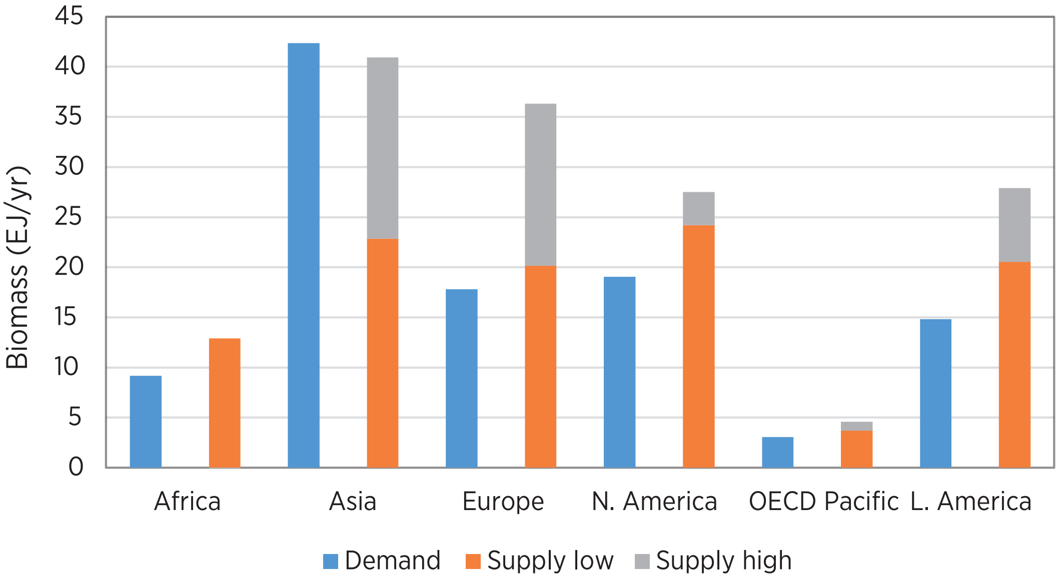


Figure 19: Comparison of global biomass demand and supply estimates in the six world regions, 2030



average cost of biomass is estimated at USD 8.3 per GJ worldwide.

The domestic supply cost of biomass ranges from as low as USD 3 in Africa (agricultural processing residues) to as high at USD 17 per GJ for energy crops. Small volumes of fuel wood from the OECD Pacific are outliers and could cost up to USD 36 per GJ. The share of exportable biomass in regions with surplus biomass in total amounts to 26% of the total supply potential. Costs related to transporting this biomass to different world regions are estimated to add an average of USD 3 per GJ (from 0.5 via rail to USD 4 per GJ via ship, depending on the distance and transport mode) to these domestic prices. For forest products, investments in the forestry sector for new plantations and in the substitution of non-renewable sources of biomass (*e.g.*, charcoal from deforestation) can be substantial and may raise the feedstock production costs further than estimated in this study (Schaeffer, Szklo and de Gouvello, 2010).

4.4 Impact on international bioenergy trade

If all REmap Options are implemented, global biomass demand could reach 108 EJ/yr, very close to the total supply potential range of 97-147 EJ/yr. Figure 19 shows a comparison of the global biomass demand with the total supply potential for the six world regions. With the exception of Asia (accounting for 40% of the global demand), all regions can meet their demand from domestic biomass sources. Compared to the current situation, in which the building sector uses most biomass sources locally, increasing global demand shows that large amounts of biomass will need to be supplied and a substantial infrastructure built to extract, transport and deliver feedstock.

Individual countries, however, may not fully meet their demand and may still rely on trade from countries in the same region and beyond. The demand/supply relationship varies across countries. Canada, Malaysia, Nigeria, Russia and the Ukraine can meet their demand from local sources (demand is less than half of supply in these countries). In contrast, countries with growing energy demands (*e.g.*, India, Indonesia, Mexico, South Africa) may require more biomass than their supply potential is able to provide. To meet this large demand, some countries will need to rely on imports.

If the use of local sources is prioritised and imports considered only after all local supply is exploited, international trade could reach up to 23 EJ/yr or some 20% of global demand – much higher than today's levels. However, countries could also choose to import biomass from the global market if the cost is lower, thereby raising the potentially exportable volume to 44 EJ/yr, 40% of total demand. The economic value of global biomass trade flows would be in the range of USD 100-400 billion per year, which represents a significant business opportunity.

The estimates of this study are in line with the estimates of integrated assessment models in which international trade is estimated to range between 14% and 26% of total global demand (Kranzl *et al.,* 2013). However, they should still be interpreted carefully because of the large growth required in trade, which will also require equally large infrastructure investments along the biomass supply chain. These include inland road and rail, as well as additional seaport infrastructure. For example, the required investment for the wood logging sector in Russia (major component is development of road network) is estimated as USD 630 million by 2030 to ensure an annual growth of 5% up to 2030 (FAO, 2012b) This represents 7% of the total required investment of USD 8.7 billion for the entire wood industry sector. Policymakers should first focus on maximising the use of local resources as the transition to international trade will take time; but in its absence, full potentials might not be reached. Therefore, policies should also deal with the potentially increasing growth of international biomass trade.

5 DISCUSSION OF BIOENERGY DEMAND ESTIMATES

5.1 Challenges in realising the estimated growth in bioenergy demand

According to the REmap 2030 renewable energy technology portfolio, biomass is the most important resource among all renewable energy technologies. It accounts for nearly 60% of the total renewable energy use in 2030. If all REmap Options are deployed, about 43% of the total biomass demand in REmap 2030 would be for heating. The remaining 57% would be equally shared between liquid biofuel use in the transport sector and power generation. Figure 20 provides a comparison of REmap 2030 biomass energy demand estimates (red bar) with scenario studies (blue bars) (all data in *primary energy* terms). The comparison shows that REmap 2030 demand estimates are similar to those of scenarios which aim to reach ambitious climate policy goals or high use of renewables, such as the IPCC (2011), Greenpeace (2007;2012) and IEA (2013c) studies. The Reference Case projections are comparable to the "business as usual" developments of scenario studies (*e.g.*, studies starting with ExxonMobil's study (2014) until and including IEA World Energy Outlook New Policy Scenario).

The largest growth in bioenergy demand across all sectors is in the transport sector with a six-fold increase between 2010 and 2030. This is much higher than solid biomass growth, including its historic developments. From 2000 to 2010, demand for annual liquid biofuels grew by 19%/yr (IEA, 2012a). However, its production has slowed down in the past few years. The Reference

Figure 20: Comparison of estimated global biomass demand of REmap 2030 with scenario studies based on IEA primary energy definition, 2030

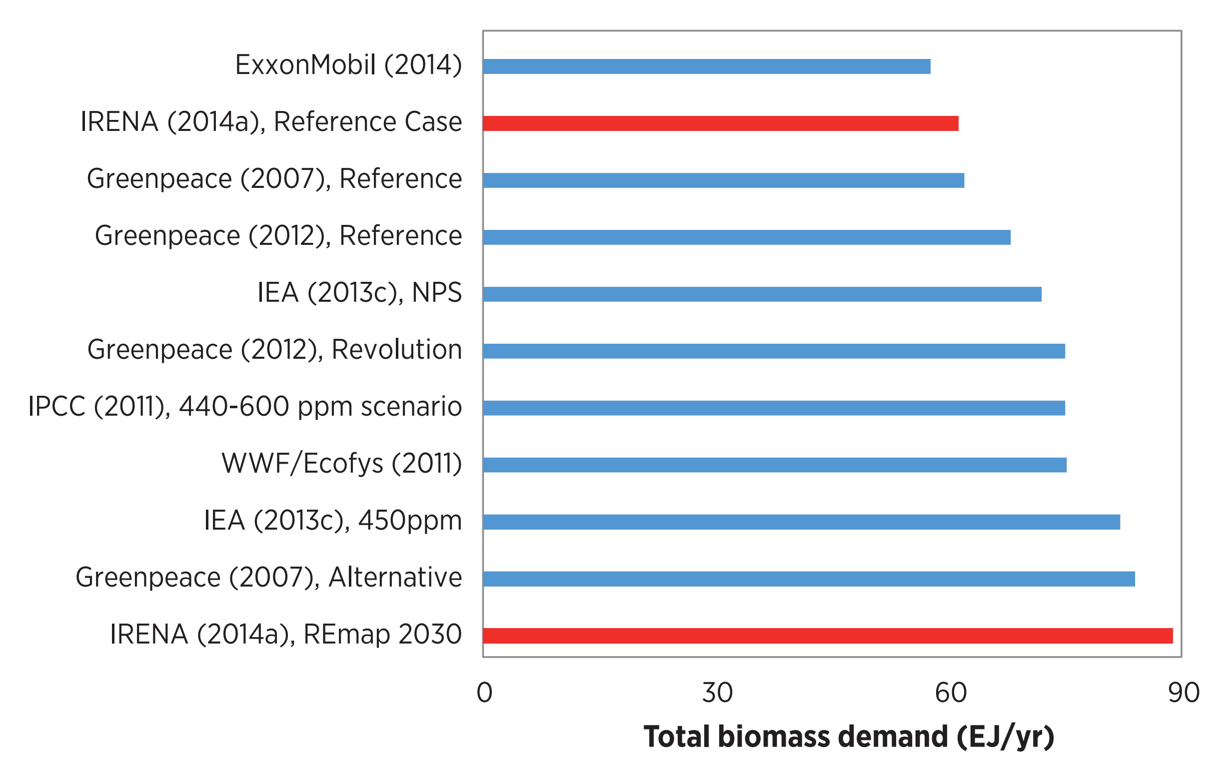
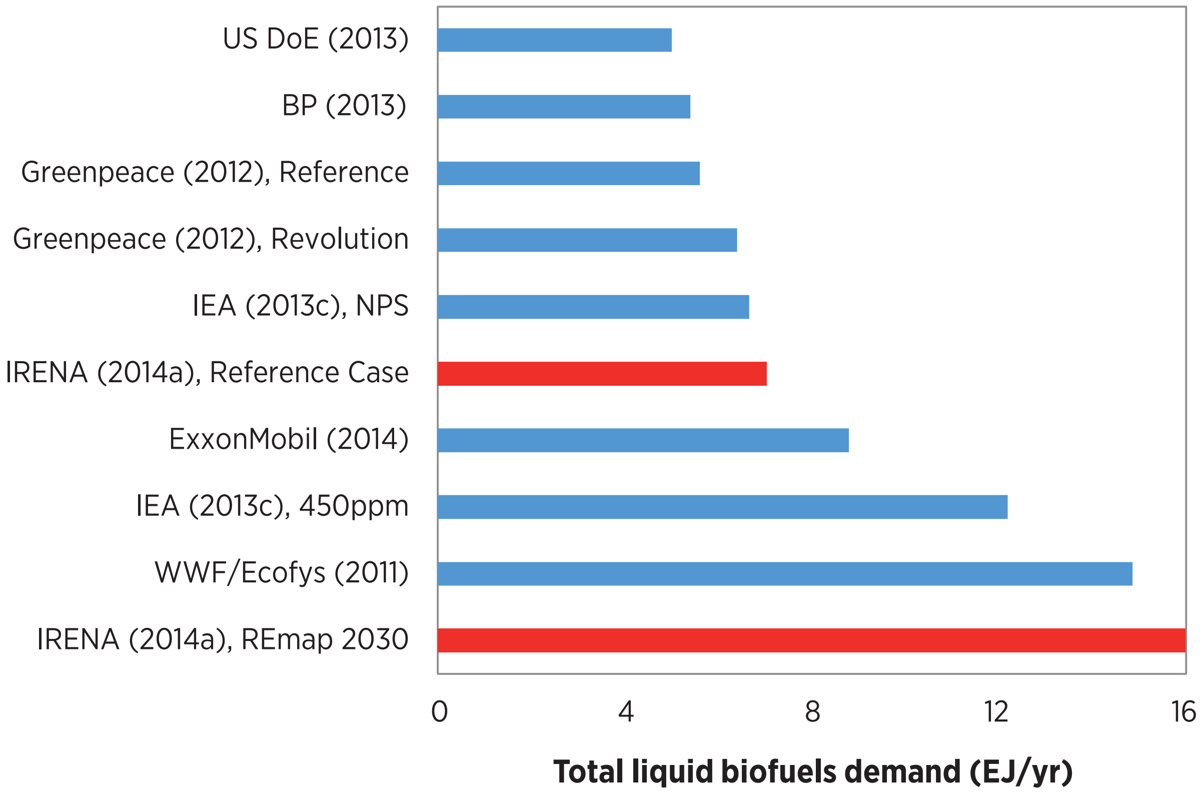


Figure 21: Comparison of estimated global liquid biofuels demand of REmap 2030 with scenario studies based on IEA primary energy definition, 2030



Case projects that biofuel demand will grow by a factor of 2.6 between 2010 and 2030 to nearly 7 EJ/yr, a continuation of the trend from 2005 to 2010 and similar to the demand estimated by a number of other scenarios, which range between 5-7 EJ/yr by 2030 (see Figure 21) (all data in *final energy* terms). The estimated liquid biofuel demand of 16 EJ/yr is very ambitious outlook and it is close to the high end of the range of 10-19 EJ/yr in more ambitious scenarios and projections. The main reason for high demand for biomass in the transport sector, according to REmap 2030, is explained by the fact that the use of liquid biofuel is the main technology option--accounting for more than 90% of the total renewable energy demand—to increase the sector's renewable energy share.

While the findings of this analysis are comparable to those of other scenario studies, there are still uncertainties whether such high demand growth will be realisable by 2030. This highlights the importance of developing the right mix of policies for demand and optimising the use of limited biomass resources across the different sectors of the economy through the deployment of cost-effective and sustainable options. In addition, the development of biomass-alternative technologies will be an important strategy to reduce biomass dependency. Each application has its own potential and challenges as elaborated below:

- For heating, alternatives are limited. As discussed earlier, this is especially the case for industrial process heat generation because high temperature process heat can only be generated by biomass. In buildings and district heating sectors, solar thermal, heat pumps (including air conditioning) and geothermal are alternatives. Although REmap shows that they offer substantial potential, on-site land availability (*e.g.*, large scale

solar thermal plants), access of plants/buildings to resources (*e.g.*, biomass) or costs (*e.g.*, high temperature solar thermal plants) could be constraints.
CHP is shown to be a cost-effective and efficient way of utilising biomass. Supplying heat by CHP means co-generation of power in the same plant as well. Power co-generation indirectly increases biomass use in the CHP. The specific case of CHP should be considered when designing related energy policies.

- Alternatives to biomass for power generation are numerous. Solar photovoltaics (PV), onshore/offshore wind, concentrated solar power (CSP), hydro, geothermal, ocean/tidal/wave technologies all have further potential beyond that estimated in REmap 2030. The conversion efficiencies of these technologies are also higher than biomass-fired power plants, which typically have an efficiency of 30-40%. Power sector policies should encompass the deployment of both biomass and other renewable technologies, and not necessarily prioritise biomass if other renewable resources are available. Rather, biomass use for power generation should be considered with the aim of increasing dispatchable renewable power generation and integrating variable renewables within the grid. Another option is to convert coal power plants to biomass plants (*e.g.*, the UK's Drax power plant), a strategy for countries where coal plants are being retired, as well as those with large and/or young coal power plant capacity
In the transport sector, liquid biofuels play by far the most important role in raising the sector's renewable energy share. Next to the use of biofuels, the contribution of electric vehicles and shift in transport modes (*e.g.*, use of high speed trains instead of aviation) are small. Both options are commercial and their share can substantially be raised to reduce liquid biofuel demand.

- Electrification offers the potential to reduce fuel demand for heating. In the industry sector, electricity-based processes for the production of ferrous and non-ferrous metals or hydrogen can save large amounts of fuel. More heat pumps can be deployed in buildings to meet the space heating demand. Ensuring that electricity is generated from renewables, and with a higher share of electricity in the end-use sectors, the renewable energy share can be doubled and beyond with a lower demand in bioenergy. Electrification as a hedging strategy to reduce biomass dependency is discussed further in Section 8.1.

- Traditional use of biomass plays an important role for the residential sector in developing countries. It is the main energy source for cooking and, in some countries, also for heating. Today nearly 40% of the global population relies on the use of traditional biomass. However, in many developing countries (*e.g.*, in Africa), biomass demand has already exceeded its sustainable supply potential. Given the expected growth in energy demand in developing countries, it will be crucial to ensure the substitution of traditional use of biomass and deployment of modern bioenergy technologies.
While use of the term "traditional" stems from the inefficient conversion of biomass to useful energy in the residential sector, biomass use in the manufacturing industry sectors of some developing countries at equally low efficiencies is *not* considered traditional. The same challenge of access to modern energy exists for the manufacturing industry sector.
The limited availability of capital, lack of infrastructure and labour, limited availability (*e.g.*, fuel) or poor quality (*e.g.*, technologies) alternatives and lack of awareness are the main reasons which make the transition to modern energy a challenge. Cultural preferences also play an important role in the transition to modern energy access.

5.2 Challenges in realising the estimated growth in bioenergy supply

Challenges for deploying bioenergy supply are specific to the type of biomass (*i.e.*, energy crops, agricultural residues and waste, and forest products). A number of key challenges for each biomass type are discussed below:

- There are both food- and non-food bioenergy crops. Forest products, non-food crops, such as willow or poplar are widely used. Dedicated bioenergy crops (*e.g.*, miscanthus, switchgrass or jatropha) are promising non-food alternatives. However, some of them (*e.g.*, jatropha) are only at a developmental stage while others pose specific challenges. For example, miscanthus is a very long lasting crop (about 20 years), but until a steady, maximum yield is reached, about four to five years could be required.

- In general, for bioenergy crops, there is a complex relationship with food production as they rely on the same land and water resources. This poses a specific challenge because of the need for affordable and continuous food supply. The key question is whether the world can supply enough food, energy and environmental services to meet its burgeoning population and demand by utilising its limited land resource under the constraints of a slowing agricultural growth rate. According to FAO, the issue is not the volume of available land, which is enough to supply growing demand, but securing the substantial financial investments to actually deploy these potential areas, plus the disparate distribution of land resource by country. For example, 60% of the world's unexploited prime land is held by only thirteen countries[12]. In view of this unequal distribution of land resources, FAO estimates that in the coming 40 years (up to 2050), the disparity of cereal production between traditional importing and exporting countries will, increase further. Namely, the resource abundant exporting countries will further increase their production and exports while the remaining countries will increase their cereal imports. Trade could play increasingly important role in food security. But these resource-poor countries still need to increase their productivity in a sustainable manner, even though constrained by limited resources, since many of these food-deficit countries lack the capital to import food (FAO, 2012a). All told, it is not recommended to promote conventional biofuels in such resource-limited countries.

- As explained in Section 4.3, agricultural residue and waste will account for the majority of biomass potential in 2030 (between 38-45% of the total). But current utilisation of agricultural residue according to IPCC estimates, is just 4% of total bioenergy use. This gap results mainly from supply chain developments, the competing use of agricultural residue, and sustainability concerns.
  Asia has the largest biomass potential, coming primarily from residues. This is a reflection of Asia's large, dense population, together with its overall actively growing economy. Current biomass utilisation is mostly limited to domestic cooking or heating applications. Since the energy density of biomass residues is lower than that of fossil fuels, large scale applications (except for food- and wood-processing residues and municipal sewage plants), which require long- distance biomass transportation, are not suitable unless low cost collection/transportation systems have already been put in place.

- The development of a reliable supply chain requires an efficient system to collect residue from widely dispersed farmlands and transfer it to the closest available conversion plants; investments in road networks / railroad development; drying and storage facilities and an optimal positioning of the conversion plant.

- As for sustainability concerns, further assessment is needed to determine appropriate extraction rates for harvesting residues from the field to maintain the soil quality and biodiversity, depending on the given climate, soil conditions and farming systems. Based on this scientific knowledge, together with information on current competing uses of biomass residue, a deployment plan for biomass residue should be determined.

- The potentials of the forestry sector are subject to uncertainties. Bringing forest resources from their actual location to the point of demand is the main challenge. For example, some forest resources in Siberia or Congo are located very far from the required infrastructure; thus, only the sustainable portion that does not result in environmental burdens should be utilised.

12 These thirteen countries are Madagascar, Mozambique, Canada, Angola, Kazakhstan, the Democratic Republic of the Congo, China, the Sudan, Australia, Argentina, Russia, the US and Brazil (in ascending order)

Russia has vast, underutilised forest resources, which account for over 20% of the world's total forest area, while its share of traded forest products is less than 4%. In fact, Russia's forestry sector is 5-6 times less productive than other developed nations, partially because of decades of underfinancing, antiquated forestry equipment that has deteriorated since the former Soviet Union collapsed in 1991, and illegal logging. The main bottleneck to utilising Russia's large forest bioenergy potential is the lack of infrastructure. Modernisation of the forest industry could lead to significant improvement in the Russian forestry sector. For example, FAO predicts that the Russian forestry production will more than double from 2010 to 2030 (*e.g.*, roundwood from 143 to 300 million m^3; wood biomass for energy from 32 to 75 million m^3 (FAO, 2012a)). This growth is based on the introduction of modern processing industry into the rich forest areas of Siberia and the Russian Far East. However, substantial investments will be required to materialise these forecasts.

- There are other challenges in the bioenergy industry; for example, concerning the conversion of bioenergy feedstocks into final products. Conversion technologies of lingo-cellulosic bioenergy crops to bioenergy commodities are at the developmental stage. So far, only a limited capacity is commercialised and capital costs are still high compared to conventional biofuel production plants.

- Economic viability poses a challenge for existing biofuels production capacity as well. For example, current developments in Brazil show that signs of new domestic investments are limited as demand for bioethanol is decreasing. Compared to gasoline, which is now less taxed, and with the discovery of new offshore oil reserves, bioethanol is less cost-competitive. The increase in bioenergy production costs, due to higher wages and depreciation of new equipment, contribute further to the decrease in its short-term economic viability (F.O. Lichts, 2013c; Washington Post, 2014). Furthermore, the renewable energy investment time series show a decreasing trend for bioenergy investments, in particular for biofuels, from 2006 to 2013. The reasons include the low price of natural gas in North America and overall policy uncertainty / risks related to the feedstock prices that limit investor confidence. Such uncertainties have an effect on investors and banks, which are then reluctant to invest in bioenergy projects. These developments will require that policy makers ensure a "level playing field" for biofuel producers.

Additional supply-side issues are discussed in Section 7 in the context of bioenergy sustainability concerns.

6 DISCUSSION OF BIOMASS SUPPLY COSTS

As mentioned earlier in Section 2.3, an assessment of the complex relationship between supply, demand and policy was excluded from this study. Instead, a fixed energy price based on the results of 26 REmap country estimates was used by matching demand and supply. This puts certain limitations on the trade assessment since energy prices could change dynamically as a result of real-world demand and supply relationships. Costs can be estimated using a bottom-up process, which aggregates each major cost component, while price is determined as a result of competition among different energy sources (*e.g.*, conventional fossil fuels, other renewable energy, traditional wood fuel), plus competition among different biomass usages (*e.g.*, food, feed and energy) with their associated prices. Major factors influencing biomass feedstock prices are summarised in Table 8.

The price of conventional fuels is one of the most important factors since fertiliser and energy costs account for a considerable share of the total costs in the crop production system. Furthermore, because of competition in the energy market, biomass and fossil fuel prices are closely correlated. For example, biomass residue could be supplied at very low costs, mainly their "opportunity costs" as defined by their fertiliser equivalent value. But if the residue could be traded in a market where other energy carriers are traded, biomass residues could acquire a higher selling price, up to the level of other energy carriers traded. According to the World Bank, crude oil price changes accounted for almost two-thirds of the food price changes from the period 1997-2004 (reference period) to the period 2005-2012 (period of food price increase) (World Bank, 2013).

Increase in food *demand*, conventional energy and bioenergy, as well as changes in diet patterns, are other critical factors which could increase biomass feedstock and food prices in the short-term. In comparison, in the long run, local farmers and the agricultural sector could benefit from higher prices. This could accelerate investments in the agricultural sector, which in turn, could increase the supply of biomass.

Decrease in food *supply* due to natural causes (*e.g.*, excessive heat, drought, floods) results in higher prices, as experienced in 2008 and 2011. Trade policy also impacts the price of agricultural commodities in both positive and negative ways, controlling the supply volume and market price through tariffs, subsidised prices or trade restriction measures.

Energy and agriculture policies have a strong impact on all of the above factors, especially increased demand and reduced supply costs. Induced by government policies to mitigate climate change, various support measures to promote bioenergy were implemented globally over the past years. These include subsidised prices (66 countries), preferential taxes (92 countries), and blending (51 countries) and heating mandates (13 countries) (REN21, 2014). In 2008, the increased demand for food crop-based bioethanol production, together with factors, including droughts, oil price surges, and food demand growth, resulted in increased food prices (*e.g.*, the cereal price index reached a peak 2.7 times higher than in 2000). Food riots and protests threatened governments, as well as social stability, in Africa, Asia, the Middle East and Latin America and the Caribbean. Massive public protests in response to higher food prices erupted in countries as distant and diverse as Burkina Faso, Cameroon, Egypt, Guinea, Haiti, Indonesia, Mauritania, Mexico, Morocco, Nepal, Peru, Senegal, Uzbekistan and Yemen (UN, 2011).

Another case in Germany followed the introduction of its biomass promotion policy in 2004. The preferential price of bioenergy promoted the installation of many medium-scale co-digestion biogas facilities using maize as a feedstock (70–500 kW_e). Supported by public policy measures, installed electric power from biogas increased significantly from 190 MW_e in 2003 to 1,450 MW_e in 2008. Approximately 5% of the total agricultural land in Germany was allocated to supply green maize for feedstock. In areas, such as in the Federal State of Schleswig-Holstein, 26% of arable land was cultivated in 2010 with green maize for biogas production, while other areas, such as Hessen or Saarland, biogas produc-

Table 8: Factors that influence biomass price

Factor	Sub-factor
Increasing demand	• Population, diet changes and economic growth • Importer policies (hoarding) • Rapid expansion of biofuels • (Future: bio-based economy)
Increased production costs	• Oil and gas prices • Fertiliser • Immature logistics for biomass feedstock
Decreased supply	• Harvest failures (droughts and floods) • Decrease in subsidised exports and food aid
Low stocks	• Global market integration reduces the need for domestic stocks • Demand growth exceeding production increase • Lagging investments in agriculture • Low commodity prices in earlier years • Commodity prices below costs (dumping) • Yield gap • Food waste
Market dynamics	• Speculation • Trade restrictions (export bans, stockpiling) • Currency exchange rates (weak dollar)

Source: Hamelinck (2013)

tion per arable land was limited (Delzeit *et al.*, 2012). As the total area used for maize in Germany has scarcely increased, there has been a shift towards less fodder and more energy maize. This trend leads to an increase in rental rates in areas with a high stocking density. A study conducted by the University of Göttingen compared the rents for arable land paid by farms with and without biogas in Lower Saxony. According to this study, the rental increase is much higher in livestock producing areas than in other regions (FMFAG, 2011).

In this analysis, the costs of production, collection and transportation are assumed to remain identical between today and 2030. There are a number of reasons for this assumption in which some components of the production costs increase in this period, while others decrease.

There are two main cost components affecting the supply of bioenergy, production costs (applies to energy crops and wood products) and the opportunity, collection and transportation costs (applies to all). The latter is mainly related to the costs of fuel. For petroleum products, an increase of nearly 50% is assumed between 2010 and 2030 for the Reference Case. In comparison, liquid biofuel production costs, which are assumed to be deployed in large volumes for transportation, are projected to increase only minimally. In a global market where demand for fossil fuels decreases, as shown by the results of REmap 2030, prices may not increase as much as is assumed for the Reference Case. Therefore, the change in transportation costs of all biomass between today and 2030 could be only limited. In this assessment, since the scope is to estimate potential and supply cost of primary biomass (biomass feedstock), pre-processing was not counted as an option to consider in relation to transportation costs. However, in the case of industrial applications for biomass residue, pre-processing is an important option to ensure long term collection / transportation to achieve economies of scale. Thorough pre-processing, including torrefaction, palletisation and pyrolysis, increases the biomass feedstock's energy density from 2-8 MJ/m^3 to 11-20 MJ/m^3, which in turn, could reduce transportation costs by more than half.

For the production of energy crops, studies show that, with technological learning and other improvements in the production system, costs could be lower than today for US corn or Brazilian sugar cane ethanol (Hettinga *et al*., 2009; van der Wall Bake *et al.,* 2009) and, therefore, the price trend is assumed not to change significantly up to 2030. The same was also assumed for the case of wood products. The main uncertainty comes from the dynamic interaction among different commodities competing with bioenergy. Next to fossil fuel prices (which are assumed to have only a limited effect in this study), food prices also have significant impacts on the bioenergy price and its demand and supply.

As for residues and waste, for which statistics are not available globally, transportation and collection costs were collected from the literature and used as a cost proxy under the assumption that harvesting systems, processing systems and logistics for collection/transportation are similar across all countries and commodities. However, large difference in production, harvesting, transport and processing systems by country and commodities do, in fact, exist, which may result in cost differences. Due to lack of information, these differences, especially in the case of developing countries, were excluded from this analysis. In view of these limitations in the assessment of biomass supply costs, the estimates should be considered as rather conservative.

To explain the complex relationship between supply cost, bioenergy volume, energy demand and price, food demand and price, land resource availability, and energy/food policy, the use of economic models offers a preferable option. In the economic model, those complex relationship are broken down into small pieces where each pieces represent rather simple relationship. Each pieces are then, translated into the form of equation and solved as simultaneous equation to determine supply and demand at one time using price/cost as common primary determinant. There are number of models to project global food demand and supply; for example, partial equilibrium models such as that developed by the International Food Policy Research Institute (IFPRI). Such models determine the production, consumption, import and ending stocks for each simulation year. The market clearing price is obtained from the equilibrium conditions through the use of the Gauss-Seidel algorithm. Bioenergy could be added as another marketable commodity in such a model.

7 SUSTAINABILITY OF BIOMASS

With bioenergy demand estimated to double between 2010 and 2030, concerns about the sustainability of its supply will grow. Sustainability issues related to all different types of biomass can be categorised as follows: economy, environment and society. Finance needs related to bioenergy deployment or energy security are among the different *economic* aspects. Land use, life cycle greenhouse gas (GHG) emissions, water use, biodiversity or soil quality are issues related to the *environment.* Food security and jobs are *social* aspects. This section deals mainly with carbon balance, GHG emissions and land use change, which are among the environmental impacts of bioenergy use (Section 7.1). Other sustainability issues are briefly discussed in Sections 7.2 and 7.3.

7.1 Environmental Issues

This section discusses environmental aspects of biomass use related to carbon balance, GHG emissions and land use.

Carbon balance and emissions

Plants convert CO_2 from the atmosphere into biomass. Carbon stored in biomass is called *biogenic carbon*. Some of this carbon stays above ground and some in the ground. When plants die, decomposition starts. As plant material decays, the stored carbon is released as CO_2 back into the atmosphere. If the amount of carbon released in biomass plantation and forests equals the amount of carbon sequestered then the biomass carbon cycle is in balance. There are also circumstances where some of the carbon is stored in the ground. The amount of carbon stored is huge, for example, in the case of peatland.

When biomass is combusted before a plant decays, biogenic carbon is also released into the atmosphere. If the total biogenic carbon released during biomass decay and/or combustion is sequestered, the system continues to be in balance. As a result, the amount of CO_2 in the atmosphere does not increase. This is fundamentally different than CO_2 emissions from the combustion of fossil fuels, which take millions of years to be sequestered; therefore, their combustion increases the volume of CO_2 emissions in the atmosphere.

The carbon cycle could, however, change in different ways when large amounts of bioenergy are used as fuel. If bioenergy is substituted for fossil fuels, there is a positive effect because fossil fuel CO_2 emissions are avoided. With increasing bioenergy use, the carbon stored in living plants and soil may also change, but the dynamics of soil carbon are not well understood. So this may have a positive or a negative effect.

When short-rotation energy crops or agricultural residues are used as fuel, they result in a balanced carbon cycle because they grow/renew themselves *annually*. In comparison, the rapid expansion of palm oil plantations in Indonesia and Malaysia, for example, has led to major problems associated with bioenergy. Logging rain forests or peat bogs for palm oil plantations has a negative effect. Plantations which were partly built on carbon-rich peat soils in the region resulted in drainage. The subsequent oxidation of peat and natural or anthropogenic fires results in substantial CO_2 emissions. Peat digging also has a negative effect, which results in an increase in CO_2 emissions in the atmosphere.

The use of forest residues could result in either a positive or negative effect. The rate of carbon sequestration into biomass or soil through the decomposition of residues is slower than the rates of forest residue combustion. Harvesting forest residues could therefore result in the accumulation of CO_2 emissions in the atmosphere. Through increased use of forest residues via thinning and other sustainable forest management strategies, forest growth can be accelerated and fires also could be prevented, thus reducing overall CO_2 emissions.

Increased recovery of residues may have either positive or negative effects on the biomass carbon cycle, but if sustainably sourced, they could contribute significantly to CO_2 emission reductions. Energy crops could also contribute to emission reductions if they were cultivated sustainably on surplus land. Transforming forest land into agricultural land for bioenergy crop growth, which would store less carbon, or just combusting beyond surplus forest growth levels, would result in a substantial volume of additional CO_2 emissions. Changes in the carbon cycle due to increased bioenergy use will substantially increase the life cycle GHG emissions of biofuels, even higher than the emissions of fossil fuels.

Land use

For both energy and food crops, the two most important factors affecting their future supply are land availability and agricultural yields. FAO/IIASA (2000) estimates that there are 2.2-2.7 billion ha of suitable land for crop production in the world. The projected food production area in 2030 is subtracted from this amount, along with environmentally sensitive areas (closed forest and protected land). In this working paper, the remaining 900-1,400 million ha is assumed to be available for energy crops in 2030. About three-quarters of this is concentrated in Africa and Latin American Countries (Africa 429 and Latin America 257 million ha). The availability of suitable land is the strongest determinant for the supply of primary biomass.

It may not always be the case that energy crops will be grown on existing agricultural land. Other non-agricultural land such as forest or pasture land could be converted to grow energy crops as well. This is called land use change (LUC). LUC, like most other effects of bioenergy use, can be distinguished as direct (dLUC) and indirect (iLUC) land use change.

dLUC occurs when bioenergy crops are grown on land not previously used for cropland or farming (*e.g.*, forests), but this could also be land that is degraded or agriculturally unmanaged. iLUC is among the different indirect effects of bioenergy, such as increase in agricultural commodity prices or food security (Dehue, Cornelissen and Peters, 2011). iLUC may occur when biofuels are produced on existing agricultural land, but the demand for food and feed crops still remains and be met elsewhere. This can imply land use change by changing, for example, forests into agricultural land in another country or region. For example, converting land with high carbon stock into agricultural land would imply that substantial amounts of CO_2 emissions would be released into the atmosphere (European Commission, 2012).

iLUC has been brought into discussion based on two studies published in 2008 by Searchinger *et al*. (2008) and Fargione *et al*. (2008). The main finding of both studies was that, when iLUC emissions are accounted for, the emission performance of bioenergy could be much higher than that of fossil fuels. Searchinger *et al*. (2008) showed that corn ethanol production could result in GHG emissions that are twice as high as those of fossil fuels. Fargione *et al*. (2008) showed that conversion of rainforests, peatlands, savannahs or grasslands to biofuel production from food-crops could release up to 420 times more CO_2 emissions than the annual GHG emission reductions from fossil fuels these biofuels would substitute. Many other studies also provide iLUC-related GHG emission estimates (Wicke *et al.,* 2012).

As opposed to GHG emission estimates from DLUC, there are large variations in the iLUC GHG emission estimates. iLUC emissions differ depending on the type of biomass feedstock, reference land use system, time frame and methodology/assumptions. The ranges observed within individual studies and across the different literature studies are high. In some cases, there is almost a factor ten difference between the low and high end of the ranges (*e.g.*, ethanol from sugarcane). Furthermore, the focus of iLUC GHG emission estimates was so far mainly related to liquid biofuels. However, the same issue applies also to bioenergy use for heat and power, particularly if energy crops grown on agricultural land are used.

iLUC is measured by market equilibrium models (*i.e.*, computable general equilibrium or partial equilibrium) or with allocation models. The former models consider inter-sector and market relationships rather well, but they are limited in terms of transparency. In contrast, the latter type of models are easier to understand and apply, but the approach is too simple to account for real-world market complexity (Wicke *et al*., 2012).

Methodologies and models are being continually improved to revise the ILUC estimates, which are subject to uncertainty. A number of studies (*e.g.*, Wicke *et al.,* 2012; Sanchez *et al.,* 2012) identified major sources of uncertainty related to iLUC estimates in existing modelling efforts, including uncertainties related to data, amounts, location and type of projected LUC, accounting of by-products and co-products from feedstock and biofuels production, applied life cycle analysis approach (*e.g.*, assumptions, methodologies, such as consequential or attributional), price effects, etc.

At present some governments are addressing iLUC-related issues in their renewable energy policies. In the Renewable Energy Directive (RED) of the EU, sustainability criteria related to minimum GHG emission savings of biofuels compared to their fossil fuel equivalents were included. However, this criteria excluded GHG emissions of biofuels from the iLUC. In response to concerns over iLUC-related GHG emissions, on 17 October 2012, the European Commission released its proposal to amend the 2009 RED with the estimated iLUC emissions for different feedstocks of biofuels, namely cereals and other starch-rich crops, sugars and oil crops (EC, 2012a). According to the same proposal, any other feedstock would have an iLUC emissions level of zero. The EU identified four rules related to the iLUC (EC, 2012b):

- Provide minimum GHG savings up to 60%, compared to fossil fuels;
- Include iLUC factors (see EC, 2012c);
- Limit conventional biofuel use to 5% of the total 2020 10% target; and
- Provide incentives for advanced biofuels.

The EU proposal also states that conventional biofuels should not be subsidised after 2020. All rules apply to both domestically produced and imported biofuels. The EU proposal is still under discussion (Ahlgren and Di Lucia, 2014).

In addition to the EU, the US has also amended its Renewables Fuel Standard 1 (RFS1) to include minimum life-cycle GHG emissions in the RFS2. RFS2 distinguishes between the production of conventional and advanced biofuels, which are defined based on their GHG abatement potential. All biofuels which can save up to 20% GHG in their life cycle compared to the petroleum-based equivalents are categorised as conventional. Conventional biofuel production is limited to 15 billion gallons to 2022. Advanced biofuels production accounts for the remainder 21 billion gallons. A biofuel can be considered advanced if it saves at least 50% GHG. Cellulosic biofuels require a 60% GHG emission reduction compared to the petrochemical equivalent (EPA, 2012). These emissions include ILUC GHG emissions.

Two terminologies which are commonly used in the context of ILUC are "carbon debt" and "carbon payback period". Fargione *et al.* (2008) defines *carbon debt* as "the total amount of carbon released during conversion of land for bioenergy growth over a total period of 50 years". *Carbon payback period* is "the number of years required to pay this carbon debt back". This would only be possible if the life cycle GHG emissions of bioenergy is lower than those of fossil fuels.

There are a number of technology measures to deal with ILUC. These are discussed in more detail in Section 8 of this working paper.

7.2 Other environmental issues

In addition to GHG emissions, there are a number of other environmental issues related to sustainability of bioenergy. These include, for example, soil quality, water use and biodiversity.

Water is as important as land for the agricultural sector. Today agriculture accounts for about 70% of freshwater withdrawals from natural systems (*e.g.*, rivers, lakes, aquifers). The share is more than 90% in some developing countries (Gheewala, Berndes and Jewitt, 2011). Water withdrawals are expected to increase by 60-90% for agricultural activities in the coming decades (Falkenmark and Rockström, 2004; Molden, *et al.*, 2007).

Expanding bioenergy use will increase "water stress" in addition to needs arising from increasing food and feed production demand. This is mainly a concern in regions where water scarcity is already high (see BioFPR, 2011).

Water is used during biomass feedstock production and during the conversion of biomass into commodities (*e.g.*, liquid biofuels). During conversion, used process water is generally returned to nearby water resources, such as a lake or river. However, water for biomass production does not necessarily go back into the natural system. Most of it evaporates (from soil etc) and is transpirated (from plants) back into the atmosphere. Therefore, it may not be available for further use until it precipitates in the form of rain.

Different crops have different water use intensities, depending on the crop's characteristics, climate, soil type, and crop management and irrigation technology. These factors are also location-dependent. Different methodologies are used to measure water demand, such as life cycle assessment, water footprint or the Global Water Tool with perspectives on environmental impact assessment, water resource management or corporate water demands (Schornagel *et al.,* 2012). These water accounting methodologies need to be developed further in order to be effectively applied for the assessment of bioenergy and conventional technology supply chains in motor fuels, heat and power production. In addition to the total amount of water needed, impacts from the changing quality of water used in bioenergy production (*e.g.*, from pesticides, fertiliser uses, high removal of residues resulting in soil erosion and subsequently resulting in eutrophication and water quality loss) and conversion needs to be accounted for (UNEP/OEKO/IEA Bioenergy, 2011). Poor land management is, for example, also interlinked with other environmental problems, such as the risk of erosion and the subsequent increase of turbidity in natural systems resulting in eutrophication. The trade-offs between water use, land use and GHG emissions of bioenergy need to be assessed further in order to develop sustainable bioenergy use policies.

Other important environmental issues that need to be addressed in the context of sustainable bioenergy use include the changes in biodiversity (*e.g.*, from deforestation, high forest biomass extraction rates) and soil quality (*e.g.*, use of fertilisers, high agricultural residue extraction rates) from bioenergy supply.

7.3 Other social and economic sustainability issues

Land is a primary, non-replaceable resource for agricultural production. In considering biomass potential, the allocation of land resources to food/energy crops is one of the most important questions, given the fact that food security is a key challenge faced by many developing countries today. There is a complex relationship between bioenergy and food security. Food (including feed) and biomass production rely on the same identical resources (*i.e.*, land, water). In this assessment, food demand always takes priority over energy demand when land availability is constrained. Land should be allocated to energy crops *only* when surplus land exists after other land demands have been addressed.

Issues around food security and prices escalate especially if more bioenergy crops (both food and non-food feedstocks) are used to meet the biomass demand. In addition, available land for food production can also be used for other purposes (*e.g.*, urbanisation, agriculture for non-food purposes) or degraded due to erosion, etc. These factors will also impact food prices and security.

According to Popp, Lotze-Campen and Bodirsky (2010), trends in food consumption are shifting to livestock-based diets. Population growth is another driver of food demand growth. Per capita food consumption and diet structure have significant correlations to income growth. In the coming decades, the global population is projected to grow on average 0.8% annually (*i.e.*, the highest growth—1.9%—will be in sub-Saharan Africa compared with an average 0.6% for the rest of the world). With increasing economic growth, the calorie intake in most countries will reach 3,000 kcal/day/per capita; potentially, animal protein will assume a greater share of the total food intake. Meat production is estimated to double by 2050 as compared to current levels and developing countries may account for most of this growth (Rosegrant and Cline, 2003; Steinfeld *et al.,* 2006; de Fraiture *et al.,* 2007). Most livestock originates from domesticated or wild animals, which will increase land demand. Overall, food demand for cereal could increase by more than 30% from two billion tons in 2007 to 2.7 billion tons in 2030 (FAO, 2012a). However, it is not only an issue of demand. There are other important challenges affecting the food supply chain. Roughly one-third of the global food produced for humans is lost or wasted (Popp *et al*., 2014). Each food supply chain challenge requires the development of a specific technology and policies and introducing an energy system that relies more on bioenergy.

Changes in the job market are an important socio-economic impact of switching from fossil fuels to bioenergy. Worldwide in 2012, about 2.4 million people were employed in jobs related directly or indirectly to the bioenergy industry. This is equivalent to more than 40% of total employment in the renewable energy sector. About half of the total employment in the bioenergy industry was related to biofuels (*e.g.*, the majority in Brazil and the US), followed by solid biomass (*i.e.*, the majority in China and EU countries) (IRENA, 2013c).

The following example of biogas in China illustrates how growth in sustainable bioenergy use could result in the creation of more jobs across different sectors of the economy. With the Chinese Government's push between 2006 and 2010 to increase the number of biogas systems, the total number of Chinese jobs directly and indirectly related to biogas digester construction reached nearly 90,000. Jobs were created in various sectors, including non-metal mineral products, technical service and machinery manufacturing sectors. According to the REmap 2030 analysis (IRENA, 2014a), doubling the share of renewable energy in the global energy mix would result in up to 150 cumulative million job-years between 2013 and 2030. Compared to "business as usual", this is an additional 60 million job-years, about one-third of which in the bioenergy industry.

Another important socio-economic impact resulting from changes in the fuel mix is energy security. For some countries that rely on fossil fuel imports, one of the main drivers for switching from the use of conventional fuels to renewable energy is energy security. Renewable energy, including biomass, could reduce import dependence. However, as this analysis showed, international trade would account for 25-40% of total global demand. This indicates that in some countries import dependence could shift from fossil fuels to bioenergy. Hence, energy security should be considered carefully as new bioenergy policies are designed.

8 STRATEGIES AND TECHNOLOGIES TO REALISE SUSTAINABLE BIOENERGY GROWTH

This section provides a number of strategies and technologies for both the demand- and supply-side that could enable and facilitate a sustainable transition to bioenergy by 2030.

8.1 Demand-side options

As the demand-side analysis shows, there is potential for biomass-derived products in all sectors of the global economy. Growth in demand for biomass can be reduced by improving energy efficiency. As REmap 2030 shows (IRENA, 2014a), energy intensity (GJ per USD value added) in the 26 REmap countries improves by 1.6 %/yr when all REmap Options are implemented. One of the three objectives of SE4All is to double the rate of energy efficiency improvements to 2.6 %/yr between 2010 and 2030 from its historic level of 1.3 %/yr. Realising this objective could reduce the estimated bioenergy demand from 108 EJ to as little as 79 EJ. This is comparable to the total global bioenergy demand according to the Reference Case and in the absence of additional energy intensity improvements.

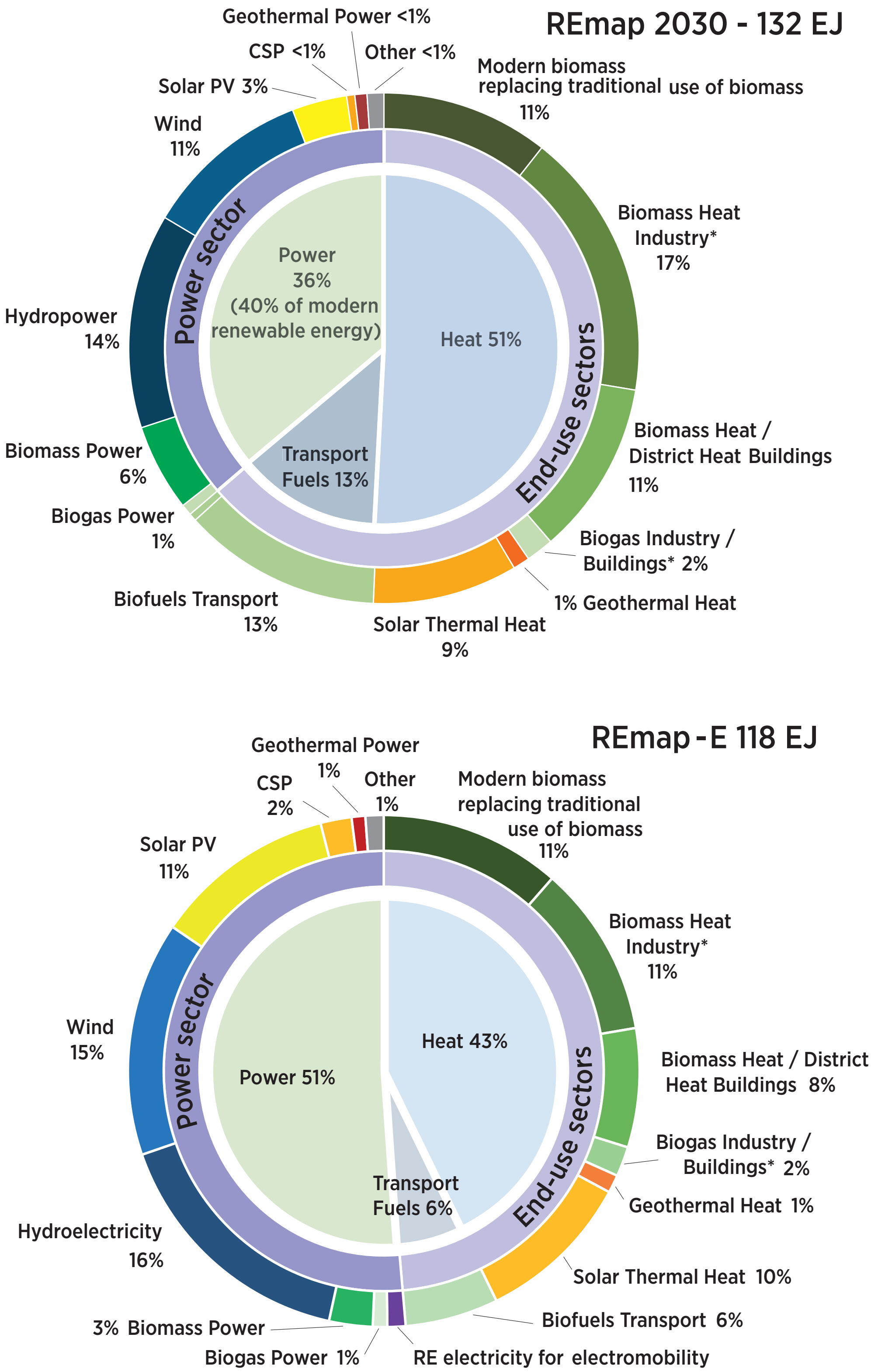
The portfolio of renewable energy technologies in REmap 2030 relies heavily on biomass. The selection of technologies required to double the global renewable energy share has an important impact on biomass resource demand. As discussed in Section 5.1, electrification is an important strategy if dependence on biomass is to be reduced. Other strategies are modal shift and industry relocation (IRENA, 2014a). Deploying these options increases demand for electricity, which can be generated from additional renewable power capacity. In this way, the global renewable energy share can be doubled by 2030.

As an alternative to the biomass-dominated technology pathway of REmap 2030, IRENA (2014a) also explored an alternative that relies on electrification for doubling the global renewable energy share. The case for electrification (including modal shift, electric heating/cooling with heat pumps, and industry relocation) is represented by "REmap-E". In REmap-E, biomass demand is lowered from 108 EJ to 65 EJ. This translates to a modest increase of approximately 10 EJ in biomass demand by 2030 compared to today's levels. This assumes that biomass demand in the industry and transport sectors remains at the level of the Reference Case. Compared to REmap 2030's levels of biomass use, this halves the demand in these sectors. In the building and power sectors, demand is assumed to be reduced even further or about one-third below the Reference Case in 2030.

In REmap-E, different strategies for each sector are presented. In the building and industry sectors, heat pumps instead of biomass deliver the required heat. In the transport sector, modal shifts (*e.g.*, public trams, electric buses and trains) replace liquid biofuel cars. Increased electricity demand of the end-use sectors is supplied by additional solar PV and wind on/offshore capacity. Additional solar PV and wind capacity also generate power which would have otherwise been generated by biomass. In REmap-E, some industry plants are relocated next to areas with affordable sources of renewable power supply. This creates additional capacity for CSP with storage, hydro and geothermal power.

The electrification strategy – REmap-E – described above increases the global share of renewable energy to 30%, about the same 30% share as estimated for REmap 2030. The global breakdown by resources are displayed in Figure 22. The total renewable energy needed to double the global renewable energy share decreases from 132 EJ to 118 EJ due to the higher efficiency of electrification technologies (*e.g.*, by a factor of more than two difference in efficiency for an electric vehicle compared to liquid biofuel car). The share of biomass in total global renewable energy use decreases from 60% in REmap 2030 to 42% in REmap-E. In com-

Figure 22: Comparison of the breakdown of global renewable energy use in REmap 2030 and REmap-E



*including CHP and district heat

parison, the contribution of renewable power increases from 37% to 51%. At the sectoral level, there are also important changes. The share of electro-mobility reaches 2% from the 1% achieved in REmap 2030, whereas the share biofuels is halved from 13% in REmap 2030 to 6% in REmap-E. The total biomass share for heating/cooling decreases from 40% to 32%.

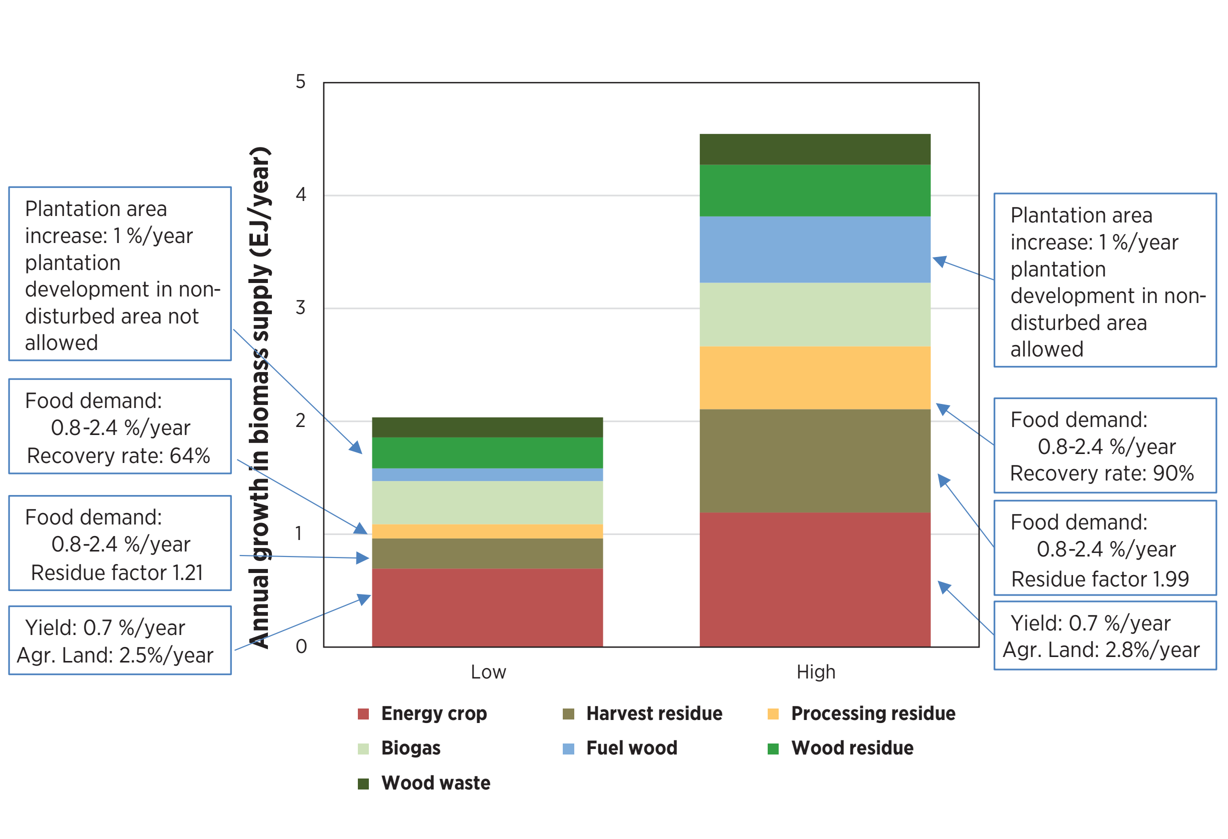
Electrification in end-use sectors results in an increase in the installed renewable power plant capacities. Total global installed renewable power plant capacity increases by nearly 60% from 4 870 GW_e in the REmap 2030 model to 7 250-8 000 GW_e in the REmap-E model. Integrating even higher penetrations of variable renewable energy adds further uncertainty to the feasibility of the REmap-E.

8.2 Supply-side options

In order to meet a growing global demand for bioenergy of approximately 2.8 EJ per year, global biomass supply would have to grow by 2.1-4.6 EJ per year. It is essential to evaluate whether this potential could be deployed in pace with the cited demand growth rate.

Figure 23 shows the contribution of different factors to supply potentials estimates in 2030, depending on the type of biomass. In the case of energy crops, investments in the development of agricultural infrastructure (production and logistics) are critical since new land is required to meet the growing food and energy demand. For fuel wood, establishment of plantations is key. Fuel wood production using surplus forest areas requires development of a logistics system. Moreover, the establishment of commercial plantations also requires long lead times: for example, of up to seven years for eucalyptus. Yield increase is another important factor. In this assessment, the yield growth rate is set to 0.7% per year (FAO, 2012a). This yield growth rate is comparable with other literature projections and about half of what has been experienced in the period between 1961 and 2007 (Popp *et al.*, 2014). A high land development rate was set at 2.5- 2.8% per year in keeping with high

Figure 23: Factors contributing to the annual growth in bioenergy supply potential between 2010 and 2030



bioenergy demand growth in the coming decades. This range is much higher than the 0.3% annual historical trend. Considering the very uneven land distribution among countries, full deployment of surplus land could only be achieved through expansion of international bioenergy and agricultural commodities trade. To create an enabling environment for market/trade expansion, a set of policy measures is required, including development of logistic systems for bioenergy, stable financial support measures for early stage of development, long-term policy targets to ensure sustainable market opportunities, awareness-raising, pilot activities and the demonstration and introduction of sustainability criteria, quality standards, technical support, and so on.

As for residues, the primary factor is the volume of food consumption since residue is generated in proportion to food consumption. The food consumption growth rate is assumed to range between 0.8 and 2.4% per year based on FAO estimates (FAO, 2013). Development of logistics systems to collect residue limits availability. As for waste and processing residues, collection systems must be expanded in future through improvements in environmental regulation and waste treatment systems. For the harvesting residue, conventional farming systems need to be adjusted to handle primary commodities and harvesting residues efficiently and sustainably. Development of such systems require assessments from different perspectives: the *agronomic standpoint* to maintain soil fertility while extracting a certain portion as bioenergy feedstock; the *mechanical standpoint* to enable harvesting and transporting two kinds of commodities (*i.e.*, the primary commodity and its harvesting residue) within one system; the *logistics standpoint* to minimise logistics investments by making use of existing logistics for the primary commodity as much as possible. An example of this approach is the integration of conventional and advanced bioethanol (*e.g.*, corn and corn stover, molasses and bagasse).

Although the estimated contributions of different factors to the growing supply are feasible and REmap 2030 findings are comparable with those of other studies, specific strategies will be required to overcome various barriers to growing biomass supply. These are discussed in more detail below:

- Biomass resources are distributed unevenly across regions because of the natural environment (land availability and agro-climatic environment) and human activity (population and the economy). As a result, there are clear differences in the types of biomass available in each region. For each region and country, it is important to set up a deployment strategy suitable to the type of biomass available locally.
  For energy crops, large-scale mechanised farming systems are critical since competitive feedstock costs are a key factor for energy applications. Latin America enjoys an advantage in this respect because of its land availability. North America also has a large volume of suitable land, but domestic food and energy demand is also high. African regions have the largest volume of suitable land; however, their potential is not fully realised because of low productivity, underdeveloped agricultural land and difficult transportation logistics. Also, the supply of sustainable bioenergy to replace the traditional use wood fuel in buildings is a critical issue for Africa. Forest resources are abundant in Europe, mainly in Russia, but domestic demand is also high in countries outside of the EU.
- The success of large-scale international bioenergy trade will require the transport of high density commodities at low costs. Transport costs can be decreased by introducing pre-treatment into the supply chain. Pre-treatment, including torrefaction, pelletisation and pyrolysis, increases energy density from 2-8 MJ/m^3 of raw biomass up to 11-20 MJ/m^3 for pre-treated biomass. By optimising the supply chain through incorporating pre-treatment, logistics costs could be significantly reduced compared with the raw materials-based supply chain.
- Land availability depends on the pace of food demand and yield growth. If yield growth outpaces food demand, land availability will increase. Estimation of yield relies on two approaches: historical trends and theoretically achievable yields. In considering how to fill the yield gap between current yield and theoretically achievable yield, the impact of food prices and timeframes is also important. Criteria to identify deployable land from the environmental and social perspective are also critical factors in assessing land availability.
  In this working paper, the term "suitable land" excludes a number of land types in view of their unsustainable land management risks; namely, closed forests, highly protected areas, land with

marginal productivity, and land required for infrastructure and housing.

A number of studies argue that marginal land could be used for the production of energy crops while avoiding land competition with food. In this working paper, marginal land is excluded from the potential land for the low end of supply estimates since further assessments are required to verify productivity, environmental impact and sustainability of such land (Wicke, 2011). Some forest land which satisfies certain conditions is, however, assumed to be available for bioenergy production. Forest areas that satisfy suitable productivity (agro-climatic conditions and soil fertility), sustainability (soil type and topography for erosion risk), and low biodiversity risk (open forest which is already affected by human intervention to a certain extent) is assumed to be available. More than 85% of total global forest lands are still excluded from the above criteria.

- By applying a number of measures and technology options, additional land demand (*i.e.*, conversion of land for agricultural purposes) for food and feed (excluding fish) production can be reduced. This reduction is important because, historically, land degradation has been a major problem. The expansion of slash-and-burn agriculture, overgrazing marginal land, cultivation of semi-arid areas without appropriate soil management, and improper irrigation are some of the main reasons.

  One key option to limit additional land conversion for food and feed demand is to improve yields. For various crops, the literature estimates a yield range between 4 and 13 t/ha in 2030. Achieving the higher rates would increase agricultural output substantially to help meet the increasing food demand. However, its impact may be limited to avoid additional land conversion if there are substantial changes in food demand. And it is also important not to exceed the optimum yields; without proper soil management, excessively high yields may lead to further land degradation and subsequently to additional land requirements.

  Plant breeding and genetic modifications can also increase the resistance of crops to diseases and insects and improve their suitability to changes in soil characteristics. But while genetic engineering may reduce resource impacts, it is subject to legal and ethical debates and may see only limited application.

  There are a number of other strategies to limit land expansion, such as the expansion of agricultural activities in degraded and abandoned lands; coupled growth of food and fuel crops, and maximising the potential from animal manure and wastes. Finally, the efficiency of livestock management and feed to food processing can be improved, diets can be switched towards less land-intensive food, and food waste can be reduced.

  The other key resource along with land for energy crop cultivation is water, the consumption of which can be reduced by improved and better managed irrigation systems.

- Increased residue use could, for example, limit land expansion, as in most regions it will be an economically viable source of bioenergy. Its potentials are estimated at about 60% of the total supply potential, but high removal rates of agricultural residues could negatively impact soil fertility, thereby resulting in further environmental damage. Its extraction should be maximised, ensuring that a sufficient amount of residue is left on the ground to ensure that soil organic matter is maintained. Further research is required to set criteria for how much crop residue could be removed in a manner that ensures sustainable soil management and biodiversity.

- As for technology options for agricultural forest residue collection, it is important to set criteria regarding a safe removal rate of forest residue through research and development. The situation for wood-based energy differs between developing and developed countries. For developing countries low efficiency, unsustainable fuel-wood utilisation must be replaced by a more efficient form of household energy, combined with sustainable forest management. For developed countries, the overall supply chain from logging site to final energy use must be improved through a combination of enhanced mechanisation, transportation (*i.e.*, road, rail, ship) and pre-processing to reduce transportation costs and improve energy efficiency for industrial applications.

- A reduction of collection/transportation costs through the development of efficient logistic systems is a key factor. The utilisation of residue

Box 4: Strategies for transition to modern uses of biomass

The current cost of fuel wood used as traditional biomass in rural areas is "hidden" because it is often supplied by means of free labour (*e.g.*, family members). Traditional biomass is less expensive than petroleum-based fuels. Therefore, its substitution is difficult. As opportunities for employment in rural areas increase, it should become apparent that free labour for fuel wood collection is actually a loss of economic opportunity. If the time to collect fuel is accounted for, traditional biomass cooking over open fires, for example, becomes *far more* expensive. This could even be the case in comparison to the annualised costs of modern cook stoves. If such realities are included in the efficiency equation, then a transition to modern energy use becomes more desirable and can be accelerated.

In urban areas, switching fuels is primarily a matter of price competitiveness. Higher standards of living from modern energy make more than merely economic sense and should be considered in view of reduced pollution and easier heat control. Furthermore, in the urban areas of African countries, modern energy is already becoming an economically viable alternative to traditional biomass, mainly explained by the increasing distances of traditional biomass transport to end-users.

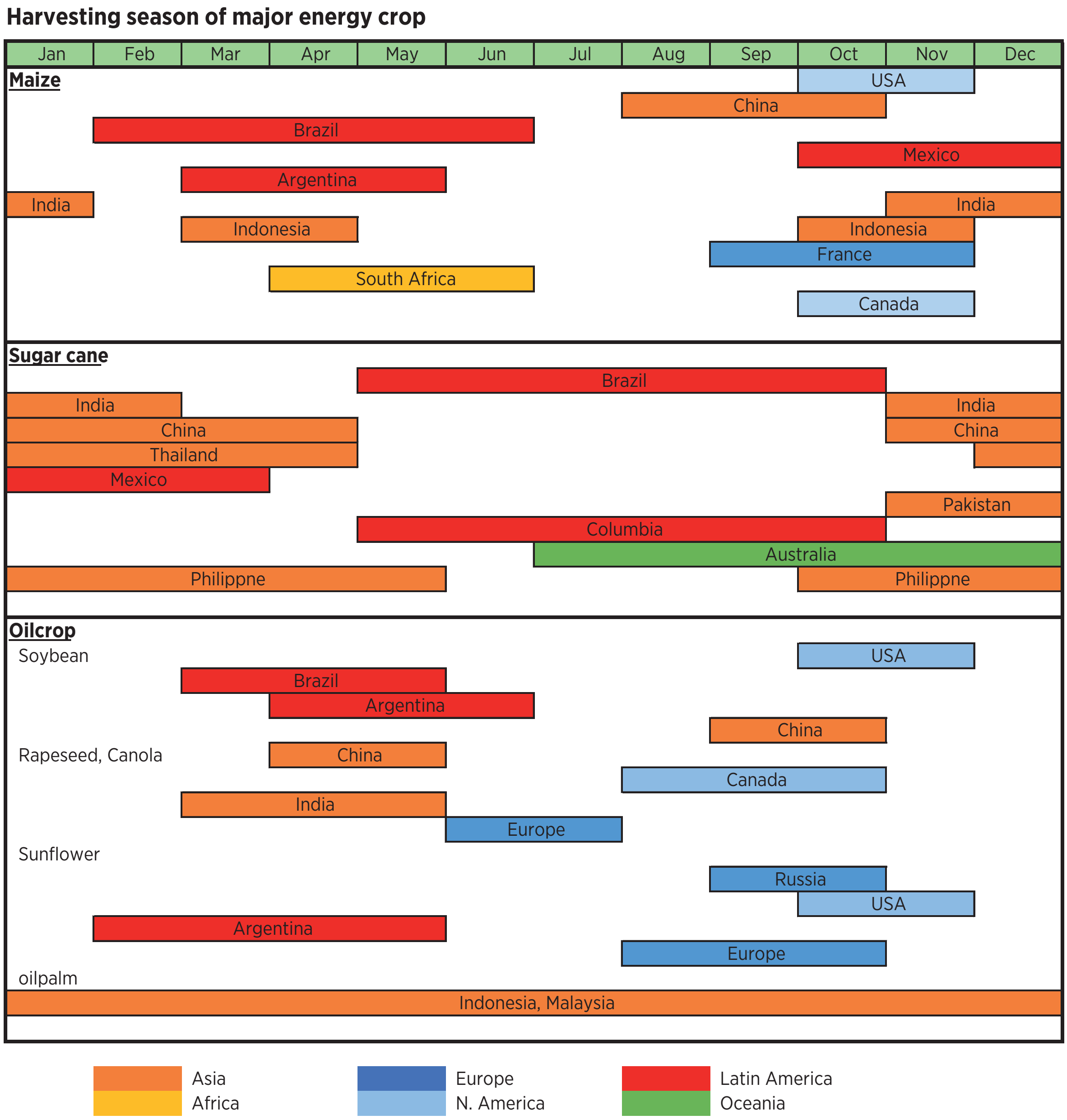
Initiatives to promote the use of modern biomass equipment have been introduced: for example, the Global Alliance for Clean Cookstoves by the US, the Clean Stove Initiative by China and the World Bank, and the National Biomass Cookstoves Initiative in India. Major programmes are also required in Africa where the majority of global traditional biomass is used. Such programmes should be supported by government policies to ensure uptake and create a market that facilitates household access to affordable and reliable equipment.

Since modern equipment uses biomass more efficiently, the unused biomass will be available for other uses. This requires special attention because these volumes could help meet the demand in other markets if economically viable. The main consideration is whether available biomass could actually be sustainably sourced. Policies should aim for the use of sustainably sourced quantities in other modern applications (*e.g.*, industrial process heat generation).

is growing but advanced technology has just begun. Asian regions do not have enough potential for energy crops to cover their burgeoning populations and food demands. However, there *is* a large latent potential for residue utilisation; but the appropriate technology plus efficient logistics must be developed in order to realise this potential. The "good practice" principles for introducing advanced-generation bioethanol plants into conventional ones currently in operation (*e.g.*, sugarcane, corn) should serve as guidelines to reduce investment costs through the utilisation of existing logistics for feedstock transportation.

- Seasonal supply fluctuation is a critical factor in realising the biomass supply potential. Seasonality of supply depends on the type of biomass and is determined by three factors: harvest season, storability and international trade.
  Harvest seasons of commodities involving fruits or seeds (*e.g.*, maize, soybeans) are sensitive to temperature and daylight. In low-latitude tropical areas, where seasonal differences in temperature and daylight are minimal, seasonality is determined rather by their rainy /dry seasons.
  Harvesting and processing residue have the same seasonality as primary commodities. Tertiary biomass residues (*e.g.*, municipal or wood waste) is not affected by seasonality. Within regions or countries, seasonal change affects biomass supply, but globally this seasonal supply gap could be mitigated through international trading (see Figure 24). However, considering biomass' lower energy density, long distance international trade of biomass feedstock is not feasible unless effi-

Figure 24: Harvesting season of major energy crops in different countries



cient transportation/storage systems are available (*e.g.*, maize, soybean, wheat). Thus, combinations of different domestic bioenergy feedstocks to reduce resource deficit period might be a worthwhile option.

- Storage is another important consideration in securing supply continuity. Cellulosic biomass (*e.g.*, wood fuel, wheat straw) have high storability while sugar or starch crops with higher water content (*e.g.*, sugarcane, cassava) are susceptible to rotting and thus not feasible for long-term storage. Cereal grain can be stored from months to years under appropriate drying and storage conditions. Biomass storage also requires storage space, which affects its final energy cost and thus need to be included in designing total systems.

This section described a number of strategies to increase global biomass supply between today and 2030. These strategies could also be applicable at the regional and national level depending on their needs and priorities.

8.3 Standards and certification of bioenergy

In view of the growing bioenergy demand estimates, the need for sustainable production and use of biomass has gained in importance amongst different stakeholders. This resulted in the preparation of related standards and certification schemes. Different environmental aspects of bioenergy were discussed in Section 7. Certification scheme standards address environmental issues but also other sustainability criteria, such as economic and societal aspects.

There are nation-wide schemes, as well as international initiatives. For example, the RED in the EU requires sustainability certification of liquid biofuels to be used in the transport sector and has outlined the related sustainability criteria. The UK, the Netherlands and Germany have developed biomass certification schemes (Goh *et al*., 2013b). In the US, liquid biofuels need to meet the minimum GHG emission standards. Many other initiatives worldwide are discussed in a study by van Dam, Junginger and Faaij (2010).

There a number of international initiatives. FAO-supported Global Bioenergy Partnership (GBEP) (2011) identified in total 24 sustainability indicators of bioenergy: eight indicators for each pillar of sustainability: environmental, societal and economic. These indicators were selected in terms of their relevance, practicality and scientific basis. Their aim is to guide domestic-level bioenergy analyses and facilitate sustainable bioenergy development (GBEP, 2011). Following the agreement on these 24 indicators, a number of countries started developing projects to test their applicability for policy making. The Gamba and Toop report (2013) provides lessons learnt from projects discussed at the GBEP meeting in May 2013.

Another international initiative has been undertaken by the International Organization for Standardization (ISO) through the project committee ISO/PC 248 for the development of "Sustainability Criteria for Bioenergy" (ISO 13065). The aim of this standard is to prevent the harmful effects of bioenergy on the environment and society. The target date for publication of this standard is mid-2015 (Kline, 2013).

There are also voluntary global initiatives, such as the Roundtable on Sustainable Biomaterials (RSB), which brings many stakeholders including farmers, companies, NGOs, governments and inter-governmental agencies together for the sustainable production and processing of biomaterials. This initiative covers both biofuels (*i.e.*, liquid biofuels, biomass and biogas for power and heat generation) and biomaterials (*e.g.*, bio-chemicals). The aims of the initiative are: "1) to provide and promote global standards for sustainable production and conversion of biomass; 2) to ensure that users and producers have credible, practical and affordable certification; and 3) to support through standards the continuous improvement of bioenergy applications" (RSB, 2014).

Another important initiative is the International Sustainability and Carbon Certification System (ISCC), a government-financed certification system of sustainability and GHG emission savings of biomass.

In 2013, the United Nations Industrial Development Organization (UNIDO) prepared a set of guidelines to help developing countries mitigate the negative impacts of liquid biofuel projects on the environment and society (Franke *et al.,* 2013). This report identifies 11 indicators which could be used for rating projects. With regard to environmental impacts, GHG emissions, land and water use, and biodiversity-related indicators are covered.

In addition to certification schemes and standards addressing different stages of the bioenergy supply chain, there are many initiatives that focus specifically on feedstock sustainability. For example, the Forest Stewardship Council (FSC) and the Sustainable Forestry Initiative (SFI) are two examples of forestry certification and standards. The Sustainable Agricultural Network (SAN), Better Sugarcane Initiative, the Roundtable on Sustainable Palm Oil and the Roundtable on Responsible Soy are related to the agricultural sector. There are also initiatives addressing sustainability issues related to other resources such as water. The Alliance for Water Stewardship (AWS) aims to promote the socially and economically beneficial, as well as environmentally sustainable use of freshwater.

Certification and standards are indeed vital to ensure the sustainable supply and use of biomass. Implementing them for all forms of bioenergy and incorporating them (*e.g.*, life cycle GHG emissions savings) into renewable energy policies will also impact future bioenergy trade, which is estimated to account for 20-35% of the global biomass demand in 2030. According to Goh *et* *al.* (2013b), certification has so far had only a limited impact on trade, but market actors who participated in their questionnaire stressed that sustainability certification will potentially impact the developments in bioenergy trade and markets in the coming years.

As renewable policies develop over the coming years, sustainability criteria for bioenergy will be more comprehensively incorporated. This will require the production of commodities that fulfil such criteria. These commodities will either be locally produced or else, as countries rely more on international trade, imported. Trade routes will develop between countries that can produce bioenergy commodities complying with such criteria. As a result, countries will either need to develop and implement technologies to produce bioenergy commodities complying with certain sustainability criteria or else risk losing their share of the global market.

9 POLICY NEEDS TO SUSTAIN BIOENERGY GROWTH AND RAISE RENEWABLE ENERGY SHARES

Realising the biomass potentials according to REmap 2030 will require effective strategies and new policies from both the demand and supply sides. These policies need to be formulated, encompassing the uncertainties in demand, supply and cost related issues and considering the land and water resource needs, as well as the bioenergy life cycle's environmental impacts discussed in previous sections.

On the demand side, policies differ according to application and technology. For each area of biomass use, new policies to increase biomass demand are discussed below:

- The starting point for demand-side policy making is creating knowledge around resource availability, prioritising food security and understanding the realistic potential of the extent to which resources can be transformed into useful solid, liquid and gaseous bioenergy products.
- In the transport sector of most countries, there are already biofuel mandates for blending. If all REmap Options are implemented by 2030, the demand for advanced biofuels will reach 240 billion litres per year. Advanced biofuels from feedstocks grown sustainably on degraded/abandoned land or from residues also have much higher life cycle GHG emissions savings compared to the performance of conventional biofuels, especially when land use change emissions are considered.

  Mandates *per se* will not suffice to promote advanced biofuels at their current stage of development. Policies first need to address the RD&D phase of advanced biofuels. There are already a number of commercial cellulosic bioethanol plants, as well as bio-refineries in the demonstration stage for the production of biodiesel alternatives. Bagasse and corn residues are two options amongst many with great potential. Utilisation of unused bagasse and corn residue and volumes which are today inefficiently combusted/burned could be used for liquid biofuel generation. Policies are required that accelerate the deployment of biofuels based on GHG emissions savings criteria and supported by financial instruments aimed at accelerating advanced biofuel use and development.
- In a number of countries, such as Brazil, Germany and the UK, biomass power generation targets already exist. In some countries, co-firing is a priority; in others, CHP. Policies could target the deployment of a number of options, depending on country's power sector structure. Coal plants can be retrofitted for biomass combustion and co-firing with biomass can be promoted in countries (*e.g.*, China) where large coal capacities have recently been introduced. Biomass gasification for power generation is still at an early stage of development; technology-specific policies can help to accelerate its deployment.

  In some countries, biomass power is related to co-generation with heat. This has a prospect of high overall conversion efficiencies. As co-generation is often linked to industry, the sector faces special challenges to switch to renewable power. Policies for increased CHP use exist, but with few exceptions (*e.g.*, Denmark), most countries do not have renewable energy targets for the manufacturing industry (IRENA, 2014a). Given that more than 40% of the total biomass demand in REmap 2030 is for space, water and process heating and the potentials of other renewable energy technologies for heating is limited, new policies with ambitious targets are required to reach the ambitious level of biomass deployment foreseen by this study. Strategies to grow industrial CHP use and district heating are required to increase biomass-based heat in end-use sectors. Additional district heating capacity is particularly interesting for Central and Eastern European countries, as well as for Northern and

Western China where both the heating demand and the availability of biomass resources are high. Policies also need to target utilising the large potential of combusting biomass and waste in cement kilns for high temperature applications. Existing kilns can already combust different types of fuels; however, it is crucial to preclude additional air pollution from waste combustion[13].

- Next to fossil fuel substitution through modern biomass, substitution of traditional biomass use and energy access are the other important goals. Modern forms of biomass (*e.g.*, bioethanol, biogas) play a central role in realising this goal. In order to meet this objective with modern biomass, affordable and sustainable biomass, as well as efficient cooking equipment, are required. There are voluntary global approaches to tackle this challenge, such as the Global Alliance for Clean Cookstoves, and some countries are taking own initiatives. However, long-term commitments, further voluntary initiatives for the deployment of clean cook stoves and new policies that take into account a country's specific circumstances are required to realise the transition to modern energy access with renewable energy.

  As countries achieve the modern energy access goal, less traditional biomass will be used. These volumes would be available for use in other applications. Policies should ensure that the sustainable part of this biomass be used for alternative applications.
- There are a number of end-use applications where renewable energy potentials are limited according to REmap 2030. These include aviation and shipping, as well as high temperature applications in industry, such as iron making. There are a number of private sector initiatives to develop bio-kerosene, such as Boeing/Embraer/FAPEST/UNICAMP and Boeing/Etihad/Honeywell/Masdar/Safran. More initiatives and policies should be developed, as well as specific goals for these high-energy using applications.

  Although the assessment of biomass use as feedstock is beyond the scope of this study, its potentials are large, given the increasing demand for chemicals and polymers. The market already started growing (*e.g.*, bio-ethylene from sugar cane in Brazil, polylactic acid from corn in the US) with private sector initiatives. In addition to the use of biomass as fuel, policies should also address its potential as feedstock for bio-based materials production.
- According to the findings of this working paper, biomass will play a key role in doubling the global renewable energy share by 2030 and will also have a role to play across different applications. Given the increasing competition and limited availability of biomass resources, polices should ensure its optimal use and avoid any technology lock-in of unsustainable solutions. In that context, it is helpful to be cognizant of the long-term policy objectives beyond 2030, as optimal biomass use may differ for more ambitious targets.

On the supply side, policies need to address the different needs of the biomass supply chain. Before the final bioenergy commodity reaches the end-user, biomass goes through a series of processes. The first step is cultivation, harvesting and collection of energy crops and residues. Depending on biomass type, pre-treatment (*e.g.*, pelletisation, briquettisation or torrefaction) may also be required. The second step is the transformation of raw or pre-treated biomass into a useful bioenergy product after being pre-treated (*e.g.*, liquid biofuel). The bioenergy commodity is subsequently consumed by the end-user (*e.g.*, as motor fuel).

The aim is to develop and supply affordable bioenergy products which are converted to useful energy in the most efficient way with minimum losses along the supply chain. Ensuring the sustainability of biomass is another critical issue requiring attention.

As this study shows, many strategies are required for the sustainable sourcing of biomass, for securing its supply and for realising demand potentials. However, none of them are a panacea. Most of these strategies go beyond energy polices and include agricultural, resourcing and forestry policies. An integrated policy framework that accommodates the issues and challenges amongst different aspects of the biomass supply chain is needed; one that integrates energy, infrastructure, agriculture (*i.e.*, food, feed), resources, forestry, environment, food and technology, and innovation policies. Some of the key components of such an integrated policy framework are discussed below:

13 In this study, the additional costs which may be required for air pollution prevention measures are excluded.

- In view of increasing concerns about the sustainability of biomass, demand-side policies should promote the use of sustainable biomass feedstocks, such as agricultural and forestry residues. Defining and applying sustainability criteria and indicators (*e.g.*, life cycle emissions, soil quality, biodiversity, socio-economic factors) as promulgated by the GBEP and several other initiatives and organisations, and implementation of bioenergy standards and certifications are strategies to ensure sustainable biomass production.
- The strategies discussed earlier suggest a number of ways to increase biomass supply without increasing land expansion. For energy crops, agricultural and land use policies need to accelerate agricultural yield improvements, increase the sustainable use of marginal and abandoned land achieved through promoting cultivation of specific crops resistant to draught or specific soil types (*e.g.*, salt-affected), in considering sustainability concerns. Food-related policies can enhance technology development to reduce losses in the food supply chain and also promote diets involving products, the cultivation of which require less land.

  Land ownership creates country-specific challenges for bioenergy growth. In some countries, land is privately owned; in others, state-owned. Furthermore, in some developing countries, the land-ownership structure is often not formalised. Governments need to establish frameworks to promote bioenergy use, thereby encouraging private land owners to invest in bioenergy crops. In countries where land is state-owned, suitable land can be made available to grow the most resource-effective feedstocks and develop a bioenergy industry.

  For residues, the most important issues requiring attention from policy makers are the development of policies which can enable an efficient logistics system and their collection/recovery, in particular from forests, while maintaining sustainability. The case of Scandinavian countries represents a "best practice" model and experiences in technology/policies can also be tailored to the needs of Russia where most forest residue potentials are estimated.
- Bioenergy trade is also important. Its volume will grow immensely in the years to come. This growth will create an inviting business opportunity. However, governments would need to coordinate infrastructure development in view of sustainability needs. International cooperation can play an enabling role, also for international bioenergy trade.
- Conversion as well as trade of large volumes of biomass, could be more efficient with commoditisation of biomass. Related technologies should be developed and/or improved for biomass pretreatment.

Innovative polices for cost reductions and technological improvements in different steps of supply chain will help to improve biomass supply costs. A "level playing field" for bioenergy should be created through various finance instruments, in particular for applications where other renewable options do not provide an alternative and where bioenergy is currently not cost-effective.

This integrated policy framework addresses many areas of national policy action. However, the development of such a framework cannot be nationally limited. It is particularly important because biomass will become a *globally traded* energy commodity. International cooperation will be crucial to accommodate the various policy needs to accelerate biomass demand and supply between today and 2030.

Finally, this working paper is based on an assessment of a *single portfolio* of technologies for doubling the global renewable energy share, which relies mainly on biomass. However, as the case of REmap-E showed, different portfolios can take the global renewable energy share to a doubling. This is a favourable outcome, in particular given that each technology option has its own challenge in terms of deployment, cost and sustainability. Hence, renewable energy policies should promote the deployment of all different renewable energy technology options and ensure the deployment of the sustainable alternatives to conventional fuels.

10 NEXT STEPS

This working paper supports the REmap 2030 analysis aimed at providing further insights into the large biomass demand growth estimated for 2010-2030 and planning how this could be supplied in a sustainable and affordable manner.

Given that bioenergy is a cross-cutting topic in IRENA's Work Programme for 2014/15 and is addressed in many of its projects, a number of activities have been developed under IRENA's bioenergy framework for 2014/15, including the following:

- On the demand side, the first activity is improving REmap country and sector analyses to refine demand estimates. On the supply side, the bioenergy supply and cost analysis for REmap 2030 will be improved through the development of Geographic Information System (GIS)-based tools.
- The policy framework for enhanced renewable energy technology adoption and deployment in developing countries will be analysed focusing on options for modern biomass in Africa and advanced biofuels in Asia. In particular, the analysis will focus on the technology and cost assessments for advanced bioenergy deployment, including energy conversion options from biomass residues and wastes.
- For biomass use in a given area, country or region, a bioenergy technology selection concept will be developed for IRENA's "Project Navigator". This will provide a basis for making investment decisions about the most cost-effective and optimal use of limited biomass resources.
- The environmental, social, economic and other impacts of biomass on sustainability will be evaluated in specific areas or countries.
- In order to improve data quality at country level, collected data from REmap countries and other sources will be reviewed and harmonised with the aim of improving the existing bioenergy statistics.
- A number of biomass-specific technology briefs will be prepared with the aim of providing policy makers, investors and other stakeholders with the latest technology, cost and market information. These briefs will include biogas production and logistics, waste to energy, biogas for transportation, algae, biofuels for aviation and wood pellets for heating.

In addition to these activities, the findings of this working paper identify further areas to expand this framework. Given the fact more than half of the global renewable energy use in REmap 2030 is based on bioenergy, IRENA's bioenergy framework will be one of its key components to support governments achieve a sustainable transition to higher shares of renewable energy.

Quality assurance, standardisation and certification of bioenergy products will be crucial to ensure a stable growth of sustainable options. Harmonisation of biofuel standards and review/improvement of existing sustainability criteria of liquid biofuels are two critical issues where IRENA can play role to support governments.

Incorporating bioenergy life cycle and land use change emissions to REmap 2030 will be crucial to derive more meaningful policy advice about bioenergy's contribution to emission reduction goals. These will also be helpful when developing sustainability certification systems for bioenergy.

One of the reasons for land use change emissions is higher crop prices, which result in more land being used for agricultural purposes elsewhere. A better understanding of the relationship between bioenergy and food sector developments will be helpful. Next to market interactions and price volatility, ensuring access to energy, water and food services and concerns about their environmental impacts are other issues of concern. The challenges and knowledge gaps regarding the climate-energy-food-land-water nexus need a better understanding in order to inform policy makers optimally in designing their strategies.

The potential of bioenergy depends on its economic viability relative to fossil fuels. This requires a detailed assessment of its supply costs and prices. This working paper makes a first attempt to estimate the supply costs of biomass by type and region. However, the findings would need to be improved by using more extensive country cost data. In the framework of REmap 2030, such data are requested from countries, but consistency of the system boundaries and comparability of data collected will still require improvements. Collection of local data would also need to be supplemented with the assessment of biomass prices by accounting for the dynamic relationship between biomass prices and factors, such as food prices and demand, energy demand and competition amongst different forms of energy and biomass use.

Finally, the impacts of increased bioenergy use on economic activity (*e.g.*, international trade, GDP, jobs, energy security, infrastructure needs) require specific focus as more insight into the benefits and opportunities created by bioenergy on the economy will provide a more complete picture.

Each of these assessments require the analysis of complex interactions. Such assessments are often done by research institutes or academia by applying partial equilibrium or computable general equilibrium models, depending on the research purpose. IRENA will explore opportunities of collaboration with these partners under its bioenergy framework to create a platform for transferring this knowledge to governments and policy makers.

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LIST OF ABBREVIATIONS

AEZ	Global Agro-ecological Zone Assessment
AWS	Alliance for Water Stewardship
BtL	biomass-to-liquids
cap	capita
CH_4	methane
CHP	combined heat and power
CO_2	carbon dioxide
CSP	concentrated solar power
d	day
DDGS	dried distillers grains with solubles
dLUC	direct land use change
DME	dimethyl ether
EJ	exajoules
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FSC	Forest Stewardship Council
GBEP	Global Bioenergy Partnership
GDP	gross domestic product
GHG	greenhouse gas
GIS	geographic information system
GJ	gigajoule
GW_e	gigawatt-electric
GW_{th}	gigawatt-thermal
ha	hectare
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
iLUC	indirect land use change
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISCC	International Sustainability and Carbon Certification
ISO	International Organization for Standardization
kW_e	kilowatt-electric
l	liter
LHV	lower heating value
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LUC	land use change
m^3	cubic meters
MJ	megajoule
MSW	municipal solid waste
Mt	megatonne
MW_e	megawatt-electric
NGO	non-governmental organisation
OECD	Organisation for Economic Cooperation and Development
PCW	post-consumer waste
PJ	petajoules
PV	photovoltaic
R&D	research and development
RD&D	research, development and deployment
RED	renewable energy directive
RFS	renewable fuel standard

RSB	Roundtable on Sustainable Biomaterials
SAN	Sustainable Agriculture Network
SE4All	Sustainable Energy for All
SFI	Sustainable Forestry Initiative
t	tonne
TFEC	total final energy consumption
TWh	terawatt-hour
UAE	United Arab Emirates
UK	United Kingdom
UN	United Nations
UNIDO	United Nations Industrial Development Organization
US	United States
USD	US dollars
WBA	World Bioenergy Association

ANNEX A: AGRICULTURAL RESIDUES

Table 9: Annual crop production growth

	1961-2007 (%/yr)	1987-2007 (%/yr)	1997-2007 (%/yr)	2005/2007-2030 (%/yr)	2030-2050 (%/yr)
World	2.2	2.3	2.3	1.3	0.7
Developing countries	3.0	3.1	3.0	1.4	0.8
Developing countries, ex China and India	2.8	2.8	3.2	1.7	1.0
Sub-Saharan Africa	2.6	3.3	3.0	2.4	1.9
Latin America and the Caribbean	2.7	2.9	3.7	1.7	0.7
Near East / North Africa	2.9	2.5	2.4	1.4	0.9
South Asia	2.6	2.4	2.1	1.5	0.9
East Asia	3.4	3.6	3.2	1.1	0.3
Developed countries	0.8	0.4	0.5	0.8	0.3
countries with over 2,700 kcal/person/day in 2005/2007*	2.6	2.9	2.1	1.1	0.4

Source: FAO (2012a)

Note: 2,700 kcal/person/day is grouped as better-off countries which have smaller potential for production growth in FAO (2012a).

Table 10: Residue coefficient and recoverable fractions used for high supply estimates

	Harvesting residue coefficient (kg residue/ kg harvest)	Recovery factor (%)	Processing residue coefficient (kg residue / kg raw material)	Recovery factor (%)
Wheat	1.33	25	0.21	90
Rice	1.33	25	0.23	90
Barley	1.50	25	0.27	90
Maize	1.50	25	0.18	90
Rye	1.86	25	0.20	90
Oats	1.50	25	0.20	90
Millet	2.33	25	0.14	90
Sorghum	2.33	25	0.10	90
Cereals, other	1.50	25	0.25	90
Cassava	1.00	25	0.18	90
Potatoes	0.67	25	0.33	90
Sweet potatoes	0.82	25	0.28	90
Yams & other roots	0.67	25	0.18	90
Sugar cane	0.28	25	0.20	90
Sugar beet	0.00	25	0.25	90
Sugar & sweeteners	0.00	25	0.00	90
Pulses	2.33	25	0.00	90
Tree nuts	2.33	25	0.73	90
Soybeans	2.33	25	0.21	90
Groundnut	2.33	25	0.30	90
Sunflowers	0.00	25	0.30	90
Rapeseed	3.00	25	0.30	90
Cottonseed	13.29	25	0.07	90
Palm kernels	3.00	25	0.45	90
Vegetables	0.41	25	0.20	90
Fruit	2.03	25	0.20	90
Stimulants	2.33	25	0.00	90
Spices	3.00	25	0.00	90

Source: Smeets *et al.* (2004)

ANNEX B: POST-CONSUMER WASTE

Table 11: Municipal solid waste generation rate and share of waste treatment system

	MSW generation rate (tonnes/cap/yr)	Solid waste disposal system (%)	Incinerated (%)	Composted (%)	Other (%)
Eastern Asia	0.37	0.55	0.26	0.01	0.18
South Central Asia	0.21	0.74		0.05	0.21
South East Asia	0.27	0.59	0.09	0.05	0.27
Western Asia & Middle East	0.21	0.74		0.05	0.21
Eastern Africa	0.29	0.69			0.31
Middle Africa	0.29	0.69			0.31
Northern Africa	0.29	0.69			0.31
Southern Africa	0.29	0.69			0.31
Western Africa	0.29	0.69			0.31
Eastern Europe	0.38	0.9	0.04	0.01	0.02
Northern Europe	0.64	0.47	0.24	0.08	0.2
Southern Europe	0.52	0.85	0.05	0.05	0.05
Western Europe	0.56	0.47	0.22	0.15	0.15
Australia and New Zealand	0.69	0.85			0.15
Rest of Oceania	0.69	0.85			0.15
Caribbean	0.49	0.83	0.02		0.15
Central America	0.21	0.5			0.5
South America	0.26	0.54	0.01	0.003	0.46
North America	0.65	0.58	0.06	0.06	0.29

Source: IPCC (2006b)

Table 12: Composition of municipal solid waste

	Food waste (%)	Paper / cardboard (%)	Wood (%)	Textiles (%)	Rubber / leather (%)	Plastic (%)	Metal (%)	Glass (%)	Other (%)
Eastern Asia	26.2	18.8	3.5	3.5	1.0	14.3	2.7	3.1	7.4
South Central Asia	40.3	11.3	7.9	2.5	0.8	6.4	3.8	3.5	21.9
South East Asia	43.5	12.9	9.9	2.7	0.9	7.2	3.3	4.0	16.3
Western Asia & Middle East	41.1	18.0	9.8	2.9	0.6	6.3	1.3	2.2	5.4
Eastern Africa	53.9	7.7	7.0	1.7	1.1	5.5	1.8	2.3	11.6
Middle Africa	43.4	16.8	6.5	2.5		4.5	3.5	2.0	1.5
Northern Africa	51.1	16.5	2.0	2.5		4.5	3.5	2.0	1.5
Southern Africa	23.0	25.0	15.0						
Western Africa	40.4	9.8	4.4	1.0		3.0	1.0		
Eastern Europe	30.1	21.8	7.5	4.7	1.4	6.2	3.6	10.0	14.6
Northern Europe	23.8	30.6	10.0	2.0		13.0	7.0	8.0	
Southern Europe	36.9	17.0	10.6						
Western Europe	24.2	27.5	11.0						
Australia and New Zealand	36.0	30.0	24.0						
Rest of Oceania	67.5	6.0	2.5						
North America	33.9	23.2	6.2	3.9	1.4	8.5	4.6	6.5	9.8
Central America	43.8	13.7	13.5	2.6	1.8	6.7	2.6	3.7	12.3
South America	44.9	17.1	4.7	2.6	0.7	10.8	2.9	3.3	13.0
Caribbean	46.9	17.0	2.4	5.1	1.9	9.9	5.0	5.7	3.5

Source: IPCC (2006b)

Note: For post-consumer waste, we did not use number from this table, instead, refer to the estimate of Smeets and Faaij (2007). The region-specific values are calculated from national, and based on partly incomplete composition data. The percentages may therefore not add up to 100%. Some regions may not have data for some waste types-blanks in the table represent the missing data.

ANNEX C: ANIMAL WASTE

Table 13: Annual livestock production growth

	1961-2007 (%/yr)	1987-2007 (%/yr)	1997-2007 (%/yr)	2005/2007-2030 (%/yr)
World	2.2	2.0	2.0	1.4
Developing countries	4.3	4.5	3.4	2.0
Sub-Saharan Africa	2.5	2.8	3.3	2.7
Latin America and the Caribbean	3.2	3.8	3.8	1.6
Near East / North Africa	3.3	3.3	3.0	2.2
South Asia	3.7	3.6	3.2	2.7
East Asia	6.5	5.9	3.4	1.8
Developed countries	1.0	-0.1	0.6	0.6
44 countries with over 2700 kcal/person/day in 2005/2007	2.7	2.9	1.8	1.1

Source: FAO (2012a)

Note: 2,700 kcal/person/day is grouped as better-off countries which have smaller potential for production growth in FAO (2012b)

Table 14: Manure management system and collectability as energy source

Management system	Definition	Recoverable for fuel
Pasture/Range/Paddock	The manure from pasture and range grazing animals is allowed to lie as is, and is not managed.	No
Daily spread	Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion. N_2O emissions during storage and treatment are assumed to be zero. N_2O emissions from land application are covered under the Agricultural Soils category.	No
Solid storage	The storage of manure, typically for a period of several months, in unconfined piles or stacks. Manure is able to be stacked due to the presence of a sufficient amount of bedding material or loss of moisture by evaporation.	No (used for manure)
Dry lot	A paved or unpaved open confinement area without any significant vegetative cover where accumulating manure may be removed periodically. Dry lots are most typically found in dry climates but also are used in humid climates.	No (used for manure)
Liquid/Slurry	Manure is stored as excreted or with some minimal addition of water to facilitate handling and is stored in either tanks or earthen ponds.	Collectable
Uncovered anaerobic lagoon	Anaerobic lagoons are designed and operated to combine waste stabilisation and storage. Lagoon supernatant is usually used to remove manure from the associated confinement facilities to the lagoon. Anaerobic lagoons are designed with varying lengths of storage (up to a year or greater), depending on the climate region, the volatile solids loading rate, and other operational factors. The water from the lagoon may be recycled as flush water or used to irrigate and fertilise fields.	Collectable
Pit storage below animal confinements	Collection and storage of manure usually with little or no added water typically below a slatted floor in an enclosed animal confinement facility.	Collectable
Anaerobic digester	Anaerobic digesters are designed and operated for waste stabilisation by the microbial reduction of complex organic compounds to CH_4 and CO_2, which is captured and flared or used as a fuel.	Collectable
Burned for fuel or as waste	The dung is excreted on fields. The sun dried dung cakes are burned for fuel.	Collectable

Source: IPCC (2006b)

Table 15: Recoverable fraction of manure

	Buffalo (%)	Dairy cattle (%)	Other Cattle (%)	Goat (%)	Poultry (%)	Sheep (%)	Swine (%)
Africa	N/A	6	3	3	6	3	6
Asia	5	51	2	2	47	2	47
Eastern Europe	24	17.5	22.5	22.5	3	22.5	3
India	56	53	55	55	39	55	39
Middle East	42	18	17	17	14	17	14
Northern America	N/A	42	0.2	0.2	51.3	0.2	51.3
Oceania	N/A	17	0	0	54	0	54
South America	0	1	0	0	8	0	8
Western Europe	20	35.7	25.2	25.2	8.7	25.2	8.7

Source: IPCC (2006a)

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