CHAPTER 5

Biomass Supply and Trade Opportunities of Preprocessed Biomass for Power Generation

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Abstract

International trade of solid biomass is expected to increase significantly given the global distribution of biomass resources and anticipated expansion of bioenergy deployment in key global power markets. Given the unique characteristics of biomass, its long-distance trade requires optimized logistics to facilitate competitive delivery value chains. Preprocessing biomass via pelletizing, torrefaction, and hydrothermal carbonization potentially improves bioenergy supply economics as illustrated by two case studies in this chapter. The case studies presented in this chapter compare woody and herbaceous biomass value chains and demonstrate that it is feasible and desirable in current conditions to establish large-scale conversion plants close to mature electricity markets and source preprocessed biomass from the international market. In the short term, conventional pellets are expected to play an important role as the internationally traded solid biomass commodity and feedstock in biopower

Developing the Global Bioeconomy.
DOI: http://dx.doi.org/10.1016/B978-0-12-805165-8.00005-7

production. In the near future, torrefied pellets may become the dominant and preferred internationally traded solid biomass commodity as the technology is commercialized. Hydrothermal carbonization technology is also still under development, but has the potential to unlock additional feedstock from wet biomass streams. Successful deployment of these technologies is expected to improve bioenergy supply chains in terms of costs and greenhouse gas impacts. Local bioenergy markets are also expected to develop, and provide localized opportunities for local biomass production and use. Utilization of herbaceous biomass and agricultural residues for power production is a promising option, but its application in cofiring is yet to be proven on a wide commercial scale. The analysis of agricultural residue mobilization in South Africa demonstrates that preprocessing also plays a major role in improving biomass delivery costs and subsequent electricity generation costs in local markets.

5.1 INTRODUCTION

Global demand and trade of solid biomass have been growing rapidly over the past decade, especially in the power and heat sectors (Lamers et al., 2012; Sikkema et al., 2011; Cocchi et al., 2012). This demand is driven mainly by renewable energy targets and incentives (Goh et al., 2012; Lamers et al., 2012), as well as energy security and environmental objectives (Chum et al., 2011; Beekes and Cremers, 2012; Tarcon, 2011). It is anticipated that bioenergy use will grow considerably in the near future. The International Energy Agency (IEA) estimates that biomass will contribute about 71.5 EJ to total global energy supply (under a Current Policies Scenario) by 2035 (OECD/IEA, 2011) and biomass power contribution is expected to increase to about 18% by 2050 (under the Blue Map scenario) (OECD/IEA, 2010). European Commission assessments (EC, 2014a) also project further increases in biomass use in the heat and power sector as the European Union (EU) implements a transition to a low-carbon economy by 2050. Biomass-based electricity is expected to grow to between 336 and 520TWh by 2050 with installed capacities of between 39 and 66 GW in the same period in the EU alone (EC, 2014b).

5.1.1 Biomass Supply and Demand Centers

Key biomass power markets are currently centered around and likely to remain in Europe, North America, and East Asia as shown in Fig. 5.1. However, apart from North America, these regions have limited available biomass resources to meet current and projected future biomass demand. Major global biomass production regions are located in North America, Russia, Scandinavia, South America, and parts of Africa and Asia

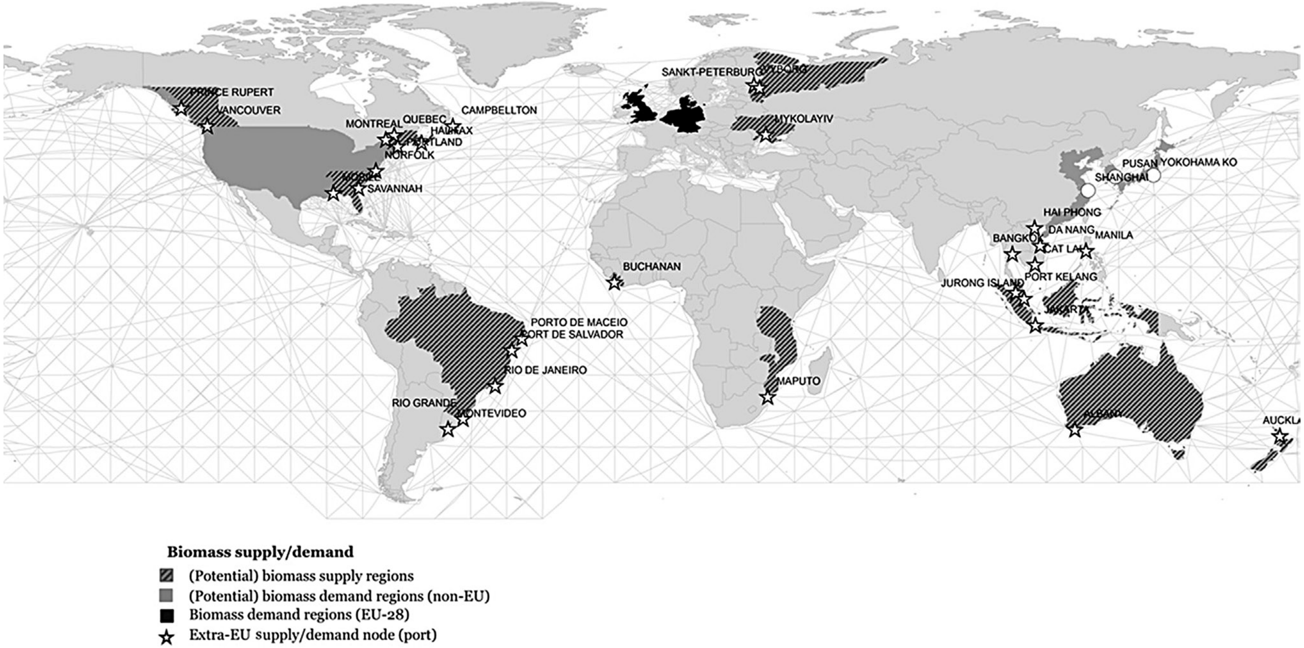

Figure 5.1 Global distribution of key solid biomass demand (solid, circle harbors) and supply regions (shaded, starred harbors) with respective harbors. *From Lamers, P., Hoefnagels, R., Junginger, M., Hamelinck, C., Faaij, A., 2015. Global solid biomass trade for energy by 2020: an assessment of potential import streams and supply costs to North-West Europe under different sustainability constraints. GCB Bioenerg. 7 (4), 618–634.*

(Goh et al., 2012; Smeets et al., 2007). Generally, countries with large biomass resource potentials have vast territories, and therefore the resources are often dispersed in a large territory and difficult to access, such as Russia and Canada.

Given the global spatial distribution of biomass and anticipated future expansion of bioenergy deployment in key global markets, substantial increases in international bioenergy trade are inevitable (Matzenberger et al., 2015). This transition to the large-scale commodification of solid biomass started a decade ago (Chum et al., 2011) and is still growing rapidly (Lamers et al., 2014). Already a burgeoning international solid biomass trade is evident, 18 Mt of solid biomass were traded in 2010 up from 3.5 Mt in 2000 (of which wood pellets trade increased from 0.5 to 6.6 Mt over the same period) (Lamers et al., 2012; Tustin, 2012). This large-scale international biomass trade is mainly linked to economic drivers and regional biomass availability (Faaij and Domac, 2006). The growth in biomass trade will assist to develop and maintain international bioenergy markets as well as develop currently underutilized bioenergy potentials in many regions of the world (Faaij et al., 2014).

To meet the growing global biomass demand and to mobilize these large-scale biomass supplies, large volumes of biomass feedstock need to be secured, and competitive feedstock value chains need to be developed and optimized, based on identification of appropriate combinations of feedstock and preprocessing technologies (Batidzirai et al., 2013).

There are two main types of solid biomass feedstocks of interest for international traded solid biomass—woody and herbaceous biomass. These two biomass types have distinct differences in their characteristics and value chains, which ultimately impact the competitiveness of delivered biomass (Batidzirai et al., 2014). Herbaceous biomass includes grasses such as switchgrass and miscanthus as well as agricultural residues such as wheat straw and corn stover. Its markets are much less mature and its international trade is currently limited due to various challenges associated with the large-scale logistics and conversion into energy or products. Compared to woody biomass, the lower heating value and lower bulk density of herbaceous biomass bales (100–140 $kg\,m^{-3}$) and corresponding pellets, result in much higher transportation costs per unit delivered energy than for woody biomass. Also, the higher sulfur and chlorine content can lead to fouling of equipment and require changes in process design; this increases conversion costs. Herbaceous biomass is also problematic as it ignites easily, posing storage difficulties. There is also limited experience in preprocessing herbaceous biomass. However, herbaceous biomass sourcing costs are typically lower than woody biomass (Batidzirai et al., 2013, 2014). It is therefore important to evaluate the implications of international supply of these two types of biomass feedstocks. Whereas woody biomass pellets are already mature and a "flowable commodity" in the power and heat market, there are uncertainties around the competitive supply of preprocessed herbaceous biomass.

This chapter assesses the opportunities for regional and international biomass supply and trade of preprocessed biomass primarily for power generation purposes. Based on two case studies, the chapter compares the performance of various biomass supply chain configurations, based on different preprocessing technologies, types of biomass feedstocks, and biopower markets.

5.2 INTERNATIONAL TRADE AND SUPPLY OPPORTUNITIES OF PROCESSED STABLE BIOMASS INTERMEDIATES FOR BIOPOWER MARKET

5.2.1 Development of Biopower Markets

As the major biomass market, solid biomass in the EU is mainly used for heating (~85%) and electricity generation (~15%). Over 90% of this biomass is domestically produced in the EU and is used mainly for household and other small-scale heating applications (EC, 2014b). The large-scale solid biomass requirements (such as for cofiring) are increasingly imported from outside the EU. There is a significant market for cofiring preprocessed biomass (predominantly woody biomass) with coal in power generation, especially in northern and western European countries. These markets are driven mainly by the availability of feed-in premiums or quotas for green electricity, and other government policies. The key biomass feedstock has been industrial wood pellets imported mainly from Canada, the United States, and Russia (Goh et al., 2012). Intra-EU solid biomass trade, for example, from the Baltic states to Sweden and Denmark or from Austria to Italy contributed about two-thirds of cross-border trade by 2010 (Lamers et al., 2012). Prospects for market growth in biomass cofiring power generation are positive, and over the past decade, there has been an increase in pellet demand for cofiring in Belgium, the Netherlands, the United Kingdom, and Denmark, mainly driven by government policies. Significant growth is projected in solid biomass-based cofiring in the EU, more than doubling from about 74TWh in 2012 to 157TWh in 2020. According to EC (2014b), wood pellet imports to the EU are set to increase from 4.3 million t[1] in 2013 to 15–30 million t by 2020 to meet the expected demand for large-scale cofiring and combined heat and power (CHP) applications. Thus the EU is likely to remain the key driver of solid biomass trade specifically targeting the power sector.

East Asia, particularly Japan and South Korea, have also set renewable energy targets, which have stimulated cofiring of wood pellets in large coal power plants. Both countries are expected to experience strong growth in consumption in the next few years (Goh et al., 2012).

5.2.2 The Importance of Preprocessing

International trade of biomass over long distances is costly and can render biomass uncompetitive (Rentizelas et al., 2009; Hamelinck et al., 2005). This is because biomass has unique characteristics that necessitate preprocessing before it can be efficiently stored, transported, or used in various applications currently designed for fossil fuels (Tumuluru et al., 2012). Biomass is often available seasonally in small quantities scattered over many locations (Junginger et al., 2001; Deng et al., 2009). It is highly heterogeneous, which results in wide variations in combustion properties (Tapasvi et al., 2012). It usually has a high moisture content and consequently low heating value (Ben and Ragauskas, 2012). It is hydrophilic and biodegradable, posing storage problems (Tumuluru et al., 2012). Its combustion efficiency is lower than fossil fuels (Crocker and Andrews, 2010), which decreases the capacity of given systems. Biomass therefore often needs to be pretreated to improve its characteristics and associated handling (Rentizelas et al., 2009; Luo, 2011). However, preprocessing costs are significant and can render biomass uneconomical (EverGreen, 2009).

Biomass preprocessing includes baling or bundling (for agricultural and forestry residues), sizing (into chips or flour, for example), drying, torrefying, and densification into conventional pellets (CPs), briquettes, or torrefied pellets (TOPs). Hydrothermal carbonization (HTC) is also another preprocessing technology especially suitable for conditioning wet biomass streams. Hence, an important logistical question is to identify combination(s) of preprocessing options which can best upgrade biomass properties for optimal downstream logistics.

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[1] 1 metric tonne = 1000 kg = 1 Megagram (Mg).

5.2.2.1 Pelleting and Torrefaction

Pelleting biomass is currently the most important preprocessing approach for solid biomass, and wood pellets are currently the most important internationally traded biomass commodity (Lamers et al., 2012). The technology is mature and markets have developed in the power and heat sectors (Chum et al., 2011; Goh et al., 2012). Although it is yet to be proven on a commercial scale, torrefied pellets appear to have more advantages compared to CPs (Batidzirai et al., 2013). TOPs have a higher energy density (12–20 GJ_{LHV} m^{-3} compared to 7–10.4 GJ_{LHV} m^{-3} for conventional pellets) (Bagramov, 2010; Tumuluru et al., 2012; Kiel et al., 2012; Melin, 2011; Boyd et al., 2011) and this has potential to lower logistic costs.

Torrefaction (combined with pelletization) is a promising biomass preprocessing technology which has potential to produce a homogeneous biomass carrier with improved energy density and combustion characteristics, and whose properties closely match those of low-grade coal (Agar and Wihersaari, 2012; Li et al., 2012; Phanphanich and Mani, 2011). This would allow cofiring with higher percentages of biomass than is currently possible with conventional pellets (Beekes and Cremers, 2012; Meerman et al., 2012).

Given the global distribution of biomass production regions and key markets (Chum et al., 2011), preprocessing biomass plays an important role in improving biomass supply chain economics, and enables biomass to be delivered to the market cost-effectively with lower downstream investments (Uslu et al., 2008; Miao et al., 2012; Bergman, 2005). This would also allow access to remote biomass resources and improve the potential of biomass as a renewable energy resource.

5.2.2.2 Hydrothermal Carbonization

Hydrothermal carbonization (HTC) enables the conversion of especially wet biomasses into a solid fuel—so-called HTC coal (Sevilla, 2009; Libra et al., 2011; Dinjus et al., 2011; Funke and Ziegler, 2010). Beside biomass types with established applications in combustion or biogas production, there is potential for harnessing wet and hardly biodegradable biomass like food industry waste, municipal biowaste, digestates from biogas production processes, and sewage sludge (Escala et al., 2013). The utilization of these wet biomass resources is of major importance for the expansion of bioenergy feedstock base (Wilén et al., 2013; Statistisches Bundesamt, 2013). Other possibilities of thermo-chemical conversion of wet biomass are very limited because of the energy demand for drying. Because the reaction medium is water, wet biomass does not need to be dried. During HTC, the biomass or waste is converted with water as reaction agent at 180–250°C and 10–40 bar. Currently, typical HTC process operational times are between 1.5 and 6 hours.

In comparison with the input wet biomass, there are improvements in major properties of HTC coal such as heating value, carbon content, volatile mater, homogeneity, and defined structure. A biomass quality close to lignite coal can be reached (Ramke et al., 2010; Kietzmann et al., 2013; Clemens et al., 2012; DBFZ, 2013). Different energy applications are possible, especially as a coal substitute (Tremel et al., 2012; Gunarathne et al., 2014). The dewatering of this coal can reach a high dry matter content and that is why energy demand for coal drying is low. In particular because of this, HTC can be the energy-efficient alternative in many cases.

Many different HTC plant concepts have been developed, mostly in Germany but also in other countries (Hitzl et al., 2014; Artec, 2015; AVA-CO2, 2015; CS CarbonsSolutions, 2015; SunCoal, 2015; TerraNova, 2015). These plants are for demonstration purposes (Klemm et al., 2015), and none is currently in commercial operation. Thus, the development of an HTC coal market is still in its early stages.

5.2.3 Location of Final Conversion Facility

The strategic location of the final biomass conversion plant (as well as preprocessing facilities) is an important consideration for the competitive utilization of biomass. Given the capital-intensive nature of conversion plants, effective use should be made of economies of scale and centralized/decentralized processing where appropriate. Typically, preprocessing can be cost-effectively achieved in decentralized small-scale operations where facilities are located near the plantation or source of biomass, which helps to reduce logistic capacity very early in the chain. However, there is a trade-off between the size of the preprocessing plant and raw biomass transportation costs, which are also affected by the availability and distribution of sufficient feedstock in the vicinity of the processing plant. Batidzirai et al. (2014) established that at current technology costs, the optimal plant size for pellet plants is around 250,000 t year^{-1}. However the trade-off between transport costs of biomass supply and unit scaling effects has to be calculated for every plant individually since multiple parameters can be decisive for this optimization. In Schipfer et al. (2015) the combination of feedstock yield, its availability, and accessibility are outlined to be critical as well as earlier inflexion points for CPs than for TOPs.

Where local economics are attractive, final conversion in the biomass production regions (early in the supply chain) can be beneficial and cost-effective. However, establishing large-scale conversion facilities in major biomass feedstock production regions (typically in developing countries) involves significant technological and commercial risk, and capital costs may be higher (Batidzirai et al., 2014). According to IRENA (2012), financiers consider biomass power projects to be risky, as existing projects in developing countries have failed to meet expected performance. Economies of scale play an important role in driving down production costs and such large-scale conversion facilities are more suited for well-developed bioenergy markets where policy measures favor their establishment. For some regions, biobased power generation may not be competitive against established technologies such as hydro. An important consideration for locating the final conversion plants is the availability of well-developed infrastructure in the importing country, such as deep harbors with storage capacity to handle large volumes of biomass imports from different countries.

In the short to medium term, western Europe is likely to remain the main market for internationally traded solid biomass and ideal location for establishing biobased power generation facilities given the regional drive to increase the share of renewables to 20% by 2020 (EC, 2014b). To enable the transition to a low-carbon economy, significant investment in renewable energy electricity is inevitable. Given the projected contribution of biomass to future electricity mix in the EU, growth in solid biomass imports from the international market is a key strategy for many EU countries. Major utilities in the region, such as RWE-Essent, Vattenfall, Dong Energy, Drax, GDF Suez, and Eon, are already actively pursuing biomass cofiring strategies and importing millions of tonnes of solid biomass every year (Verhoest and Ryckmans, 2014). Stakeholder consultations in the EU have shown that trade is essential for reliability of supply of biomass and offer flexibility as sourcing biomass from different regions reduces the feedstock supply risks (EC, 2014b). The case studies presented below demonstrate that it is feasible and desirable at current conditions to establish final conversion plants close to the electricity market and source biomass feedstock from the international market.

5.2.4 Energy Crop-Based Supply Chains: Mozambique Case Study

To demonstrate the competitiveness of international supply of preprocessed biomass for cofiring in the power sector, we present a case study that compares the supply of conventional pellets (CPs) and torrefied pellets (TOPs) from southeast Africa and subsequently use in cofired power plants in western Europe, taking Rotterdam as a location of the final conversion facility. First, we compare the economic performance of TOPs and CPs based on different feedstocks (eucalyptus and switchgrass). Second, the study evaluates the impact of supplying biomass from different regions (productive and marginal land quality in Mozambique, Nampula, and Gaza, respectively). Third, we compare dedicated biomass-fired power generation (BtP[2] or TtP) and cofiring biomass with coal in a coal-biomass to power (CBtP or CTtP) plants. Lastly, the study compares the competitiveness of supplying different markets (close to biomass production sites in southern Africa or in major international bioenergy markets in the Netherlands). This comparison is performed for both the short term (current) and long term (2030). Costs are given in $US\$_{2010}$.

In this case study, biomass feedstock (eucalyptus and switchgrass) is produced in Mozambique, and undergoes preprocessing before shipment to Europe for power production. A comparison is also made for the local conversion of biomass in Mozambique. Key assumptions include interest rates of 8% (international), 13% for Mozambique (Trading Economics, 2014) and exchange rate of 1.30 US$/€, 30 Mozambican Meticais/US$. Further assumptions and input data are available in Batidzirai et al. (2014).

Figs. 5.2 and 5.3 show the economic performance of different supply chains considered in this case study, for the short and long term, respectively.

It is apparent that feedstock, truck transport, and conversion costs are dominant and together constitute up to 90% of final, delivered electricity costs. Conversion is the most important cost element and represents up to 56% of overall power supply costs. Preprocessing costs are also important, contributing up to 20% to the final electricity costs. Also, lower-cost electricity is produced from chains based on the more productive Nampula region (\$81–107 GJ^{-1}) compared to Gaza (\$85–107 GJ^{-1}). It is also clear that electricity from supply chains based on switchgrass is produced at lower cost than from eucalyptus for both the short term and long term. This is mainly attributed to the lower production costs of switchgrass. In the short term, biomass from switchgrass (both CPs and TOPs) is delivered at \$5.1–7.3 GJ^{-1} compared to biomass from eucalyptus (\$5.4–7.5 GJ^{-1}).

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[2] Final conversion is denoted by XtP, where P is power, X is either coal (C), biomass/pellets (B), TOPs (T) or combinations such as CB for cofiring.

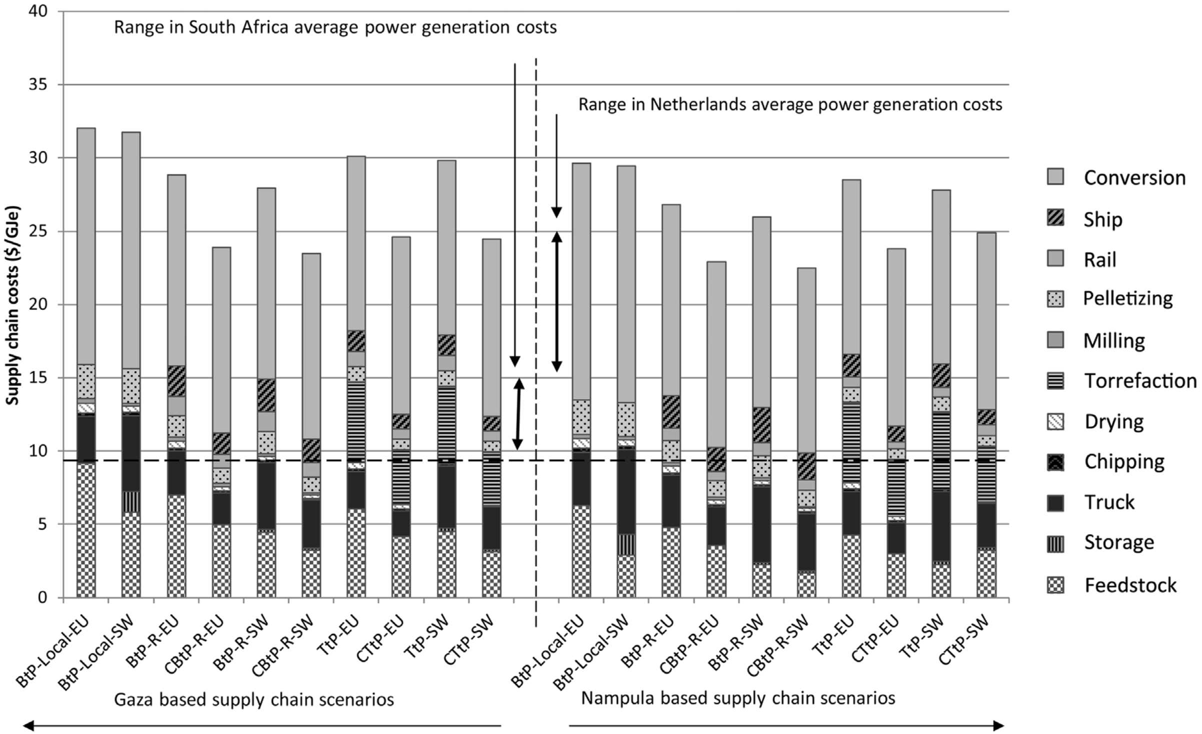

Figure 5.2 Comparison of short-term biomass-based electricity production costs against current average national electricity production costs in South Africa and Netherlands.

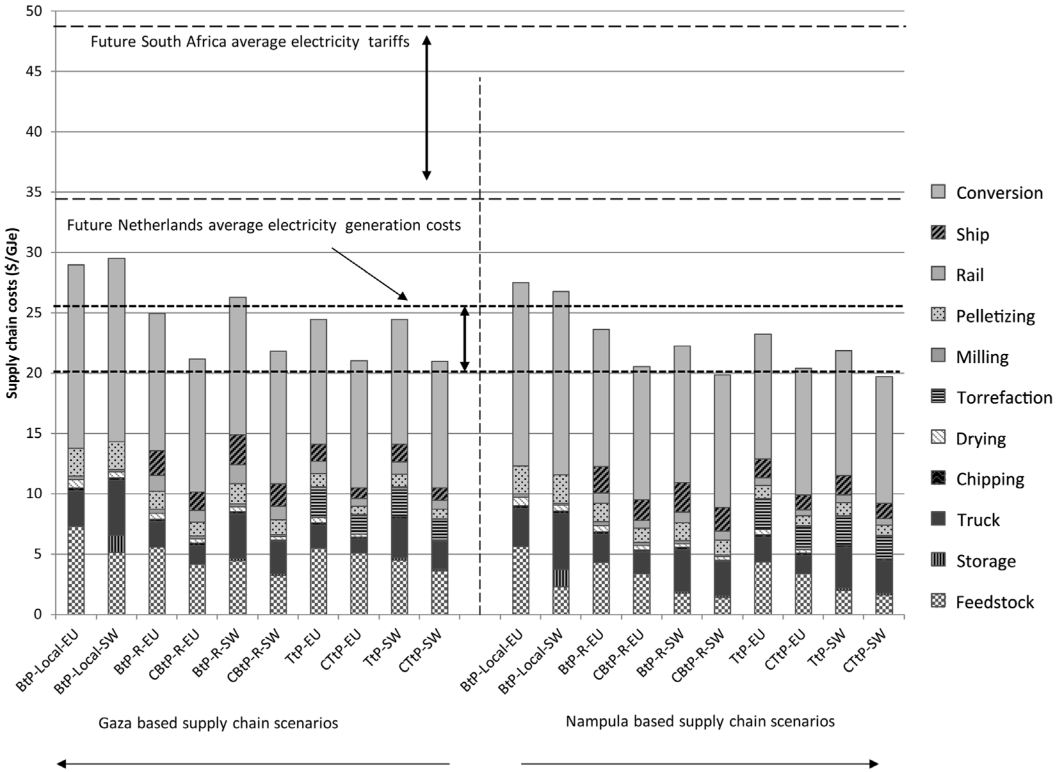

Figure 5.3 Comparison of long-term biomass-based electricity production costs against projected national electricity production costs in the Netherlands and electricity tariffs in South Africa.

In the long term, switchgrass is delivered at \$4.3–5.8 GJ^{-1}, while eucalyptus is delivered at \$4.8–5.8 GJ^{-1}. Due to the low bulk density of switchgrass bales (100–140 kg m^{-3}), truck transportation from the field costs for switchgrass are much higher (\$1.7–2.0 GJ^{-1}) than for eucalyptus (\$1.1–1.4 GJ^{-1}), as logs have a bulk density of around 460 kg m^{-3}. In addition, switchgrass incurs high storage costs at the farm, as it is more susceptible to moisture increases and dry matter losses if stored in the open.

Currently, torrefied pellets are delivered in Rotterdam at higher cost (\$6.5–7.5 GJ^{-1}) than conventional pellets (\$5.1–6.2 GJ^{-1}). In the long term, torrefied pellets are expected to decline in cost (\$4.7–5.8 GJ^{-1}) and converge with conventional pellets (\$4.3–5.3 GJ^{-1}). These differences are due to lower efficiency of torrefaction chains and the higher torrefaction production costs compared to CPs. Torrefaction is an additional costly step (at least \$2 GJ^{-1} in the short term) compared to conventional pelletizing (about \$0.5 GJ^{-1}). However, due to improved logistics and lower conversion investment requirements, electricity production costs from TOPs are lower than from CPs, especially in the long term. Final power production costs are influenced by the properties of the feedstock as raw biomass conversion requires additional investment and results in decreased plant capacity and efficiency. These additional costs are lower for TOPs than for CPs as TOPs have characteristics that are closer to coal. However, the additional costs of torrefying biomass do not offset the benefits of lower conversion costs as conventional pellet-based chains deliver lower cost electricity (\$81–115 GJ^{-1}) than the TOPs (\$86–108 GJ^{-1}), albeit marginally.

It is also apparent from these scenarios that cofiring biomass with coal results in lower electricity production costs (\$81.0–89.7 MWh^{-1}), compared to biomass-only fired power plants (\$93.5–108.4 MWh^{-1}), since new capital investment for retrofitting cofired power plants is much lower than when establishing greenfield power plants. Cofiring scenarios (CXtP)—based on switchgrass from productive land—have the best economics for both the short and long term (\$22.5 GJ^{-1} or \$81.0 MWh^{-1}). Although delivered biomass feedstock costs are much lower in Mozambique due to avoided international logistics, power production in Mozambique (\$106–115 MWh^{-1}) is more costly than in Rotterdam (\$81–108.4 MWh^{-1}). This is due to the relatively higher investment costs of smaller-scale plants (assumed for Mozambique) and higher interests rates (13%) compared to the Netherlands (8%). In addition, power production is not competitive in the Mozambican market, as these costs are much higher than the average levelized electricity generation costs for southern Africa (\$32–54 MWh^{-1}) (IEA, 2010).

For comparison, the average electricity tariffs in southern Africa are about \$70 MWh^{-1} (NERSA (http://www.nersa.org.za)).

For the Netherlands, power production costs (\$81–108.4 MWh^{-1}) are competitive against the average power generation costs in the Netherlands (\$55–91 MWh^{-1}) (IEA, 2010); and much lower compared to average electricity tariffs in Netherlands (estimated to be \$198 MWh^{-1}) (Europe Energy Portal, 2013).

Long-term power production costs across all scenarios are estimated to be 6–21% lower at \$71–106 MWh^{-1} than in the short term. This is attributed to technological learning and scaling up of facilities across the bioenergy value chain, especially in critical components of feedstock production, preprocessing, and conversion. Conversion into final products dominates overall costs representing 42–57% of power production costs across all scenarios. Although feedstock costs are important, they account for a much lower proportion of total costs (7–25% of overall costs). Regional cost differences across the scenarios are marginal but evident; long-term power production in Gaza scenarios range from \$76 MWh^{-1} to \$106 MWh^{-1}, while in Nampula costs are \$70–99 MWh^{-1}. Power production in Mozambique (\$96–106 MWh^{-1}) is more costly than in Rotterdam (\$71–95 MWh^{-1}). As shown in Fig. 5.3, the lowest cost power pathway (\$19.7 GJ^{-1} or \$71 MWh^{-1}) is associated with the cofiring switchgrass TOPs in Rotterdam. For the Netherlands, these future power production costs are competitive compared to future expected electricity generation costs (\$70–90 MWh^{-1}) (van den Broek et al., 2011). However, future electricity tariffs in southern Africa[3] are expected to be much higher at \$120–173 MWh^{-1} (DOE, 2011)—but these tariffs already include transmission, supply charges, and taxes.

5.3 LOCAL/REGIONAL TRADE AND SUPPLY OPPORTUNITIES OF RAW BIOMASS FOR BIOENERGY MARKET

Local and regional markets for biomass offer opportunities for developing the bioenergy sector in different parts of the world. Several countries

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[3] We compare the power production costs in Mozambique with southern African tariffs (since power supplies in the region countries are intricately linked under the southern African power pool [SAPP]). Mozambique both exports and imports electricity from SAPP, its 2075 MW hydro plant supplies mainly South Africa while 850 MW are imported from South Africa to supply the southern region 136. In addition, future electricity prices are available for southern Africa based on South African projections and not for Mozambique.

have established small- to large-scale biomass-based power generation facilities, for example, Sweden, Germany, and the United Kingdom. Local and regional biomass markets are important especially for the utilization of biomass resources in regions without adequate infrastructure (large-scale preprocessing and logistical) for supplying large volumes of biomass to international markets. Forestry and agricultural residues are especially an important resource which can be sustainably harnessed and utilized locally with minimal preprocessing such as bundling and baling. Regional trade of such biomass feedstock allows small-scale biomass producers to add value to biomass and get additional income through diversification of their operations.

Several countries such as Denmark, the United Kingdom, Spain, Sweden, China, and India have developed large-scale crop residue to energy facilities (Peidong et al., 2009; Purohit, 2009; Urošević and Gvozdenac-Urošević, 2012). Key crop residues include corn stover, wheat straw, rice straw and husks, and bagasse (Chum et al., 2011; Perlack et al., 2005; Kline et al., 2008). Globally, the use of sugarcane bagasse for power and heat production is the most common and mature energy application of crop residues for those countries with large sugarcane industries (REN21, 2011). There is less experience in energy conversion for other crop residues, but interest is significant in using corn stover for advanced biofuels, especially in the United States (Tyndall et al., 2011; Chum et al., 2011; USDOE, 2012). In Europe, Denmark pioneered large-scale power generation using straw and has commercialized the technology since 1989 (Skøtt, 2011; Kretschmer et al., 2012).

According to IPCC biomass energy deployment scenarios (Chum et al., 2011), agricultural residues are likely to play an important role in future energy systems contributing between 15 and 70 EJ to the long-term global energy supply. Agricultural residues represent an important energy resource for countries with a large agricultural production base (WBGU, 2009; Chum et al., 2011; Dornburg et al., 2010). Although there is a large untapped potential for agricultural residues globally, there is little experience in their application for large-scale power production. Also due to the diversity of agricultural residues and differences in their chemical and physical characteristics, their utilization requires modifications in value chain and at the final conversion plant. Thus their local and regional application could allow the resource to benefit from technological learning and eventual deployment into the international market. We discuss below a case study conducted for South Africa to establish the feasibility of mobilizing agricultural residues for large-scale energy applications.

5.3.1 Agricultural Residues-Based Supply Chains: South Africa Case Study

This case study assesses the feasibility of mobilizing corn and wheat residues for large-scale power production in South Africa by establishing sustainable residue removal rates at the farm level and electricity production costs based on different biomass production regions at Camden (1600 MWe out), a depreciated power plant in Mpumalanga province. A key outcome of this case study was to estimate the national crop residue harvesting potential for bioenergy use, while maintaining soil productivity and avoiding displacement of competing residue uses. At every stage of the agricultural residues value chain, the study identified measures that would improve the performance of the overall crop residue supply chain and enhance the competitiveness of biomass- compared to fossil-based power generation. This included a comparison of applying different preprocessing technologies such as pelleting and torrefaction.

Currently, the sustainable bioenergy potential from corn and wheat residues is estimated to be about 6 million t (104 PJ), out of an annual gross crop residue potential of about 14.4 million t. This sustainable potential included 5.1 million t of corn stover and 600,000 t of wheat straw. About 4.2 million t of corn stover would be required for soil erosion control while 9.3 million t would be required for soil organic carbon (SOC) maintenance. Also, about 260,000 t of corn stover are required to meet cattle feed demand. Similarly, 870,000 t and 100,000 t of wheat straw are required to maintain SOC and prevent erosion, respectively. About 70,000 t of wheat straw are utilized as livestock bedding.

There is potential to increase the amount of crop residues to 238 PJ through measures such as no till cultivation and adopting better cropping systems. These estimates were based on minimum residue requirements of 2 t ha^{-1} for soil erosion control and additional residue amounts to maintain 2% SOC level.

5.3.1.1 Corn and Wheat Residue Costs at the Farm Gate

Overall the cost of collecting, baling, and storing corn stover at the farm is estimated to be about \$1.5 GJ^{-1}. Compensation for the farmers for lost nutrients dominates the cost of corn stover at the farm accounting for 58% of total costs (or \$0.87 GJ^{-1}). Baling is also a very important cost element representing 29% of the total costs. A 10% farmer profit margin on direct costs is allowed in the estimated direct costs and this also represents about 4% of the total costs. Wheat straw at a typical dryland farm costs about \$1.5 GJ^{-1} assuming a yield of 2 t ha^{-1}. Baling dominates the overall wheat straw costs at 43% (or \$0.66 GJ^{-1}) and farmer nutrient compensation accounts for 41%.

Overall, about 7% of crop residues (6.8 PJ) are available at costs below \$1 GJ^{-1} at the farm gate while 34% of the residues are available at costs below \$1.2 GJ^{-1}. About 96% of the residues are available at cost below \$1.5 GJ^{-1}.

5.3.1.2 Crop Residue Costs Delivered at the Conversion Plant

Fig. 5.4 shows the combined cost supply curve for the corn and wheat residues at the factory gate delivered to the conversion plant for the various scenarios considered in the case study. These costs include crop residue harvesting, collection, baling, and storage at the farm, transport to a local distribution point as well as long distance transport by truck to the conversion plant. We included a base case scenario where bales are transported by truck from the farms to the conversion plant and improved scenarios where further preprocessing is undertaken close to the farms and rail transport is used for long-distance transport to the power plant.

On average, crop residues in South Africa are delivered at the power plant at a cost of about \$7.1 GJ^{-1}—this is a weighted average cost for

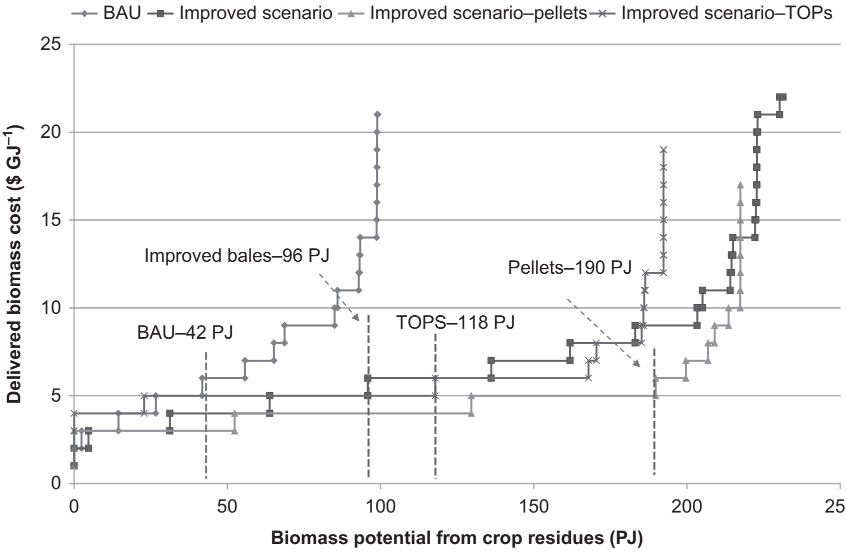

Figure 5.4 Cost–supply curve for corn and wheat residues delivered to the conversion plant in central South Africa. The dashed vertical lines indicate available crop residues below \$5 GJ^{-1} delivery costs.

biomass from all regions. About 11% of the biomass is delivered at the conversion plant at less than \$3 GJ^{-1}, whereas about 36% can be delivered at less than \$5 GJ^{-1}. About 82% is delivered at less than \$10 GJ^{-1} and only 5% of the biomass is delivered above \$15 GJ^{-1}.

At current conditions, the supply chain that delivers conventional pellets has the lowest cost biomass (\$4.1 GJ^{-1}) followed by TOPs (\$5.7 GJ^{-1}). As TOPs processing costs decline in the future, average delivered costs of TOPs are also expected to decrease to \$4.7 GJ^{-1}. The base case (with raw biomass bales) shows the highest delivered cost of \$6.9 GJ^{-1} compared to the improved case supply chain (\$6.6 GJ^{-1}). This is because train transport becomes more efficient with larger volumes of biomass (and longer distances traveled) associated with the improved case (raw bales).

Despite the additional preprocessing costs of biomass (\$13.3 t^{-1} for CPs and \$52.4 t^{-1} for TOPs), the pellet chain and TOPs chain deliver lower-cost biomass to the conversion plant as shown in Fig. 5.4. About 24% and 14% of pellets and raw bales, respectively, cost below \$3 GJ^{-1} at the factory gate. For TOPs, 12% is delivered at costs below \$3 GJ^{-1}. About 87% of CPs and TOPs are delivered at \$5 GJ^{-1}, compared to 42% of raw bales. About 92% of conventional pellet-based biomass is delivered at the factory gate at costs below \$6 GJ^{-1}, while corresponding values for TOPs and raw bales are 89% and 60%, respectively. Nearly all CP- and TOP-based biomass (99%) is delivered below \$10 GJ^{-1}.

In absolute terms, only 42 PJ is delivered in the base case scenario below \$5 GJ^{-1} compared to 96 PJ (for raw biomass-improved scenario), 190 PJ (CPs) and 168 PJ (TOPs). Therefore, considering cofiring 30% biomass at Camden (1600 MWe out) requires 36 PJ biomass feedstock—at current conditions, there is adequate biomass below \$5 GJ^{-1} to meet this demand. For this particular power plant, supplies can therefore be built up over time with changing demand and improvements in supply.

5.4 CONCLUSIONS

Global bioenergy markets have been growing and key bioenergy feedstocks such as wood pellets are becoming global commodities that are traded on the international markets. The EU is likely to remain the center for bioenergy markets, key importer and driver of solid biomass trade especially for the power and heat applications, given the projected growth in biopower and challenges to meet demand with local biomass production in the region. North America, eastern Europe, and Russia are already supplying woody biomass to the EU, and in the future, Brazil and coastal Africa are likely to be the major suppliers of biomass feedstock as well. Local markets in these producing regions will also become important as bioenergy technologies mature.

Trade will remain an important enabler for developing the bioenergy sector by facilitating the production and supply across regions. Optimized logistics based on an efficient transport system and preprocessed biomass feedstock are key to the delivery of competitive biomass. From the results of the case studies, in the short term, conventional pellets are still expected to play an important role as the internationally traded solid biomass commodity and can also in the longer term be cost-effectively used as a feedstock in biopower production. In the near future, torrefied pellets may become the dominant and preferred internationally traded solid biomass commodity as the technology is commercialized. This should result in improvements in bioenergy supply chains both in terms of costs and greenhouse gas impacts. Therefore, in the short term, it would be more cost-effective to ship densified solid biomass from different regions of the world where low-cost biomass is available to the major bioenergy markets for final large-scale conversion, given the advantages of economies of scale offered by these markets and risks of market immaturity for developing large-scale power production from biomass in the major biomass-producing regions. Local markets are expected to develop also, and provide localized opportunities for local biomass producers and conversion plants. Utilization of agricultural residues for power production is a promising option, but its application in cofiring configuration is yet to be proven on a wide commercial scale. More investigations are required to establish the technical feasibility and economics of large-scale mobilization of agricultural residues for such bioenergy applications.

Given the distribution of biomass production regions and markets as well as the nature of raw biomass, preprocessing biomass plays an important role in improving biomass supply chain economics. Logistics and transport are key cost components in the biomass value chain and major investments in infrastructure and capacity are required to realize large-scale biomass supplies. Establishing this infrastructure is gradual and takes time, which also applies to the mobilization of large volumes of biomass. These two aspects are interrelated and region-specific due to the unique settings for biomass feedstock production and local infrastructure. Given this context, there is a need for examining the entire biomass supply value chain so as to understand the many elements involved in bioenergy mobilization.

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