MOBILISATION OF AGRICULTURAL RESIDUES FOR BIOENERGY AND HIGHER VALUE BIO-PRODUCTS: RESOURCES, BARRIERS AND SUSTAINABILITY

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Mobilisation of agricultural residues for bioenergy and higher value bio-products: Resources, barriers and sustainability

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1 Preface

IEA Bioenergy aims at supporting a development where bioenergy contributes substantially in the future global renewable energy mix. Several working groups (´Tasks´) under IEA Bioenergy have been established to help achieve this overall goal of IEA Bioenergy by providing a scientific basis for such development. Each Task addresses different links in or aspects of the bioenergy supply chain.

When addressing questions related to technical feasibility, economic profitability and social and environmental sustainability, it is important to address these issues along the whole supply chain. An inter-Task project has been commissioned by IEA Bioenergy to facilitate collaboration among experts from multiple disciplines represented in the various Tasks in order to facilitate further mobilization of sustainable bioenergy supply chains in different operational environments. The project should also inform the debate around bioenergy feedstocks and end-uses, and make suggestions to improve governance of biomass supply chains.

Five cases were selected for this purpose. This report addresses the case study that related to the use of agricultural crop residues as raw material for bioenergy and biorefineries that produce both high value products and energy. The study is a collaboration between Task 37 (Energy from Biogas), Task 38 (Climate Change Effects of Biomass and Bioenergy Systems), Task 39 (Commercializing Conventional and Advanced Liquid Biofuels from Biomass), Task 40 (Sustainable International Bioenergy Trade), Task 42 (Biorefining) and Task 43 (Biomass Feedstocks for Energy Markets).

2 Summary

Agricultural crop residues are relevant types of biomass for bioenergy and other bioproducts as they are by-products of agricultural crop production, and do not require additional land for harvest. Estimates of the potential available for bioenergy and other uses vary significantly. While the theoretical potential is high, the economic availability can vary greatly. It depends on numerous factors including the yield and site specific parameters, the type of crop rotation, slope and soil type, length of the harvest window, the presence of a local processor or aggregator, and whether the agriculture producer sees value in collecting a portion of the crop residue. Several product-based sustainability schemes were reviewed, namely Global Bioenergy Partnership (GBEP), ISO 13065, PROSUITE, LEEAFF and a new scheme developed by U.S. DOE. While these schemes all address the three pillars of sustainability - social, environmental and economic – they vary in terms of the level of application and data requirements. Dale et al. (2015) propose a process for clearly defining the goals of the assessment to select the most appropriate tool.

National cases of supply chains were assessed more closely. A sustainability assessment using the GBEP framework was made for Denmark. Ten sustainability indicators were evaluated and it was found that the use of agricultural residues for energy contributes to GHG emission reductions, to diversification of the energy supply, to income generation in rural areas. The most critical issue from an environmental point of view is the risk of depleting soil organic matter through continued removal of crop residues. The area affected by crop residue harvest has increased since 2000 putting increased pressure on carbon stored in agricultural soils. Business economic viability of the Danish supply chains are ensured by a strong political focus and mandated use of crop residues for energy combined with economic incentives as tax exemption and feed in tariffs.

The Danish case also evaluated the applicability GBEP framework and highlighted a number of issues that could be discussed and may be further developed. The framework is data intensive, unambiguous attribution of impacts to processes and supply chains is difficult, and boundary crossing data and imported feedstock is not covered adequately. The GBEP framework is, however, not special in that respect as these issues pertain to most sustainability assessment frameworks.

Research was done to define categories for indicators of environmental and socioeconomic sustainability for the U.S. Here focus is on the use of crop residues for liquid fuels. Targets set by the Renewables Fuel Standard 2 (RFS2) drives research and industry development toward lignocellulosic ethanol production. The most critical barriers for the continuous expansion of the U.S. cellulosic biofuel industry are related to economic viability and project finance. The industry is considered as a high risk investment due to technical barriers and uncertainty about the projects' profitability.

For Canada, here exemplified by Ontario, a corn stover to bioenergy case is not viable, and higher value products would have to be produced in a biorefinery type configuration to ensure economic profitability. A system based on partial corn stover removal added to corn grain harvest was compared with an existing corn grain only harvest using LEEAFF. The stakeholder exercise showed that neither system was without some issues or sensitivities. A corn stover system would likely provide benefits for categories of sustainability, such as land use efficiency, broad stakeholder acceptability, GHG emission reduction, and employment. Corn stover feedstock supply chains are not operational currently and several new technologies would have to demonstrate financial profitability at scale, and there are unknowns to address regarding nutrient addition and long term soil health.

It is concluded that further opportunities for sustainable use of agricultural residues exist. Opportunities are, however, country and site specific, making it difficult to predict the global impact.

3 Introduction

Bioenergy that is generated from sustainably produced biomass has the potential to contribute substantially to the future global renewable energy mix. Accelerating production and use of environmentally sound, socially accepted and cost-competitive bioenergy can increase security of energy supplies while at the same time reduce greenhouse gas (GHG) emissions from fossil fuel consumption. Currently close to 56 Exajoules (EJ) of energy is derived from biomass worldwide. Sixty percent of this energy is used for traditional heating and cooking while the remainder is used in modern conversion technologies for the production of heat, transport fuels, and electricity (REN21 2014).

Various bioenergy targets are set to meet different goals on energy security and climate change mitigation. The International Renewable Energy Agency (IRENA), estimates that 108 EJ yr^{-1} of biomass must be used by 2030 to meet the Sustainable Energy for all (SE4All) target of doubling the share of renewable energy in the global energy mix before 2030 (Nakada et al. 2014). Meeting the targets set by the Global Energy Assessment (GEA 2012) requires significant growth in bioenergy production. Between 80 and 140 EJ yr^{-1} of biomass is required by 2050. Similarly the IPCC, in the 5th assessment report (Bruckner et al. 2014) outlined bioenergy use by 2100 to reach up to 200 EJ yr^{-1} depending on climate ambitions and chosen policy instruments. Breaking down these analyses, attainment of the SE4All target requires 13-30 EJ yr^{-1} of agricultural residues, while the GEA target would be met with extensive use of agricultural residues with an estimated technical potential of 49 EJ yr^{-1}.

In Europe, the National Renewable Energy Action Plan (NREAP) outlines how 27 EU members plan to meet the targets in the RED directive. It is estimated that the annual demand for biomass will increase from 2.5 EJ in 2006 to 5.9 EJ in 2020 (European Commission 2014). The Renewable Energy Directive (RED) (European Parliament and the Council 2009) has set a target of 10% renewable transportation fuels by 2020, and in the U.S., the Renewable Fuel Standard set a target of 174 billion litres (46 billion gallons) of biofuels yr^{-1}. This has created a significant demand for biofuels in the EU and North America.

Bioenergy targets are not exclusive to Europe and North America. A large number of South American, Asian, African and Oceanian countries have policies and targets on bioenergy deployment. To mention a few: Brazil has a target of 19.3 GW bio electricity capacity by 2021 and blend mandates for bioethanol in gasoline (E20) and biodiesel in fossil diesel fuel (B5). Nigeria has a target for bio-electricity of 50 MW by 2015 and 400 MW by 2025, and Ethiopia aims at installing 103.5 MW of electricity capacity based on bagasse sometime in the future. In India 2.7 GW of bio-electricity should be added to existing capacity from 2012-2017. By 2015 China expects to have 13 GW of bio-electricity and by 2030 Japan aims to have 6 GW of bio-electricity capacity. A global overview is provided by the Renewable Energy Policy Network (REN21 2014).

On the global scale IEA estimates for 2020 an installed capacity for bio electricity of 133 GW, up from 88 in 2013, 47 EJ of biomass used for heat generation (including traditional use of biomass), and liquid biofuel production to reach 140 billion litres (IEA 2014). First generation biofuels are to a large extent based on existing agricultural crops – sugars, grains and oilseeds that have traditionally been used for food, animal feed and some industrial uses, and can be readily converted into liquid biofuels. Public concerns over rising food prices and the perceived risk that further growth in first generation biofuels will increase food prices has led the European Commission (EC) to propose a limit of 7% for the amount of first generation transportation biofuels that can be counted towards the 10% renewables RED target (European Commission 2016). Similarly the U.S. has capped biofuel production from corn grain at 15 billion gallons yr^{-1} (57 billion litres). Public concern over direct and indirect land use changes resulting from the conversion of forest and grassland into crop production have also been seen. This has resulted in a greater focus on the use of biological wastes and residues, including agricultural crop residues, for the production of bioenergy and non-food bio-products. By definition, agricultural residues are by-products of crop production, and as such they do not require additional land. To a small extent, crop residue is used for animal bedding, as feed and as growth media. Additional residue removal could provide supplemental income for agriculture producers and has been shown to increase subsequent crop yields through earlier soil warming and seeding in colder climates. However, additional residue removal also involves the transfer of carbon and nutrients from the soil, so removal strategies need to be developed that meet environmental needs over the long term.

One of the world's first demonstration-scale cellulosic ethanol plants, Beta Renewables Crescentino, started in operation in Italy in 2012. The production is based on giant reed (*Arundo donax*) and wheat straw, and they produce 60,000 metric tonnes per year (76 million litres or 20 million gallons). Three new cellulosic biofuel plants came online in the U.S. in 2014. DuPont enacted a 30 million gallon per year plant in Nevada, Iowa, which will use corn stover as a feedstock. Poet-DSM has a new facility in Emmetsburg, Iowa that will produce 7 to 12 million gallons of ethanol a year using corn cobs and corn stover as a feedstock. Abengoa had built and operated a plant in Hugoton, Kansas, with a capacity of up to 25 million gallons of cellulosic biofuel production primarily from corn stover. Due to the financial situation of the Spanish mother company by the end of 2015, it was unclear whether and under which ownership the Hugoton plant would continue operation in 2016 (Voegele 2015). In Canada, lignocellulosic value chain development is happening at a smaller scale and targets the chemicals instead of the fuel market. Comet Biorefining has announced its intention to build a 23,000 tonnes cellulosic sugar plant with co-products to be sold into the animal feed market. If the necessary investment can be obtained, then a new facility could be built in Sarnia by 2018.

The purpose of this inter-country study is to explore further mobilisation of agricultural residues for bioenergy and biorefineries (fuel driven and non-fuel driven) applications, and provide an assessment of potential opportunities, barriers and sustainability issues. The study assesses different uses of agricultural residues in Denmark (for energy and biofuels), the U.S. (for advanced/second generation biofuels) and Canada (for potential use for bio-chemicals and bioenergy). The respective agriculture residue supply chains are at different stages of development, and each country is taking a slightly different approach with respect to the scope of their evaluation and sustainability assessment. Denmark has adopted a national scale assessment using the GBEP indicator framework, while Canada is evaluating the suitability of several sustainability schemes, including GBEP, ISO 13065, Prosuite and LEEAFF, to study a lignocellulosic supply chain under development in a high crop yielding region of the country. In the U.S., there are efforts (McBride et al. 2011) to further develop indicators building off the approaches proposed by the Roundtable on Sustainable Biofuels (Roundtable on Sustainable Biofuels 2010), Global Bioenergy Partnership (GBEP 2011), Council on Sustainable Biomass Production, and several other national and international efforts. McBride et al. (2011) identify major environmental categories of sustainability to be soil quality, water quality and quantity, greenhouse gases, biodiversity, air quality, and productivity, and propose a minimum number of indicators that fit into those categories.

4 Feedstock production systems

4.1 Policy and economic drivers for bioenergy and feedstock production

4.1.1 Denmark

The oil crisis in 1973-74 is often considered the starting point of Denmark's political interest in renewable energy. Prior to the crisis Denmark, as well as many other Western countries, was totally dependent on oil imports to drive the energy sector (Lund 2009). High energy prices increased the use of domestic straw and wood in household and farm heating immediately, and in 1976 the first Danish energy policy paved the way for use of more biomass also in district heating and combined heat and power production. The policy aimed at increasing energy security (Nygård 2011), and plans were to achieve end-user energy savings, while also increasing the production of energy from nuclear power, domestic natural gas, and renewables, such as solar and wind power and straw for heat and electricity.

The earliest political intent to focus on biomass for energy is found in the 1985 'Windmill agreement' between the Ministry of Energy and the utility sector, which acknowledged the need for further talks on the use of straw for energy (Ministry of Energy 1985), and in the 1986 'Electricity agreement' (Ministry of Energy 1986) that stipulated the construction of 80-100 $MW_{electricity}$ combined heat and power production based on domestic fuels as e.g. natural gas, straw, wood chips or biogas. At the time of the adoption of the Climate Convention in 1992, new CO_2-taxes were introduced with the aim of reducing greenhouse gas emissions, and energy policies shifted to take account of environmental concerns around fossil fuel use. The first targets specifically for biomass- based energy were set in the 'Biomass agreement' (Danish Government 1993) in 1993. The agreement mandated the use of 1.2 million tonnes of straw and 0.2 million metric tonnes wood chips for energy by 2000 (Figure 1).

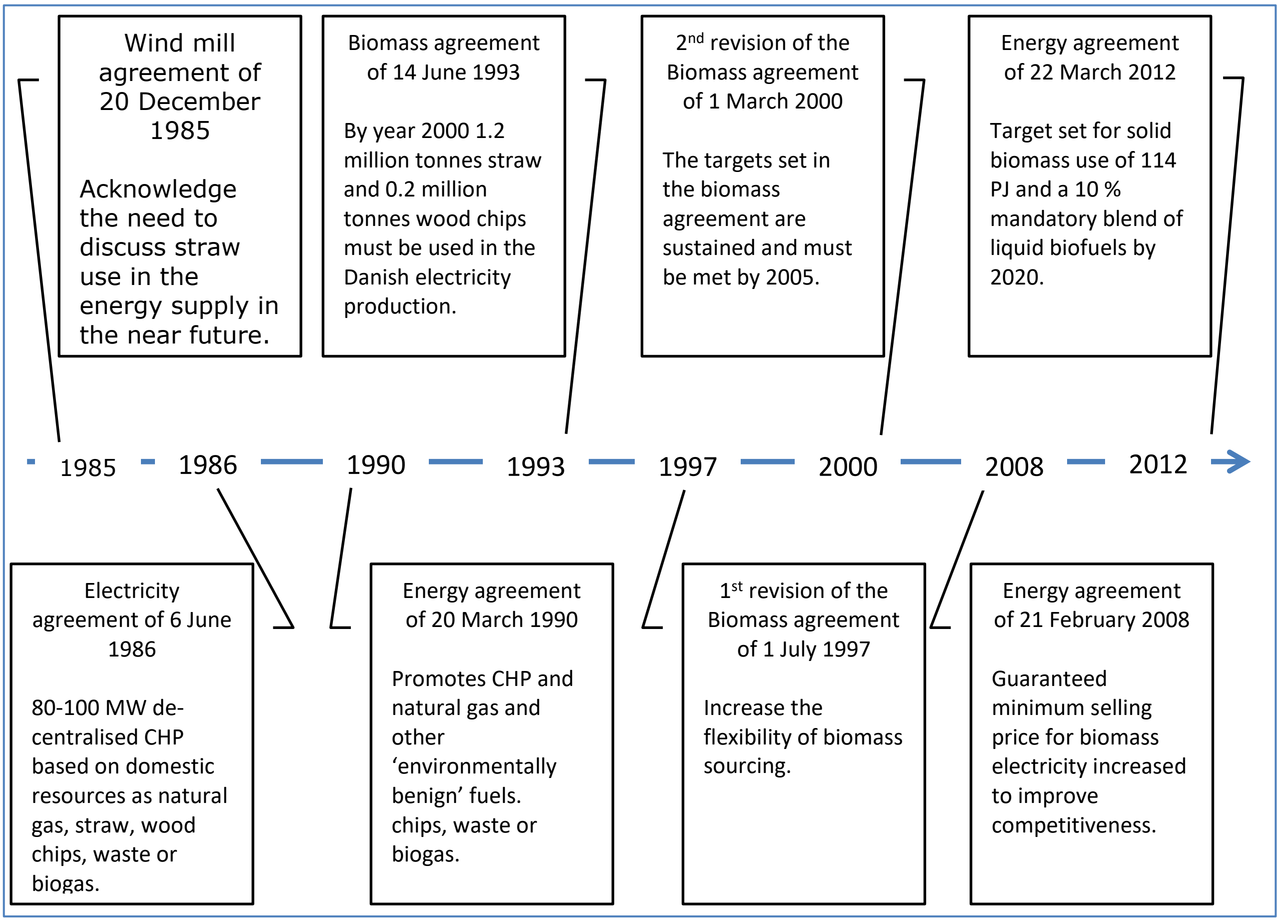

Figure 1: Time line of political agreements and incentives to support the development of bioenergy in Denmark.

The ‘Biomass agreement’ was subsequently revised in 1997 and again in 2000. In 1997 more flexibility was put into the agreement. The overall target for biomass use was maintained, but straw now had to make up at least 1 million tonnes instead of the previously mandated 1.2 million tonnes. As the biomass target was not met by 2000 the second revision of the ‘Biomass agreement’, the deadline was extended to 2005. After a period in the mid-2000s with energy policy focusing on economic growth and liberalization of the electricity market, focus shifted again in late 2000s to create a fossil free future (Nygård 2011).

Another policy driver was the European Union’s Renewable Energy Directive (RED), which was adopted in 2009 (European Parliament and the Council 2009). RED sets targets for the deployment of renewable energy by 2020 for each member state and for the EU as a whole, and mandated blending of biofuels in gasoline and diesel in all member states. The targets are implemented in national strategies and legislation as described in RED mandated national renewable energy action plans (NREAP). According to the Danish NREAP a slight increase in the use of straw for energy is required to meet the targets. By 2015 additional (compared to the use in 2006) 500 TJ (34 thousand tonnes) of straw should be used and by 2020 additional 1000 TJ (69 thousand tonnes) (Klima og Energiministeriet 2010).

The increased flexibility of fuel choice together with conversion of co-fired plants to wood pellets and chips has reduced the use of straw for heat and electricity since 2010. It is expected that straw will increasingly be used for production of bioethanol and bio-oil through thermo-chemical conversion, but energy utilities are holding back investments due to uncertainty around long-term policy commitments for second generation biofuels1. It is also likely that straw will be used in future biogas production, but straw suppliers fear that the efficient infrastructure that has been built during the last 10 years will be lost in the gap between former and new energy uses of straw. Cereal straw has now contributed significantly to the Danish energy system for more than 20 years and continues to play a role. The increased use of biomass in the energy system has been primarily been policy driven (straw mandate), using several financial policy incentives over the last 30 years. Together with the adoption of the first energy policy in 1976, taxes were introduced on oil and electricity, and investment support could be obtained. In the 1980s taxes on coal and natural gas were introduced, together with fixed and premium feed-in tariffs for renewables.

4.1.2 USA

A complete list of all renewable energy policies and measures with respect to the U.S. can be found at the International Energy Agency policy database (International Energy Agency 2015). Due to the expanse of the U.S. with 50 individual states, only federal laws are referred to here. State laws can be found on the respective State’s governmental websites as well as the Alternative Fuels Data Center (U.S. Department of Energy 2015). The latter provides a database with details on clean transportation laws, regulations, and funding opportunities in a particular jurisdiction as well as on the federal level.

4.1.2.1 Targets for Bio-electricity

There is no federal mandate for the production of bio-electricity. Most states however have renewable portfolio standards or goals in place (Figure 2). These standards require that utility

[1] Second generation biofuels are liquid fuels based on feedstock other that sugar, starch and primary vegetable oils. For bioethanol second generation fuels are based of cellulosic material as e.g. straw, stover, grass, cob, wood, and processing wastes. For biodiesel second generation fuel are based on e.g. used cooking oil, other waste oils, or wood, straw, stover etc. converted through gasification to diesel like fuels (Fischer-Tropsch). Terms are not use unambiguously and second generation biofuels may also be termed advanced biofuel or cellulosic biofuel. See also Figure 3.

companies generate a certain amount of energy from renewable resources by a certain date. For example, a certain percentage of the utility's electric power sales must be generated from renewable energy sources. Biomass is however only one from of renewable energy eligible to meet these targets, in addition to wind, solar, hydropower, etc.

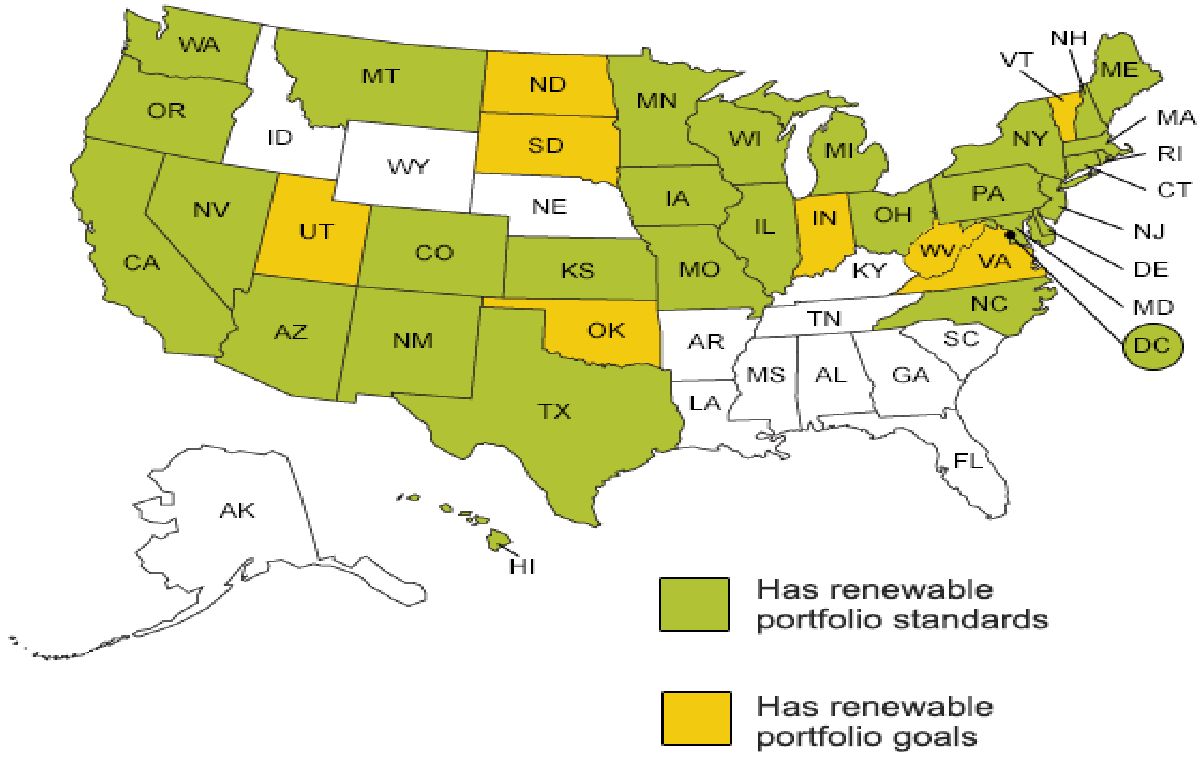

Figure 2. Distribution of renewable portfolio standards or goals (U.S. Energy Information Administration 2012).

On August 3, 2015, President Obama and the Environmental Protection Agency (EPA) announced the Clean Power Plan, which defines standards for power plants and customized goals for states to cut carbon emissions (U.S. EPA 2014). The plan sets up a national framework that gives individual states the power to chart their own customized path to meet the CO_{2e}-emissions targets proposed for each state. By 2030 the plan should result in 32% less carbon emission from the power sector across the U.S. when compared with 2005 levels.

4.1.2.2 Federal Targets for Biofuel Production

In 2007, Congress passed the Energy Independence and Security Act (EISA), amending the Renewable Fuel Standard (RFS) as established by EPACT in 2005. By 2022, the U.S. shall produce 36 billion U.S. gallons (136 billion litres) of biofuels. Of that, 21 billion U.S. gallons (80 billion litres) shall be advanced biofuels (derived from feedstock other than corn starch) i.e. second generation biofuels. Of the 21 billion U.S. gallons, 16 billion U.S. gallons (60 billion litres) shall come from cellulosic ethanol. The remaining 5 billion U.S. gallons (19 billion litres) shall come from biomass-based diesel and other advanced biofuels (U.S. Congress 2007). The U.S. Environmental Protection Agency (EPA) is revising its current RFS to reflect the changes in the EISA.

In 2011, the EPA implemented the Renewable Fuel Standard 2 (RFS2) program, a credit trading system along with biofuel volumetric mandates. The RFS2 establishes specific volumetric requirements for the four overlapping categories of renewable, advanced, biomass-based, and cellulosic biofuels (Figure 3). Compliance with these requirements is tracked through renewable identification numbers (RIN), which are numbers that are used to identify specific fuel volume by category. The RIN market is complex relative to other credit trading systems with four categories of credits each corresponding to a RIN biofuel category (see Warner et al. (2014) for a detailed assessment of the RIN market).

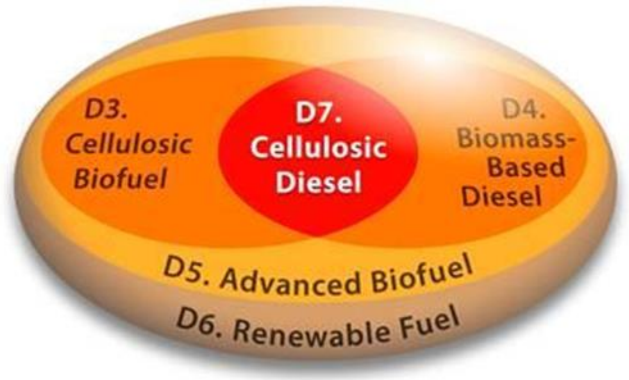

Figure 3: Nesting of biofuel categories under the RFS (Warner et al. 2014).

Figure 4 below shows the initial targets for biofuels production as prescribed by EISA. They were updated by EPA to reflect actual production developments (U.S. Environmental Protection Agency 2015). E.g., total production targets for 2016 were dropped from the initial 23 billion U.S. gallons down to 18 billion U.S. gallons.

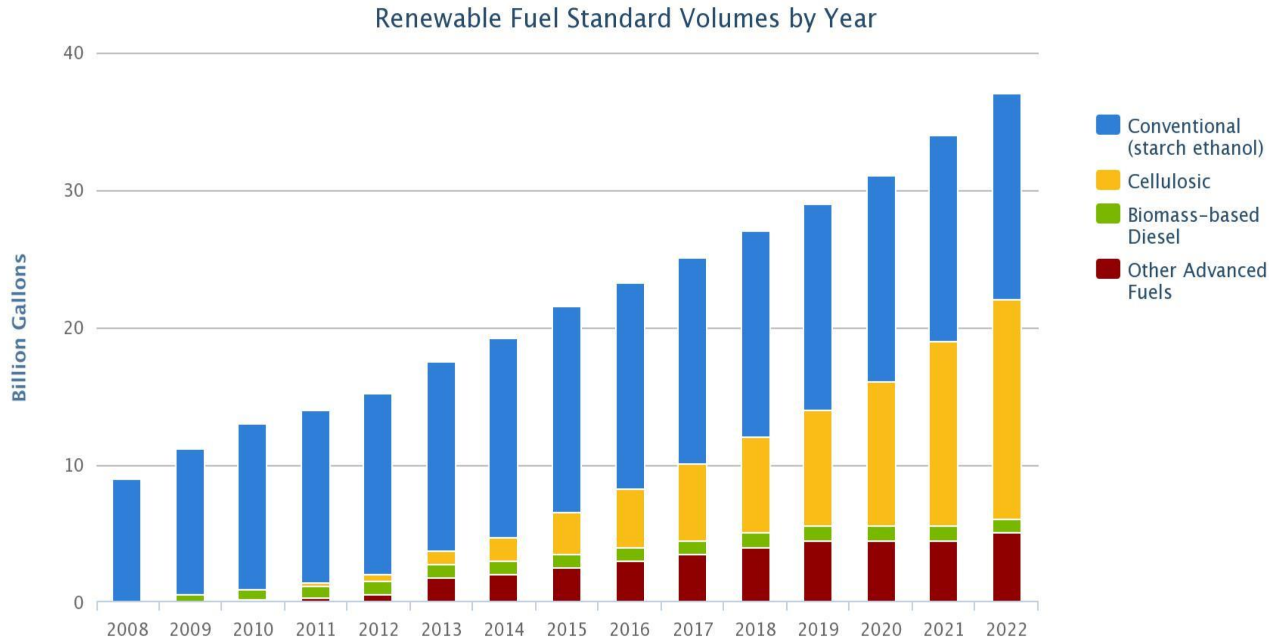

Figure 4. Renewable Fuel Standard Volumes by Year (U.S. Department of Energy 2015).

Historically, the first federal endorsement of biofuel came with the passage of the 1978 Energy Tax Act. The act introduced a 100% exemption of the gasoline tax for alcohol fuel blends (which was US$ 0.04 at the time). With the exemption still in place, biofuel, particularly ethanol, received more attention as a possible oxygenate to be used in reformulated gasoline as outlined in the Clean Air Act Amendments of 1990, which directed the U.S. EPA to establish a standard for reformulated gasoline. Another possible oxygenate defined in the Clean Air Act was methyl tertiary butyl ether (MTBE). Until recently, MTBE was the preferred oxygenate because it was less expensive and easier to distribute than ethanol.

However, concerns over MTBE's effect on ground water quality has resulted in many states adopting laws that ban or significantly limit its use in gasoline sold in those states. Twenty-five states have laws that phase out MTBE partially or completely. In light of the MTBE bans in these states, one element of the EPACT of 2005 repealed the oxygenate requirement as described in the 1990 Clean Air Act Amendments. A provision of the repeal required refiners to blend gasoline so that they still maintain the Clean Air Act-mandated emissions reductions achieved in 2001 and 2002. EPACT also established an RFS that required that 7.5 billion U.S. gallons (28 billion litres) of ethanol and biodiesel be produced by 2012 (U.S. Congress 2005).

Prior to EPACT, Congress passed the American Jobs Creation Bill of 2004, which established a blender's tax credit for ethanol and a comparable credit for biodiesel production. As of 2011, blenders received a US$ 0.45 per US gallon tax credit, regardless of feedstock; small producers received an additional US$ 0.10 on the first 15 million US gallons; and producers of cellulosic ethanol received credits up to US$ 1.01. Tax credits to promote the production and consumption of biofuels date back to the 1970s. For 2011, credits were based on the Energy Policy Act of 2005, the Food, Conservation, and Energy Act of 2008, and the Energy Improvement and Extension Act of 2008.

The import tariff and tax credit for ethanol both expired at the end of 2011. The biodiesel tax credit was set to expire by the end of 2013 but got extended to the end of 2014 (Kotrba 2014).

Since the end of the ethanol production tax credit, production volumes have fallen behind the legislated EISA and EPA required volumes (Figure 5).

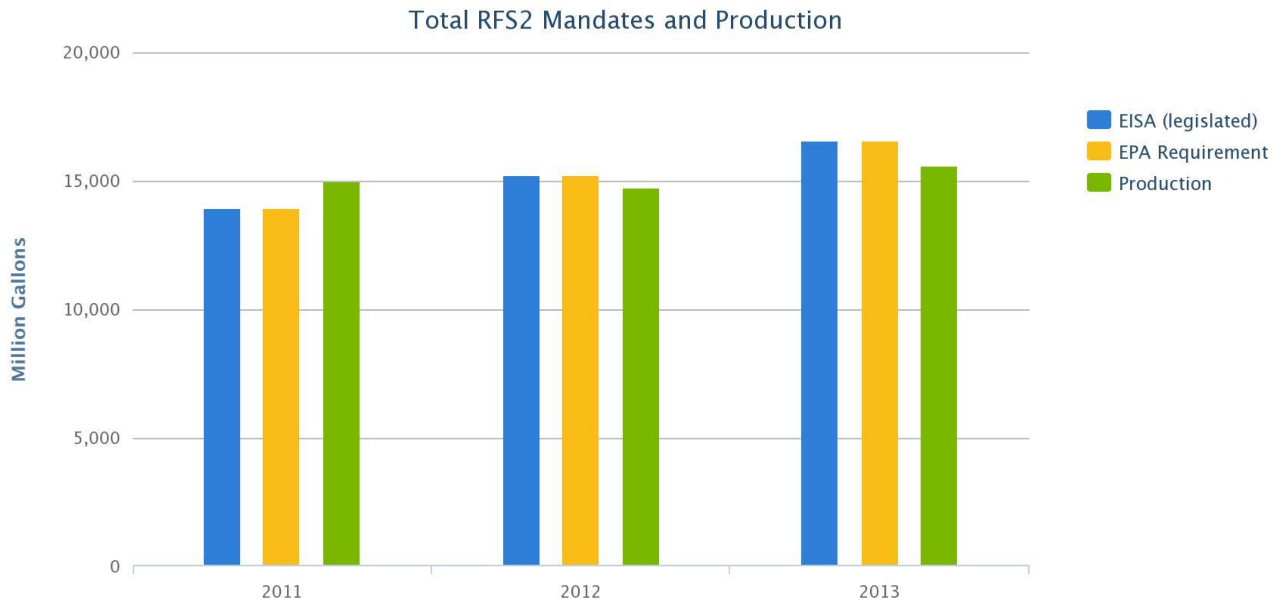

Figure 5. Recent RFS2 mandates vs. actual production volumes (U.S. Department of Energy 2015).

4.1.2.3 Financial Support Measures for Biomass

A detailed analysis of subsidies provided in the energy sector including biomass was undertaken by the Energy Information Administration for the year 2013 (U.S. Energy Information Administration 2015). In this section, we limit our presentation to the two main sources, the Biomass Crop Assistance Program (BCAP) and the Demonstration and Deployment (D&D) subprogram.

4.1.2.3.1 Biomass Crop Assistance Program (BCAP)

While tax credits for ethanol and biodiesel have been terminated (ethanol at the end of 2011, biodiesel at the end of 2014), the biofuel industry is still able to benefit from indirect financing via agricultural and forest feedstock support programs, predominantly the Biomass Crop Assistance Program (BCAP).

The BCAP for USDA’s Farm Service Agency (FSA) was created as part of the 2008 Farm Bill (The Food, Conservation, and Energy Act of 2008) to reduce U.S. reliance on foreign oil, improve domestic energy security, reduce carbon pollution, and spur rural economic development and job creation (U.S. Department of Agrigulture 2010).

BCAP was set in place to help address bioenergy’s “chicken-and-egg” challenge of establishing commercial-scale biomass conversion facilities and sufficient feedstock supply systems simultaneously:

- Conversion facilities must have reliable, large-scale feedstock supplies to operate, but there are no existing markets for accessing these materials
- Biomass feedstock producers do not have sufficient incentive to produce these materials because of the lack of existing markets to purchase their biomass.

The BCAP provides financial assistance to owners and operators of agricultural and non-industrial private forest land who wish to establish, produce, and deliver biomass feedstocks. It provides two categories of assistance:

(1) Matching payments may be available for the delivery of eligible material to qualified biomass conversion facilities by eligible material owners. Qualified biomass conversion facilities produce research, heat, power, biobased products, or advanced biofuels from biomass feedstocks.

(2) Establishment and annual payments may be available to certain producers who enter into contracts with the Commodity Credit Corporation (CCC) to produce eligible biomass crops on contract acres within BCAP project areas.

For instance, in 2006, 20% of the U.S. corn harvest was used for ethanol production. The total agricultural subsidies through the CCC (i.e., BCAP) for corn that year totalled US$ 8.8 billion[2]. Thus, an estimated US$ 1.8 billion went to subsidize corn destined for ethanol production.

4.1.2.3.2 Demonstration and Deployment (D&D)

The Demonstration and Deployment (D&D) subprogram (Duff 2013) (formerly the Integrated Biorefinery Platform) is focused on demonstrating and validating biomass conversion technologies through successful construction and operation of cost-shared pilot, demonstration, and commercial scale integrated biorefinery (IBR) projects.

The purpose of the D&D subprogram is to "de-risk" emerging biomass conversion technologies sufficiently so that broad replication and industry expansion can occur. The U.S. DOE Bioenergy Technologies Office (BETO) does this by providing financial assistance for scale-up and demonstration of emerging technologies. BETO works in partnership with private-sector technology developers to leverage federal financial assistance funding. The D&D subprogram plays a vital role in "de-risking" technologies in two primary ways:

- Technologically, to scale-up and validate conversion process performance so that "Wrap-around" performance guarantees can be provided by EPC firms.
- Financially, to verify the CAPEX and OPEX so private-sector financing can invest without fear of default.

To date, 33 projects of R&D, pilot, demonstration, and commercial-scale IBR projects had been selected. Of these, five were mutually terminated, five completed, 19 are still active, while an additional four new awards are currently under negotiation. Figure 6 and Figure 7 show the geographic and pathway diversity of the projects.

[2] Testimony by Keith Collins, chief economist, U.S. Department of Agriculture, before the U.S. Senate Committee on Agriculture, Nutrition, and Forestry, Washington, D.C., January 10, 2007. Retrieved from: http://www.usda.gov/oce/newsroom/archives/testimony/2007files/Collins_011007.pdf, Accessed 7 January 2014, and U.S. Department of Agriculture, Commodity Credit Corporation, Commodity Estimates Book, FY 2008 President's Budget, (Washington, D.C, February 5, 2007), p. 1. Retrieved from: http://www.fsa.usda.gov/Internet/FSA_File/pb08_tbl35a.pdf, Accessed 7 January 2015

Figure 6. BETO IBR Project Portfolio – Geographic Diversity (Duff 2013).

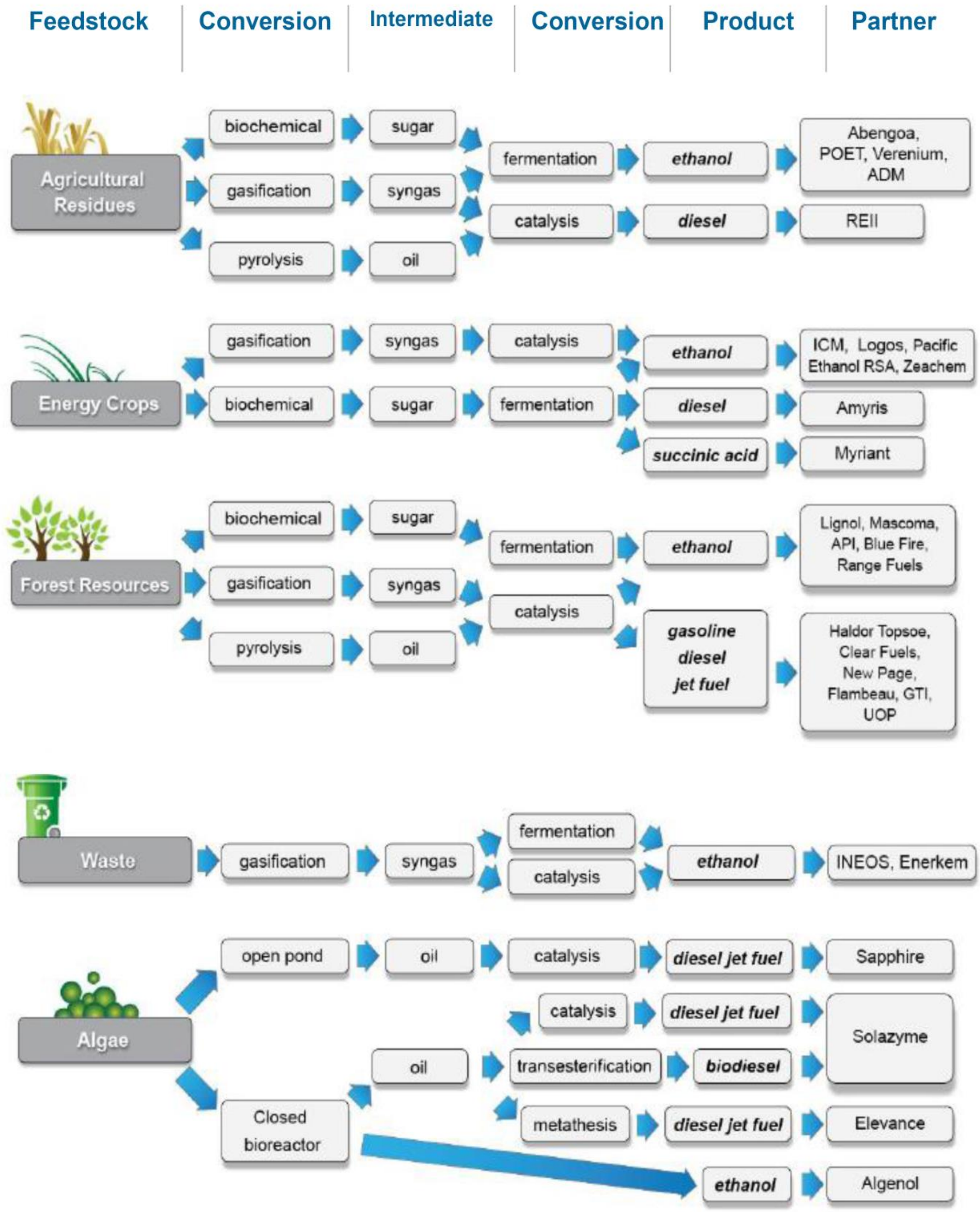

Figure 7. BETO IBR project portfolio – pathway diversity (Duff 2013).

4.1.3 Canada

In Canada, the drivers for the development of bioenergy and biorefining have changed over time. The forest products industry remains the major producer and user of bioenergy in Canada, generating 508 GJ of heat and power in 2014 (Statistics Canada 2016). It was the oil crisis in the 1970s combined with pollution concerns that led the forest products industry to install hogfuel and recovery boilers, and move to energy self-sufficiency. Public R&D investments supported the development of new conversion technologies, including gasification, pyrolysis and biochemical conversion of lignocellulose. In the 1990s climate change mitigation became an important motivator for bioenergy and renewable energy R&D. One decade later, the first generation (1G) biofuels industry emerged along with growth in solar and wind energy installations. Around this same time, the forest products industry initiated its transformation program to reinvent itself for the new century. In 2009, the Pulp and Paper Green Transformation Program was launched, a CAN$ 1 billion fund to improve the environmental performance of Canada's pulp and paper mills and renew the industry's position in the global marketplace. The program helped to support more than 14,000 jobs and resulted in 195 MW of new renewable energy capacity.

At the federal level, Canada has established a biofuel mandate of 5% renewables in the gasoline pool and 2% renewables content in the diesel pool. This mandate is being met through domestic production of 1G biofuels and imports. In addition, 5 provinces have set their own biofuel targets and several provinces have incentives for new bioenergy production. In its decision to replace its coal-fired power generation, the Province of Ontario did consider the use of agricultural biomass. However, given the large volumes of biomass required and the undesirable inorganic content of agricultural materials, the replacements have been either natural gas or woody biomass. The Atikoken Generating Station in Northern Ontario burns 100% wood pellets because the energy content of these pellets is very similar to the lignite coal that the generating station was designed to burn, allowing much of the existing equipment to be easily adapted. The wood pellet supply is procured through a competitive process requiring the biomass to be sourced from sustainably managed forests.

Consequently, there is no large scale energy production based on agricultural crop residues in Canada. Small on-farm applications exist in rural areas to heat farm buildings, often using a blend of wood and crop residues as feedstock. Also, crop residues are used in small amounts as a supplemental feedstock for anaerobic digesters. The use of agricultural residues for CHP could be feasible in remote settings without access to natural gas and where users rely on propane, electricity or diesel fuel for heating. However such areas generally have greater access to woody material than agricultural biomass.

At present, there are no specific mandates for second generation biofuels production or use in Canada. These policies could be revisited in the light of new climate change commitments. Until now, the higher cost of cellulosic ethanol production relative to grain based ethanol presents a significant disincentive for the development of large scale ethanol production. The international aviation industry is looking to introduce renewable fuels into its fuel mix over the next decades, but the type of biofuels and feedstock they will be derived from is not yet known. For Canada, it is estimated that 923 million litres of bio-aviation fuel will be required by 2035 for Canada's aviation industry to achieve carbon neutral growth. Further technological developments, such as economical production of bio-aviation fuel from lignocellulose and the valorisation of lignin, could result in large scale conversion of lignocellulosic material in the future.

Over the last few years, agricultural crop residues have been evaluated as sustainable feedstocks for biorefinery applications that produce high value chemicals and bioenergy. The conversion of agricultural residues into cellulosic sugars and other valuable products appears to make a better business case than the conversion into energy or biofuel. The chemicals and plastics industries are seeking renewable, non-food sources of biomass to produce sustainable intermediate chemicals as well as specialty chemicals in their production processes. From the agricultural and regional development perspectives, building a sustainable agricultural residue supply chain could provide diversification and additional revenue for agriculture producers; new jobs related to the harvesting, transport, storage, cleaning and processing of residues; increased wealth of rural communities; and slow the exodus of people from rural areas and small communities. The economy of scale of such an application is also expected to be smaller than that of a cellulosic ethanol plant and a better fit for a sustainable supply of agriculture residue in Canada.

4.2 Current agricultural residue production and use

Agricultural residues constitute a large biomass resource; however they are not always well-defined. They may be sub divided into primary residues, which originate from harvest operations and comprise e.g. straw, leaves, stover, stalk, husk, bagasse, and cob. Secondary residues originate from industrial processing and comprise e.g. pit, shell, peeling, husk, and bagasse. Secondary residues may also include animal waste as dung, manure, slurry, slaughterhouse waste (Torén et al. 2011).

4.2.1 Denmark

While the amount of straw produced in Danish agriculture has increased slightly over the last 15 years, the fraction collected and utilized in particular for energy purposes has decreased. Currently approximately 50% of the straw resource is collected for various purposes, and of this fraction 45-50% is used for energy generation (Figure 8).

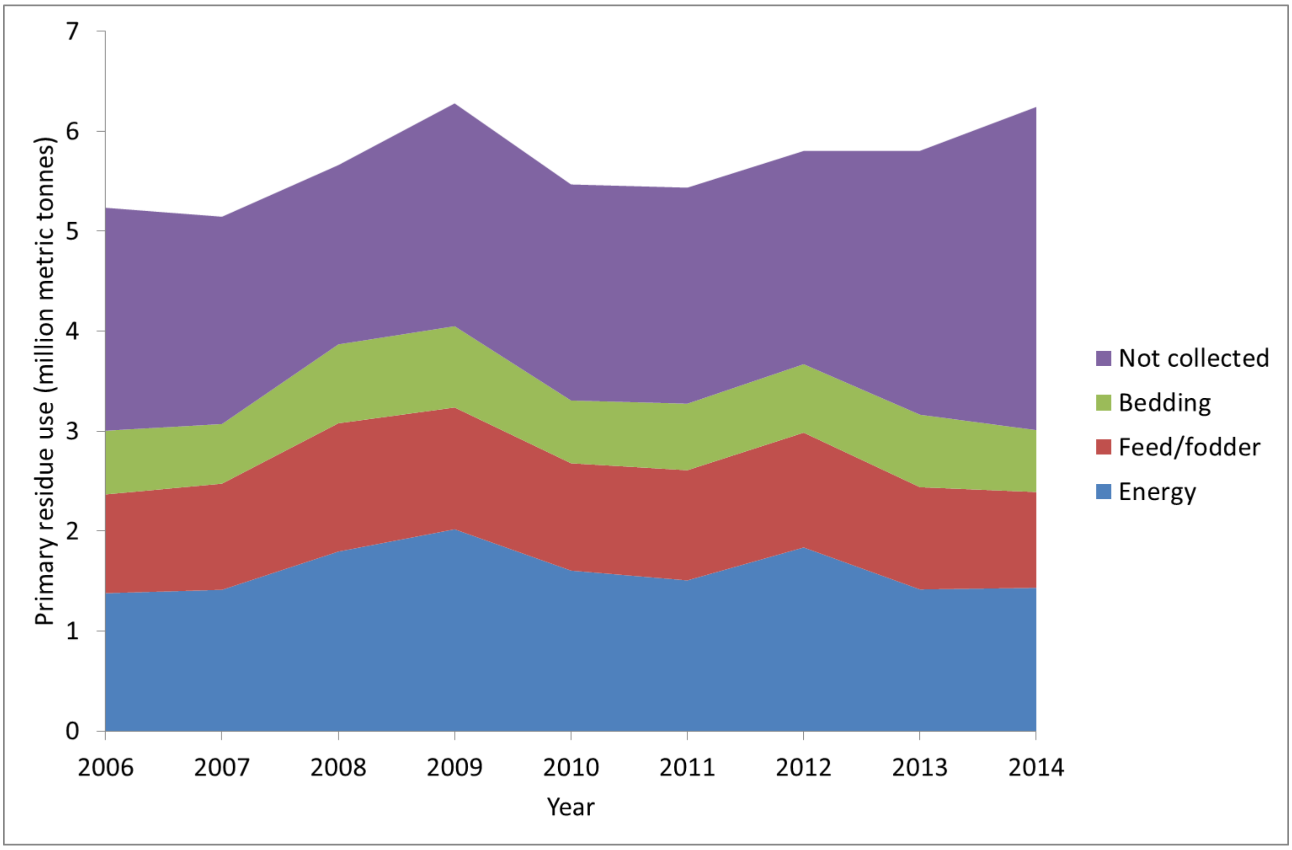

Figure 8. Agricultural residue production and use in Denmark from 2006 to 2014. Data from Danish national statistics (Danmarks Statistik 2015).

Straw was also used for energy before the 1986 agreement on the use of domestic resources for CHP, but predominantly for heating in individual households i.e. farmhouses at cereal producing farms (Figure 9).

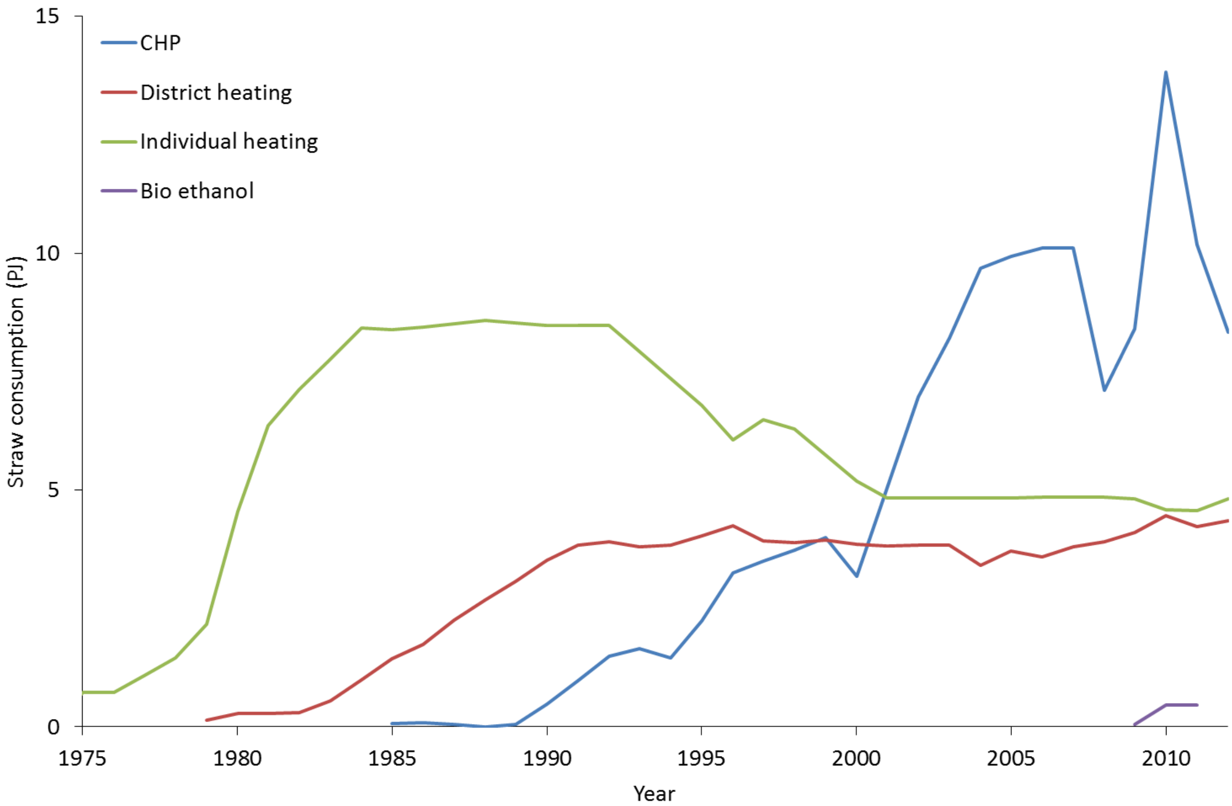

Figure 9. Straw used for energy and its allocation to different energy sectors in Denmark from 1975 to 2012. Data on CHP, district and individual heating are derived from the Danish energy statistics (Energistyrelsen 2012). Data on ethanol production are calculated from ethanol production statistics from EIA (U.S. Energy Information Administration 2014) assuming a conversion rate from straw to ethanol of 0.27 MJ/MJ (Bentsen et al. 2009).

Today, the annual consumption of straw for heat and power production is approximately 1.4 million tonnes (fresh weight). This accounts for some 16% of the renewable energy production in Denmark or 2-3% of total energy production.

Parallel to the use of straw for heat and electricity, Danish companies have in the last 10-12 years been working intensively on developing technologies for converting straw/agricultural residue biomass into ethanol. One is the Inbicon project, which, since 2003, has been operating a pilot scale plant and since 2009 in demonstration scale (Larsen et al. 2012). The demonstration plant has a capacity of four tonnes of straw input per hour and is integrated with a power plant. Inbicon sees their technology as part of a more general biorefinery framework making not only energy products but also chemicals and materials. Straw has been tested as feedstock for low temperature gasification in the Pyroneer project with the aim of producing syn-gas for stationary applications. Although promising results were achieved in the initial stages (Thomsen et al. 2015), the pilot scale gasifier operated by Dong Energy has stopped operation.

4.2.2 USA

U.S. DOE (2016) estimates that 144 million dry tons (130 million tonnes) of agricultural resources are currently used in a diverse range of applications across the U.S. Corn stover makes up the majority of this total supply and is concentrated in the Midwest region, including the states of Illinois, Indiana, Iowa, Kansas, Minnesota, Missouri, Nebraska, Ohio, and South Dakota.

Since the introduction of biofuel policies in the U.S., the area of corn has increased by over three million hectare. The highest residue yields are realized from corn, which produces roughly 10 metric tonnes per hectare of grain and approximately the same amount of stover in an average year.

Assuming a crop to residue ratio of 1:1 (Kim and Dale 2004), the U.S. corn stover production rose significantly between 1950 and 2013 (Figure 10). This is largely due to productivity increases as the total area planted only rose by 20 million acres (8 million hectare) across the same period. The partly drastic fluctuations in annual yields are related to inclement weather patterns, including droughts (1980, 1983, 2012) and floods (1993).

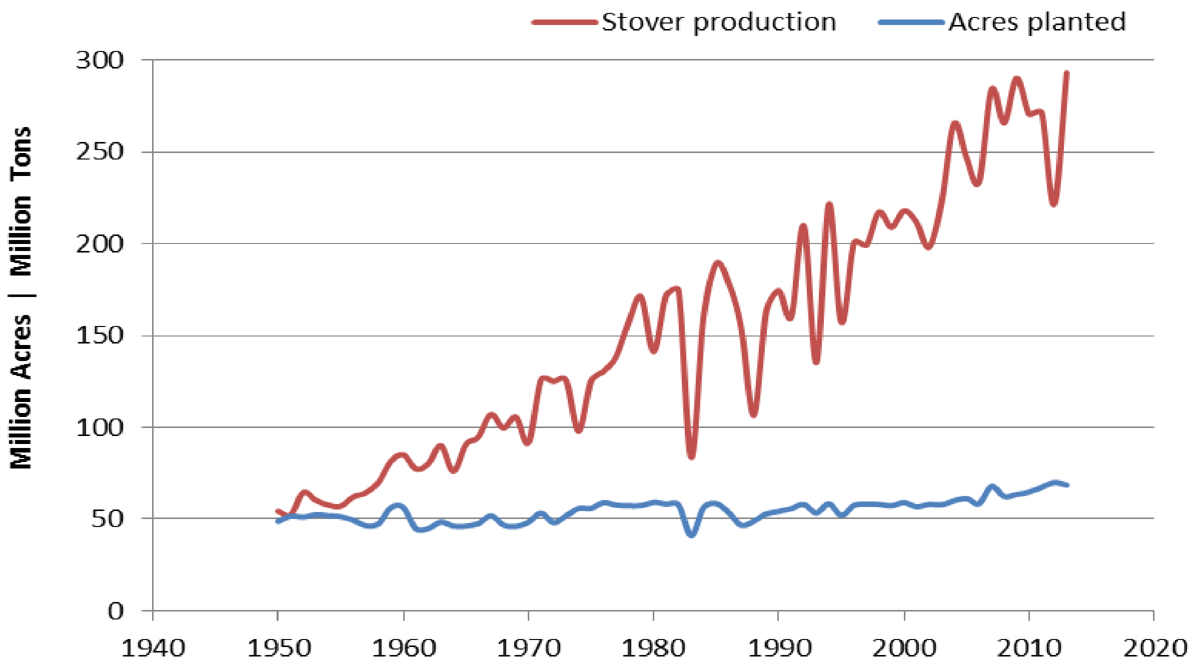

Figure 10. Corn stover production across the U.S. Midwest (including Illinois, Indiana, Iowa, Kansas, Minnesota, Missouri, Nebraska, Ohio, South Dakota) from 1950 to 2013 (USDA 2014).

4.2.3 Canada

In Canada, the suitability for agricultural production and hence the potential availability of agriculture residues varies across the country. Li et al. (2012) estimated the annual production of crop residue, averaged over the period 2001-2010, to be 82 million tonnes (dry) The annual variability by major crop type is shown in Figure 11.

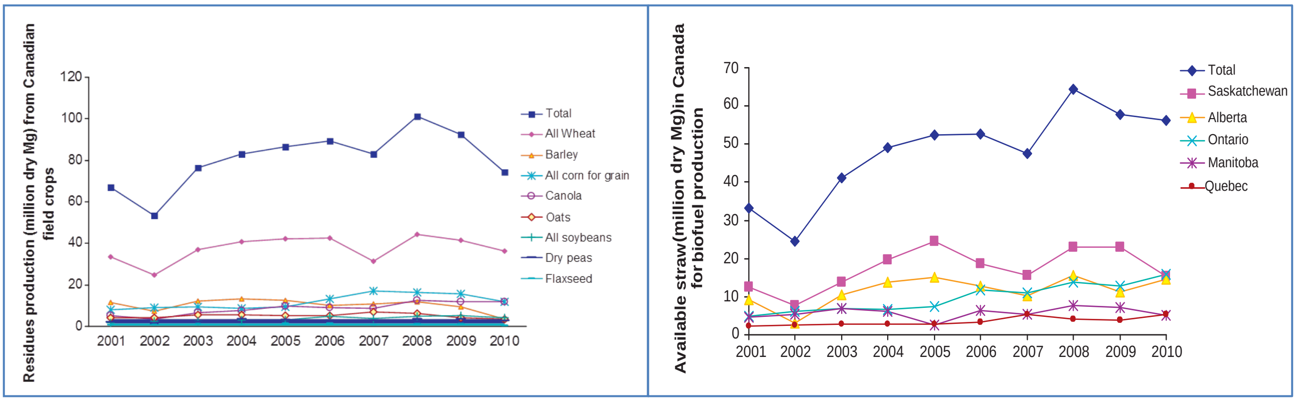

Figure 11. Canadian crop residue production (2001-2010) and annual variability. Left pane shows total production. Right pane shows residue availability after deducting residue needs for soil conservation and livestock uses. From (Li et al. 2012).

For the 2011 census year, it was estimated that 3.6 million tonnes (dry) of crop residues were used for animal bedding and less than 1 million tonnes (dry) for mushroom and horticulture applications. Also, cereal straw can be used to supplement forage crops, such as tame hay and fodder corn that are used for animal feed. The current markets for crop residues, namely animal bedding, feed and mushroom substrate, appear to represent a small fraction of the total residue produced on a national scale. However the fractions could be much larger in regions with significant livestock populations. In large countries like Canada, residue availability should be discussed at a regional scale.

4.3 Theoretical residue potential

A study by Bentsen et al. (2014) estimates the current global theoretical potential of primary agricultural residues from cereals and sugar cane to approximately 3.7 billion tonnes of dry matter annually, corresponding to ~65 EJ yr^{-1} of primary energy. Earlier studies find the theoretical potential of cereals and sugar cane to 2.7 – 3.5 billion tonnes yr^{-1} (Smil 1999, Lal 2005, Krausmann et al. 2008, Hakala et al. 2009), corresponding to 47-61 EJ yr^{-1}. Cereals and sugar cane account for 80% of the total residue production and constitute the most harvestable part (Lal 2005).

4.4 Technical residue potential

Very few countries collect data on residue production and use; but a number of modelling studies find, on a global level, a current appropriation (incl. for energy) of 2.9 billion tonnes yr^{-1} (66% of total production) (Krausmann et al. 2008) a figure corroborated by (Rogner et al. 2012). In contrast Wirsenius (2003) find the fraction of agricultural residues appropriated by humans to 41%. The IPCC special report on renewable energy (Chum et al. 2011) reviewed the vast body of literature on bioenergy resources and reports a technical potential of agricultural residues by 2050 of 15-70 EJ yr^{-1}, i.e. enough to meet the SE4All target (Nakada et al. 2014), but not necessarily enough to meet the GEA target (GEA 2012).

The Biomass Energy Europe project (BEE) worked on harmonizing biomass resource assessments and found a theoretical potential of primary residues in the EU27 of 2.7 EJ and a technical potential of 0.8 EJ. Corresponding figures for secondary residues including rice and sunflower husks and sugar beet pulp were 89 and 52 PJ (Böttcher et al. 2010). A more Recent EU wide project (S2Biom) found a technical potential of crop and agro-industrial residues for the EU28, Western Balkans, Turkey and Ukraine by 2030 of 400,000 tonnes dry biomass per year (Panoutsou et al. 2016).

4.4.1 Denmark

The +10 million tonnes study (Gylling et al. 2013) assessed the availability of biomass resources in Denmark on the shorter term to the year 2020. The study found that straw harvest could sustainably be increased from the current 1.4 million tonnes annually to approximately 3 million tonnes annually. An additional amount of straw could be made accessible through increased mobilization of the produced straw and increased production of straw through selection of cultivars with similar crop yields but lower harvest indices. Without the contribution from cultivar selection additional mobilization of straw could yield a total straw harvest of approx. 2.5 million tonnes by 2020.

4.4.2 USA

The recent assessment of potential U.S. biomass resources (U.S. DOE 2016) determines technically available resources. However, the availability is linked to specific prices and as such represents economic potentials – under the assumption that respective markets exist. Actual market availability of these resources is obviously dependent upon future market demands defining the economic viability of their mobilization. Results of U.S. DOE (2016) are presented as economical potentials in Section 4.5.2.

4.4.3 Canada

Potentially, there could be 48 million metric tonnes (dry) of agricultural crop residue available in Canada to furnish new markets such as the production of cellulosic biofuels, bio-based sugars and chemicals, biomaterials, and agri-wood pellets. However, the real opportunity for agricultural residues to supply these markets depends on many factors including the crop yield, the cost and properties of the residues, the distance from the processing facilities, the cost of converting residues into bioproducts and the profit potential, the degree of substitutability by other lignocellulosic feedstocks, and the existence of a government mandate and/or consumer preference for bioproducts.

The concentration of biomass in a given region is key to determining feedstock costs and financial viability of a proposal. As shown in Table 1, the residue concentrations can vary significantly between crops and provinces. The publicly-available mapping tool known as BIMAT (Biomass Inventory Mapping and Analysis Tool) can be used to determine the amount of biomass available in a certain geographic area in Canada. This model reports residue volumes, associated with wheat, barley, oats, flax and corn grain production, based on 30 years of Canadian agriculture census data (see http://www.agr.gc.ca/atlas/bimat). The volumes can be adjusted to account for: 1) agriculture producer participation rate; 2) competing uses; and 3) tillage practice. Knowing the amount of biomass needed for bioenergy or biorefinery operation, BIMAT can be used to estimate the collection radius from a proposed facility location based on a 30 year history.

Table 1. Estimated average concentration of residues from selected crops from 2001 to 2010 (dry tonnes per hectare).

Province	Wheat straw	Barley straw	Corn stover	Oat Straw
Prince Edward Island	3.58	2.91	-	3.87
New Brunswick	3.90	3.13	4.44	3.81
Nova Scotia	4.72	2.92	7.08	3.65
Quebec	3.65	3.05	8.00	3.75
Ontario	6.06	3.32	8.58	3.87
Manitoba	4.62	3.22	5.99	4.28
Saskatchewan	3.05	2.62	-	3.59
Alberta	3.78	3.18	6.07	3.90
British Columbia	-	2.74	-	3.78

4.5 Economic potential

A study on mobilizing cereal straw in the EU to feed second generation biofuel production (Kretschmer et al. 2012) emphasises that even if studies of technical (or theoretical) biomass potentials suggest that a substantial amount of straw is available this does not necessarily mean that the economic potentials for bioenergy are large. An uncertainty parameter is that a proportion of the straw is used for other purposes. The most common other uses today are animal feed or bedding, and as mulch for use in vegetable and mushroom production. Such parameters are site specific and can vary from year to year.

Bloomberg (2011) projected the potential supply of agricultural residues in the EU by 2020 to be approximately 170 million tonnes at an average supply cost of €67 per tonne. The majority of the volume (80%) consists of straw from grain crops such as wheat and barley. Bloomberg (2011) estimates that already today, it would be profitable to collect 92 million tonnes at a delivered gate price of €60 per tonne. Projection for the availability of various biomass feedstocks in the EU are also reported by de Wit and Faaij (2010). By 2020 approximately 3 EJ (~200 million tonnes) of agricultural residues would be available at a plant gate cost of €3.5 GJ^{-1} (€51 $tonnes^{-1}$).Taking into consideration the uncertainty in projecting future supplies at various prices it is estimated that 170-200 million tonnes would be available at a price between €50 and €70 per tonnes (delivered at plant gate) by 2020.

4.5.1 Denmark

In Denmark there are still 1-1.5 million tonnes yr^{-1} of residues that technically could be mobilized. The economic potential of straw seems to be very dependent on the price of alternative biomass fuels as the access to e.g. wood chips at competitive (not necessarily equal or lover) prices influence the demand. Figure 12 shows the economic potential of various biomass fractions as estimated by the Danish TSO (Transmission System Operator) for scenario analyses of future energy system configurations (Energinet.dk 2015).

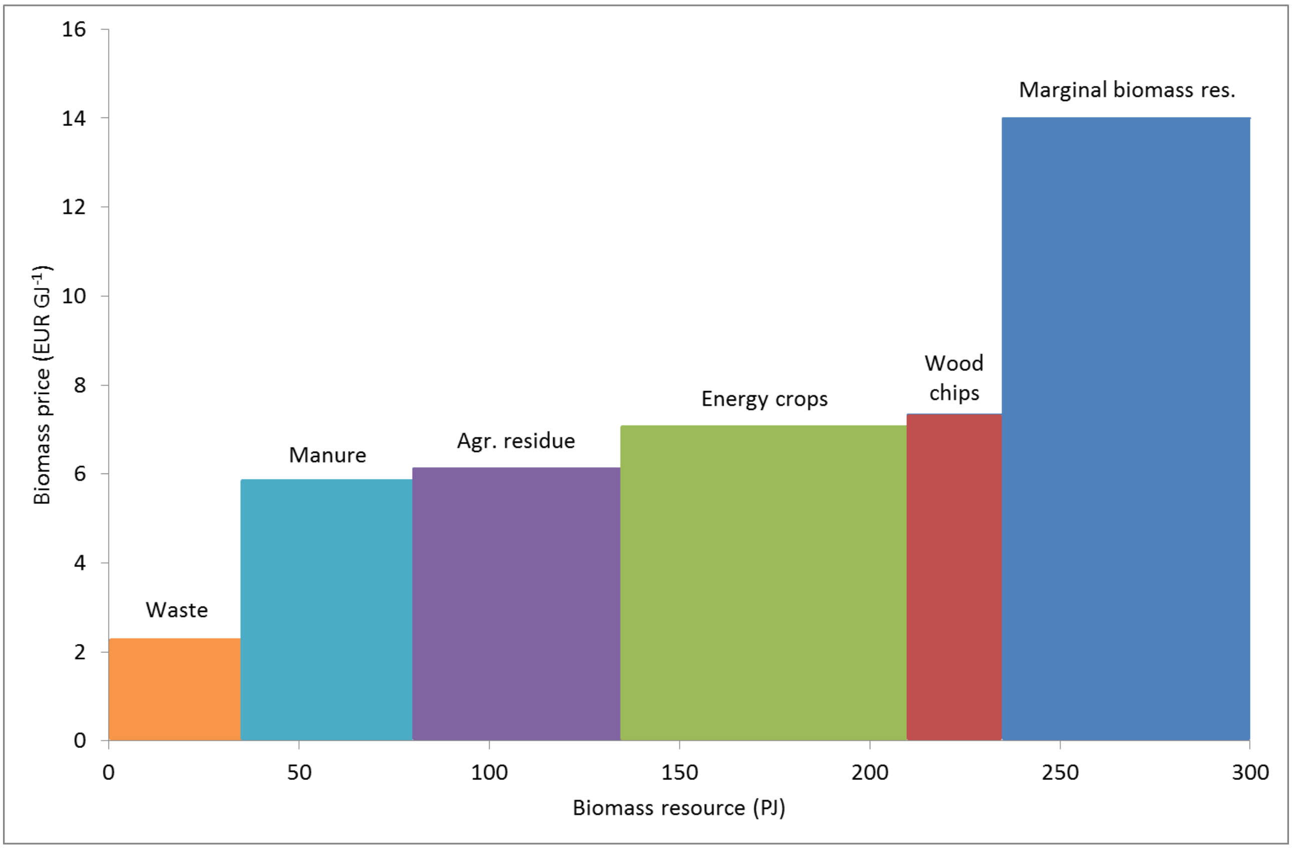

Figure 12. Supply-cost relation for Danish domestic biomass resources (Energinet.dk 2015).

4.5.2 USA

The U.S. DOE (2016) estimates that the 2017 agricultural crop residue potential at $60 per dry short ton ($66 per tonne) or less is in the range of 104-105 million short tons (94 million tonnes) (Table 2). This potential includes barley straw, corn stover, oats straw, sorghum stubble, and wheat straw, and is expected to increase up to 176-200 million short tons (158-180 million tonnes) by 2040 (U.S. DOE 2016) (Table 2). The geographic distribution of the potential for 2017 is depicted in Figure 13 and for 2040 in Figure 14 . A stepwise cost-supply curve for a base-case yield scenario increase of 1% per year is provided in Figure 15 and a high-yield scenario of 3% yield increase per year is given in Figure 16.

Table 2. Summary of Currently Used and Potential Forest, Agricultural, and Waste Biomass Available at $60 per Dry Ton or Less, Under Base-Case and High-Yield Scenario Assumptions (microalgae excluded) (U.S. DOE 2016).

Feedstock	2017	2022	2030	2040
	Million dry tons			
Currently used resources				
Forestry resources	154	154	154	154
Agricultural resources	144	144	144	144
Waste resources	68	68	68	68
Total currently used	**365**	**365**	**365**	**365**
Potential: Base-case scenario				
Forestry resources (all timberland)[a, b]	103	109	97	97
Forestry resources (no federal timberland)[a, b]	84	88	77	80
Agricultural residues	104	123	149	176
Energy crops[c]		78	239	411
Waste resources[d]	137	139	140	142
Total base-case scenario potential (all timberland)	**343**	**449**	**625**	**826**
Total base-case scenario (currently used + potential)	***709***	***814***	***991***	***1,192***
Potential: High-yield scenario				
Forestry resources (all timberland)[b, e]	95	99	87	76
Forestry resources (no federal timberland)[b, e]	78	81	71	66
Agricultural residues	105	135	174	200
Energy crops[c,f]		110	380	736
Waste resources[d]	137	139	140	142
Total high-yield scenario potential (all timberland)	**337**	**483**	**782**	**1,154**
Total high-yield scenario (currently used + potential)	***702***	***848***	***1,147***	***1,520***

Note: Numbers may not add because of rounding. Currently used resources are procured under market prices.

[a] Forestry baseline scenario.

[b] Forestry resources include whole-tree biomass and residues from chapter 3 in addition to other forest residue and other forest thinnings quantified in chapter 5.

[c] Energy crops are planted starting in 2019. Note: *BT2* assumed a 2014 start for energy crops.

[d] The potential biogas from landfills is estimated at about 230 billion ft^3 per year as shown in table 5.12.

[e] Forestry high-housing, high biomass-demand scenarios.

[f] The high-yield scenario assumes 3% annual increase in yield.

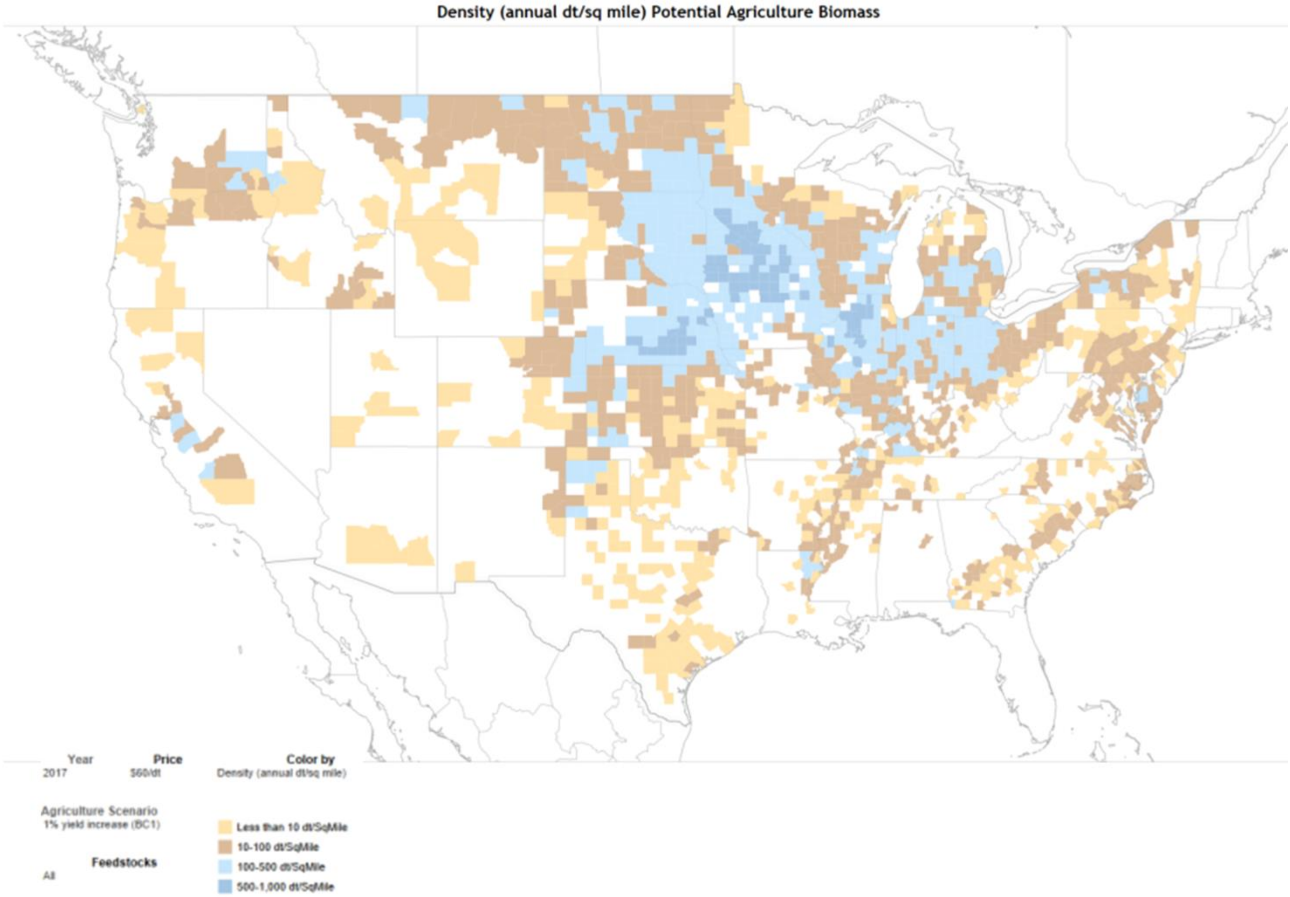

Figure 13. Combined potential agricultural residue supplies at $60 per dry ton or less at roadside under agriculture 1% yield increase assumption for 2017 (U.S. DOE 2016).

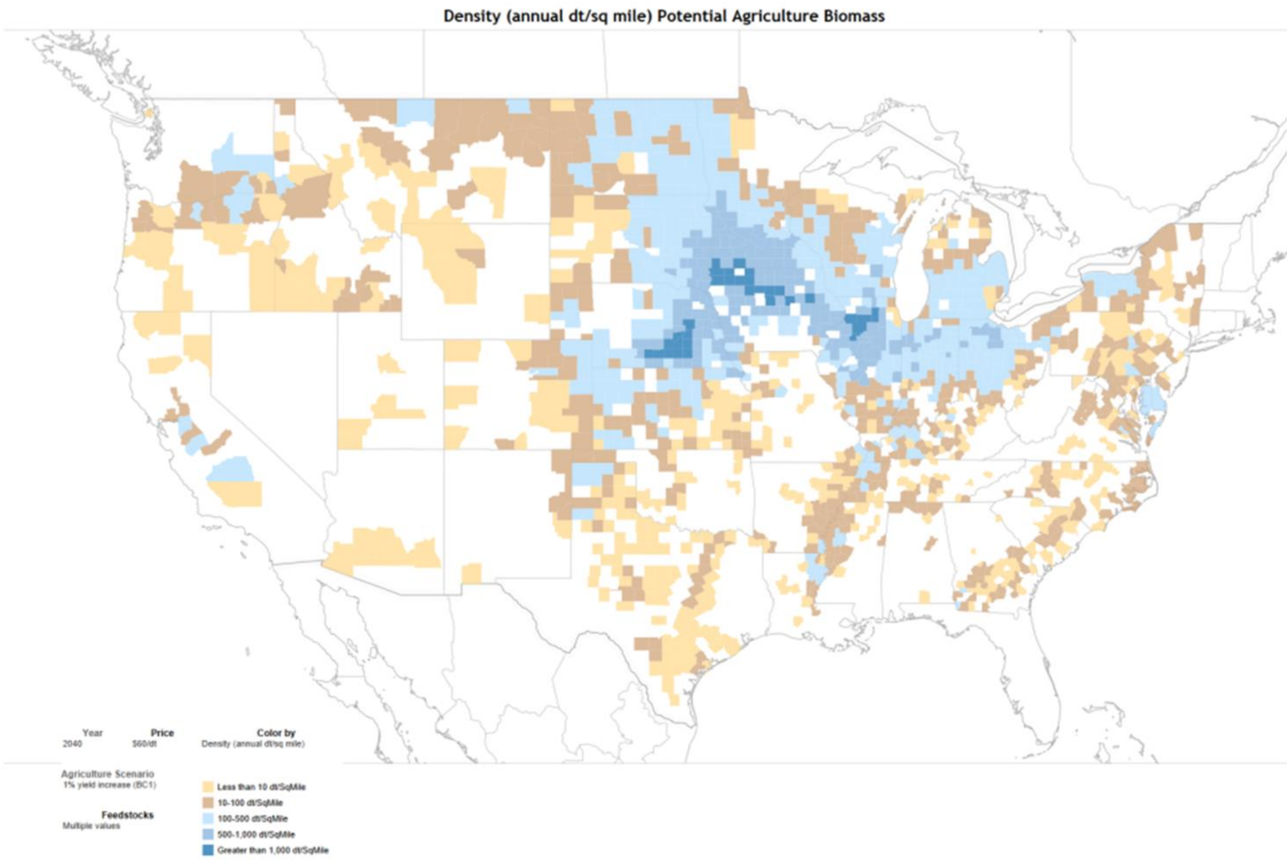

Figure 14. Combined potential agricultural residue supplies at $60 per dry ton or less at roadside under agriculture 1% yield increase assumption for 2040 (U.S. DOE 2016).

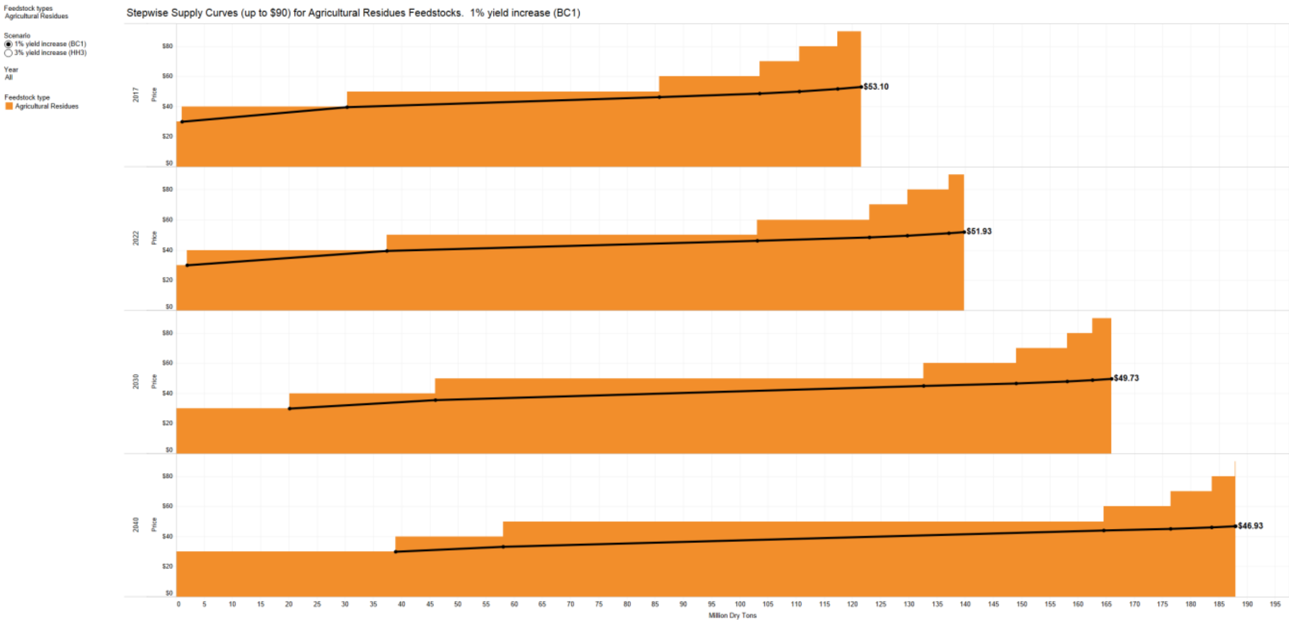

Figure 15. Stepwise Supply Curves (up to $90 per dry ton) for Agricultural Residues Feedstocks: 1% yield increase (U.S. DOE 2016).

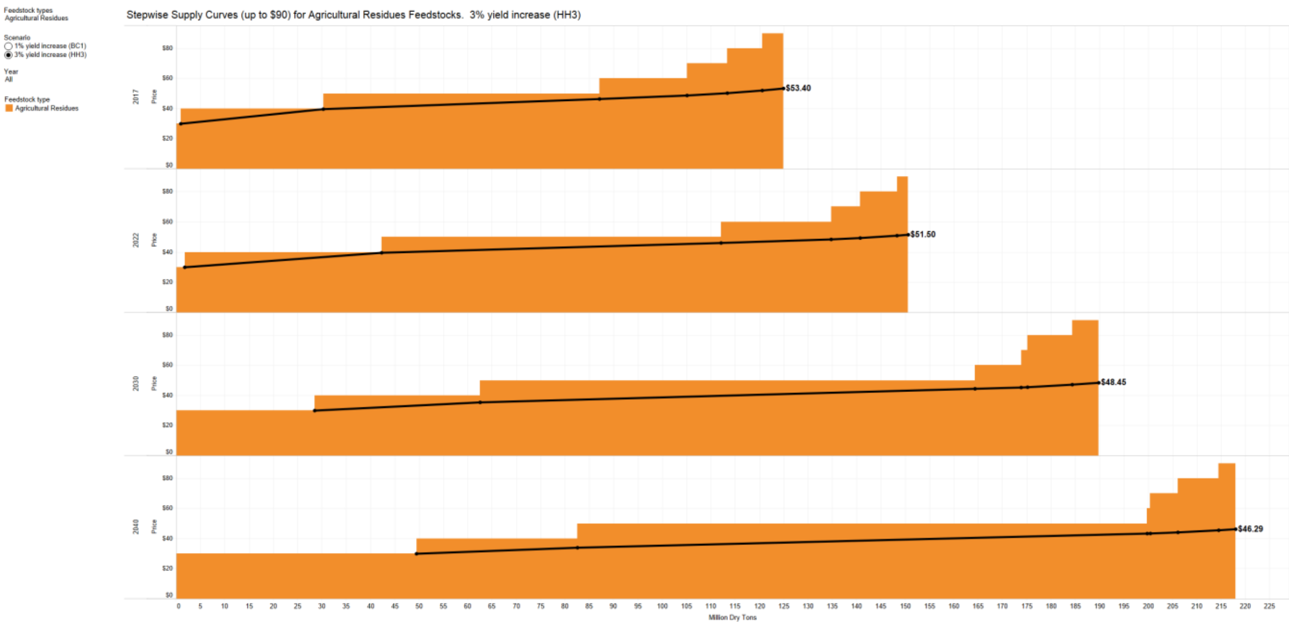

Figure 16. Stepwise Supply Curves (up to $90 per dry ton) for Agricultural Residues Feedstocks: 3% yield increase (U.S. DOE 2016).

4.5.3 Canada

Agricultural residue supply-cost curves are not publicly available for Canada. Modelling carried out by Kumarappan et al. (2009) showed the volume of agricultural residue available below US$50 per tonne to be relatively small, when compared with forest and mill residues (Table 3).

Table 3. Biomass supply cost estimates for Canada (in 2008 US$) (Kumarappan et al. 2009).

Biomass Price, US$/dry tonne*	**Quantity Available (million dry tonnes)**				
	Municipal Solids Waste	**Agricultural Residue**	**Forest & Mill Residues**	**Energy Crops**	**Total****
30	1	6	12		20
40	2	7	12		22
50	3	7	30		40
60	4	31	43		79
70	5	37	43		85
80	6	42	43	26	117
90	7	42	43	30	121
100	7	42	43	31	123

* US$ (2008) at the biorefinery gate
** Total values may differ from summed amounts due to rounding.

Another study, undertaken in 2009, estimated the logistical costs associated with agricultural residue procurement in Canada. The aim of the study was to identify feedstock types and costs in order to supply 700,000 dry tonnes of agriculture residue to a future second generation biofuel facility. Residue costing included harvesting, storage, transport and a growers' payment costs. The study estimated residues to cost:

- CAN$65 per dry tonne of cereal straw or CAN$0.33/dry tonne/km in Western Canada; and
- CAN$86 per dry tonne of corn stover or CAN$0.43/dry tonne/km in Eastern Canada.

These values were significantly greater than the CAN$35 per dry tonne value that was frequently reported in the literature at this time. Over time, figures cited on feedstock availability and cost have varied greatly and precaution should be taken to confirm the methodology used in the estimation before making claims about the potential.

Relative to many other countries, there may appear to be vast amounts of residues potentially available in Canada. The real opportunities are site specific. The supply chain case study described in this report, conversion of corn stover into cellulosic sugars in Southwestern Ontario, is one such opportunity. The first estimates of the cost of stover were carried out in 2012-2013 using existing harvesting equipment. Since this time, several stover harvest trials have been undertaken in this region using more specialized equipment developed in the U.S. for large volume collection. This has provided a better understanding of how producers might integrate stover collection into their operations and reduced the cost of stover collection. A comparison of these two cost estimates, broken down by element, is presented in Table 4.

Table 4. Cost of corn stover collection, storage and transport in Southwestern Ontario (Marchand 2015).

Itemized Harvest Cost	**CAN$ /tonne stover at 15.5% moisture 2013 Estimates**	**CAN$ /tonne stover at 15.5% moisture 2015 Revised Estimates**
Flail chopper/inverter	17.28	9.43
Rake	7.68	0
Large square baling	36.45	14.03
Stacking end of field	4.55	5.72
Storage end of field, tarped	6.76	8.30
Nutrient replacement	9.78	9.86
Production management	12.38	7.10
Corn stover cost at farm gate	94.88	54.44
Transportation to facility	13.49 (for 75 km)	26.78 (for 100 km)
Administration	0.85	0.85
Corn Stover Cost, delivered	109.22	82.07

At a finer spatial scale, crop residue removal can also vary with soil type and topography. That is, these site parameters affect susceptibility to soil erosion and future crop yields, and could result in different harvest protocol requirements. Modelling work by Dr. Jian Gan of Texas A&M shows how stover costs change with the rate of removal. Jian Gan modelled the stover removal costs for the four main soil types in six counties of Southwestern Ontario. Marginal cost calculations were derived using approaches developed by Gan and Smith (2012), and according to assumptions on harvest and baling cost, nutrient losses, and erosion outlined by the authors. The preliminary results for one of the soil types (Brookston) are shown in Figure 17. At a low removal rate, baling costs dominate the total marginal costs, but as removal rates increase the nutrient replacement costs and future yield losses due to soil erosion become more important. The optimal removal rate for the Brookston soil under conventional tillage practice is approximately 25%, above which the costs rise rapidly. At a field level, both soil type and agricultural practices can influence the total stover cost and the optimal rate of residue removal from a field.

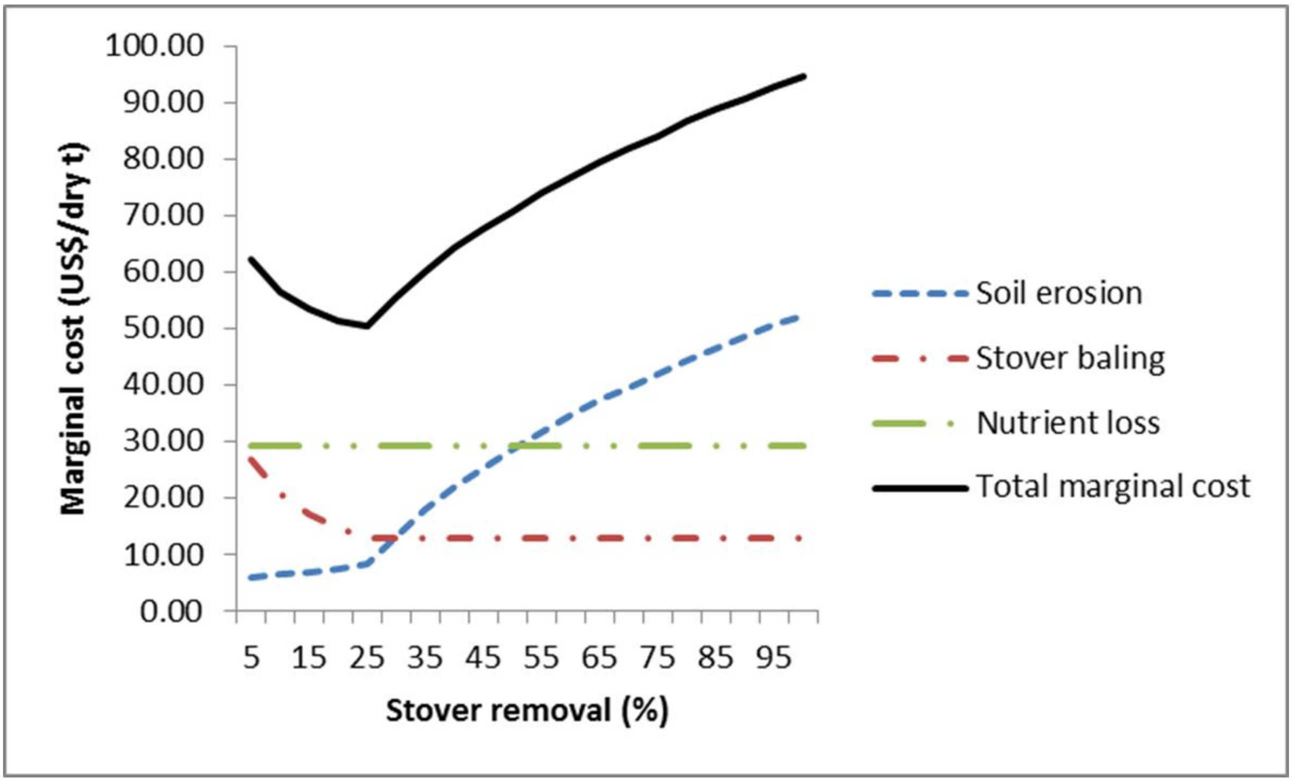

Figure 17. Marginal stover cost for Brookston soil (conventional tillage, 1% discount rate).

4.6 Environmental potential

4.6.1 USA

A sustainability assessment (Volume 2) to the 2016 Billion Ton Update (Volume 1) by U.S. DOE (2016) was published in January 2017 (U.S. DOE 2017). The report assesses the environmental impacts of the scenarios developed in Volume 1, but does not restrict the potentials further that what is presented in Table 2 above.

4.6.2 Canada

Several provinces, such as Alberta, Ontario and Quebec, have carried out more detailed biomass inventory work at regional scales. Annually, Ontario producers grow 2.5 million acres (1 million ha) of soybeans, 2.3 million acres (0.9 million ha) of corn and one million acres (0.4 million ha) of winter wheat. Studies completed for the Ontario Federation of Agriculture showed that 3 million tonnes (2 million tonnes of corn stover and the rest wheat straw) could be sustainably removed for ethanol or biorefinery production in the Province of Ontario while maintaining soil organic matter (Oo 2012). Recommended residue harvest numbers were developed for each county taking into account soil organic carbon levels, tillage practices, livestock numbers and typical crop rotation. As shown by the example in Table 5, the total and recommended residue harvest levels for a typical rotation can serve as a useful guide for siting decisions. This county level of detail is needed to develop a sustainable biomass feedstock chain to site a facility that would use large volumes of agricultural residue on a multi-year basis.

Table 5. Recommended residue harvest for Lambton County, Ontario (Oo and Lalonde 2012). Soy bean alone cannot maintain soil organic matter and requires addition of organic matter from other crops through crop rotation or manure fertilisation.

Year	Crop	Harvestable residues (tonnes/ha)	Recommended residue removal (tonnes/ha)
1	Corn	5.0	2.8
2	Soybeans	-3.5	0.0
3	Winter wheat	4.2	3.0
Total (tonnes/rotation/ha)		**5.7**	**5.8**

In the Province of Québec, 387,000 ha of corn grain and 280,000 ha of soybeans are generally produced annually. Also, there is an estimated 300,000 to 500,000 ha of marginal and unexploited agricultural land suitable for purpose grown agricultural biomass. Due to Quebec's climate, there is very limited winter wheat production; however, there are 232,500 ha of other cereal grain production that could contribute crop residue volumes.

Given the different economies of scale of ethanol versus chemical production and the residue distribution patterns, these might be better suited to a smaller biochemical-driven biorefinery than larger scale lignocellulosic ethanol production. Further technological developments and the use of feedstock blends, such as agricultural residues mixed with perennial crops, could give rise to a variety of different opportunities.

Environmental sustainability is a key factor in determining the feasibility of commercial scale conversion of agricultural residues. In addition to obtaining adequate financial returns, agriculture producers are concerned with maintaining environmental sustainability. As shown in the work by Jian Gan, there is a cost to soil erosion and a point where stover harvest does not make sense from both environmental and economic perspectives. Ontario Federation of Agriculture recommends that only one third of the available stover be removed from a field. La Coop fédérée, the Province of Quebec's largest agriculture cooperative, is developing guidelines for residue removal to ensure that soil productivity will be maintained.

The remainder of Canada sections of this report focus on the regional case of a corn stover-based biorefinery being contemplated for Southwestern Ontario. This region has been targeted for future biorefinery development as it has high biomass yields per acre that are expected to continue to grow, a well-developed transportation corridor, is in close proximity to a variety of manufacturing industries, including the Sarnia biohybrid industrial park, and is close to the U.S. marketplace. Further description of this case is included in Appendix A.

4.7 Availability at operational level

There is growing recognition that supply chain development for lignocellulosic production is site specific. It needs to make economic sense, be environmentally sustainable and fit with the rotations of agricultural production in a given area. As crop residues are by-products of grain production – the core business of agriculture – residue availability will be affected by the demand for grain and how well the harvest of residue fits into a farm operation. Agriculture producers will grow what the market demands and can be profitably produced on their land. They enjoy this flexibility in production, and may choose to keep this flexibility rather than to tie themselves into long term contracts. For this reason, it is unrealistic to assume 100% participation rate even if the economics appear to work and environmental sustainability issues are addressed. Also, in colder climates, the window of opportunity for fall residue removal could be very small or even non-existent some years. For example, a late harvest combined with an early winter could lead to a difficult choice between harvesting residue and preparing the field for the next crop cycle. Heavy rains during the residue harvest period may also limit accessibility to harvest machinery and increase the residue storage costs.

At the level of the agriculture producer, decisions on residue utilization follow a logic model to ensure long term sustainability. As shown in Figure 18, there are a number of key factors that help to determine whether crop residue could be harvested in a sustainable manner. The presence of adequate soil carbon levels and crop grain yield, hence sufficient biomass to consider harvesting are at the base of the pyramid. In the case of Southwestern Ontario, soils with at least 2.0% organic carbon are considered to be suitable for corn stover harvesting as long as grain yields exceed 150 bushels per acre (9.4 tonnes per hectare). Assuming both factors are positive, a producer would implement best management practices to ensure that the residue and other inputs being returned to the soil are sufficient to support the future crop production. These practices would depend on the soil type and topography, and could include reduced tillage, different crop rotations, use of cover crops, and application of digestate or manure. Soil erosion control practices become critical to support the consistent removal of, for example, 2.5 to 5 dry tonnes of corn stover per hectare on a regular basis.

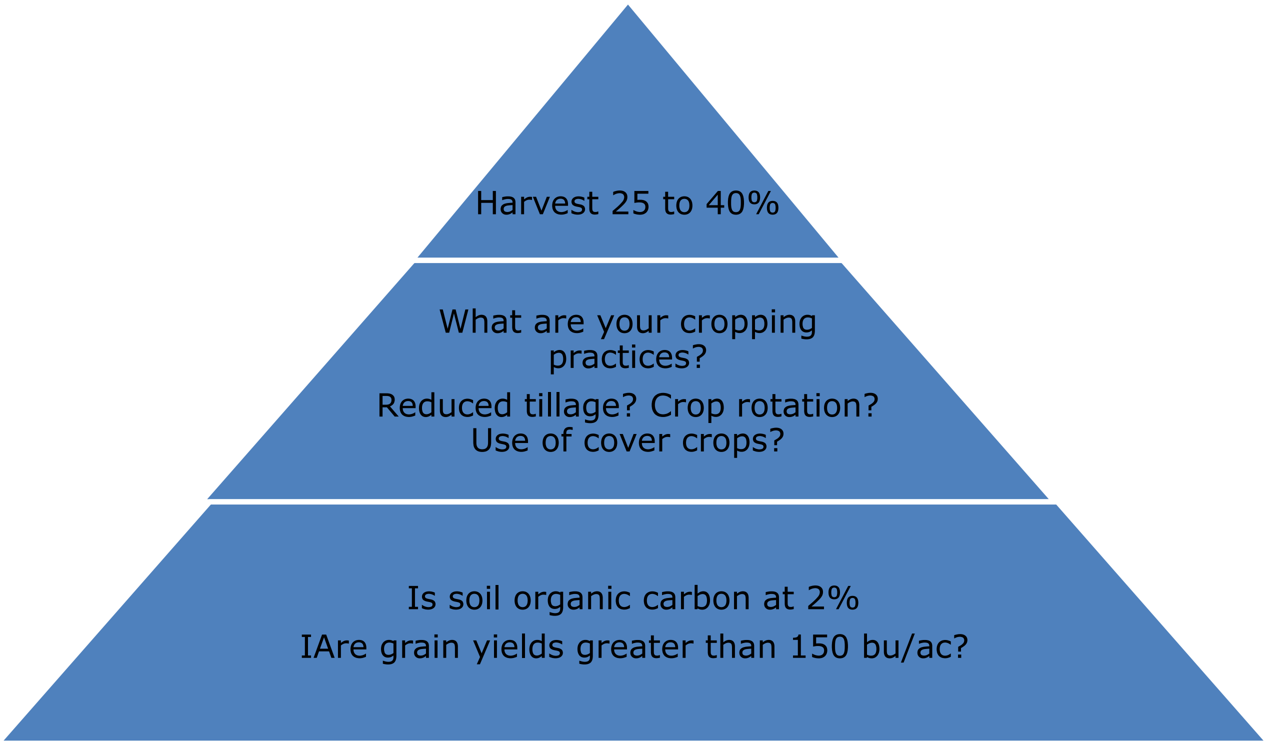

Figure 18. Decision-making pyramid for an agriculture producer.

For all of the above reasons, the potential availability of biomass from a given area should be considered as a range. As crop residue use becomes more common place, supply logistics systems would ensure that a consistent reliable supply could be delivered to downstream processors. These supply systems however will not evolve automatically. The establishment of an agricultural residue supply chain that meets the criteria of its (probably diverse) clients will require a consistent and stable policy framework, long-term contracts, incentives for farmers to bear the initial investment risk, and credible sustainability guidelines. Significant investments in harvesting equipment would be required mobilize large volumes, particularly if the harvest windows are short. Bloomberg (2011) estimated that the EU agricultural sector would require an annual investment of €760 Million in agricultural machinery to mobilize the crop residue fractions that are economically viable given a gate price of €80 per tonne. The amount of biomass that is consistently available for many foreseeable years will also influence the type of bioproduct that is produced. For example, the different economies of scale of ethanol versus chemical production will indicate a preference for a certain amount of biomass available in a given region. Smaller feedstock areas might be better suited to a smaller biochemical-driven biorefinery than larger scale lignocellulosic ethanol production. Further technological developments, new designs for feedstock logistics, and greater use of feedstock blends, such as agricultural residues mixed with perennial crops, could give rise to a variety of different opportunities.

Estimated potentials of agricultural residues vary widely among studies. A review by Bentsen and Felby (2012) showed a variation in estimated technical potentials of agricultural primary residues in the EU27 by 2050 to range from approximately 0.5 to 5.0 EJ yr^{-1}. The apparent lack of reproducibility requires caution when interpreting resource potentials. Within the Biomass Energy Europe (BEE) project causes for variability were examined. The project found that the major reasons contrasting resource potentials were attributable to (Torén et al. 2011):

- Ambiguous and inconsistent definitions of concepts of potentials
- Lack of consistent and detailed data on (current) biomass production and land productivity
- Ambiguous and varying methods of estimating (future) biomass production and availability
- Ambiguous and varying assumptions on system-external factors that influence potentials (such as land use and biomass production for food and fibre purposes).

In the case of very large differences between resource estimates, Torén et al. (2011) state that the latter reason is the most influential.

4.8 Economic competitiveness relative to reference energy systems

Many drivers influence the economic competitiveness of agricultural residues and biomass more generally as alternatives to fossil resources. In Denmark biomass is exempt from CO_2 taxes making them competitive relative to oil and natural gas (Figure 19). Straw has historically been the cheapest biomass fuel available.

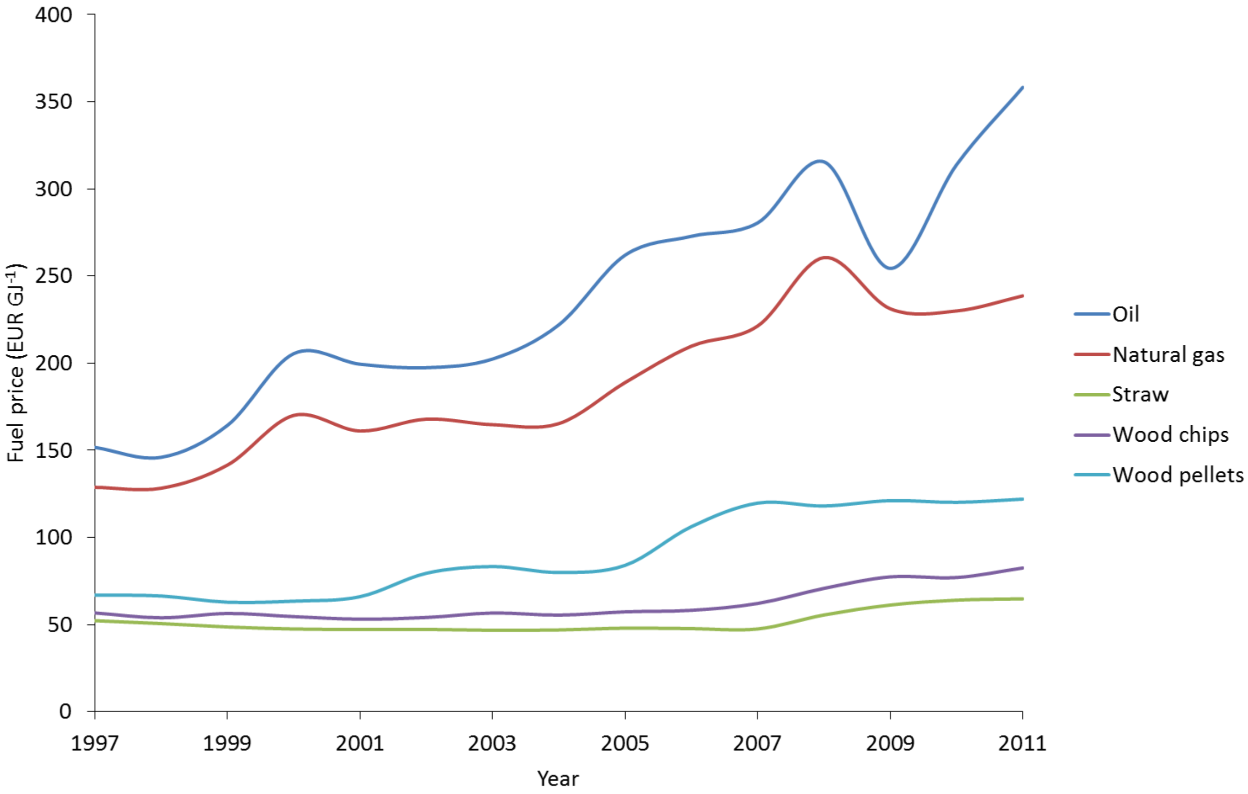

Figure 19. Fuel prices incl. taxes in Denmark for fuels delivered to district heating plants (Dansk Fjernvarme 2012).

As part of government plans on future bioenergy deployment projections on biomass prices have been made (Ea Energianalyse 2014). Straw delivered to district heating or CHP production is expected to increase from the current approx. DKK40 GJ^{-1} (€5.33) to approx. DKK55 GJ^{-1} (€7.33) by 2050. Deliveries to CHP plants are considered to be slightly more expensive (+€0.50-€0.66 GJ^{-1}) than to district heating plant due to longer transportation distances (Figure 20).

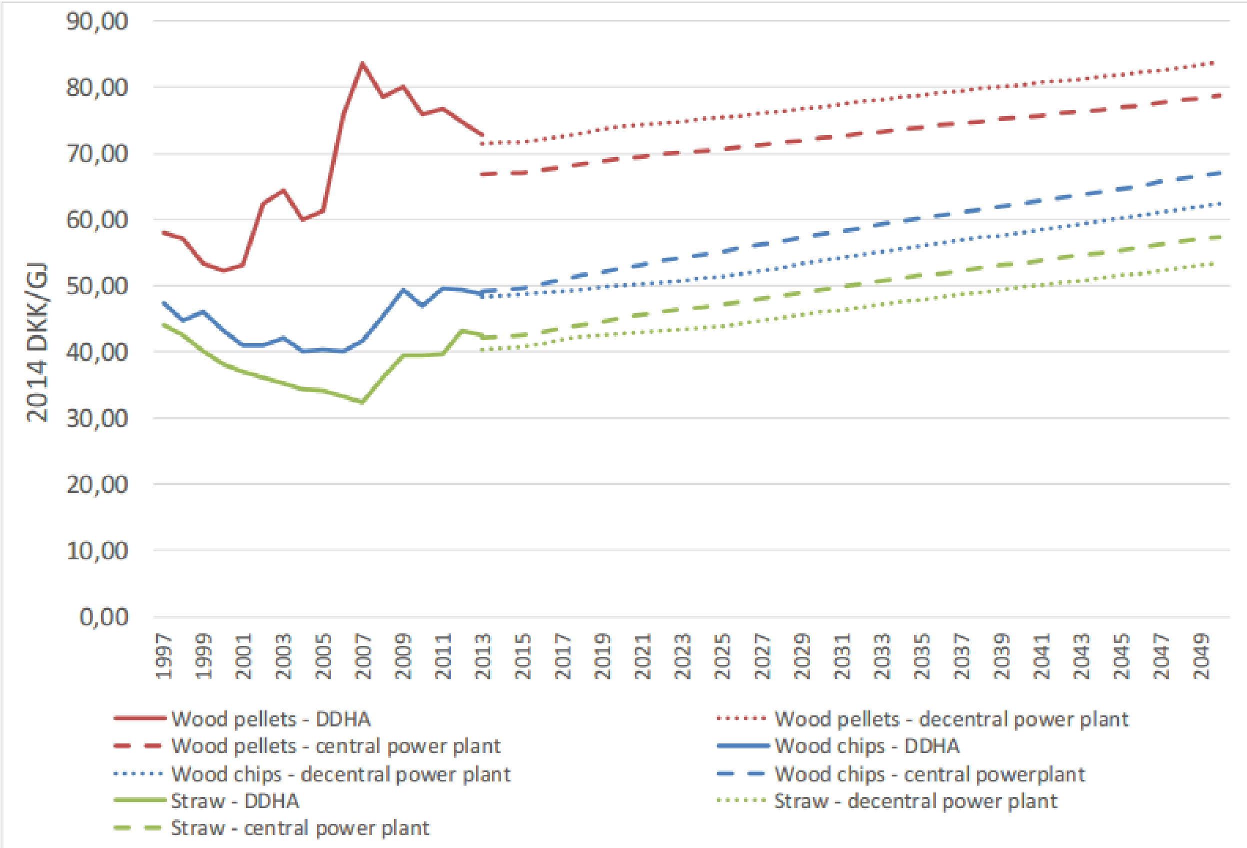

Figure 20. Price projections for biomass delivered at centralized CHP plants and more distributed district heating plants (Ea Energianalyse 2014).

In the U.S. and Canada, bioenergy has often been more expensive than other forms of fossil fuel and renewable energy. In both countries, policies and programs have been used as temporary measures to help with the installation of new equipment or facilities. Although neither country has implemented a national carbon tax, new policies are expected to increase the use of renewable energy and reduce GHG emissions. Several provinces (in Canada) and states (in the U.S.) have GHG reduction obligations which indirectly reduce the cost of bioenergy when compared to fossil fuels. However, the increased value is still not always sufficient for bioenergy to replace fossil fuels. As shown in Figure 21, the cost of bioenergy (energy derived from biomass pellets) is significantly greater than the price of natural gas and below that of oil and propane. These values date from the year 2011 and the recent drop in oil prices have shifted bioenergy further to right.

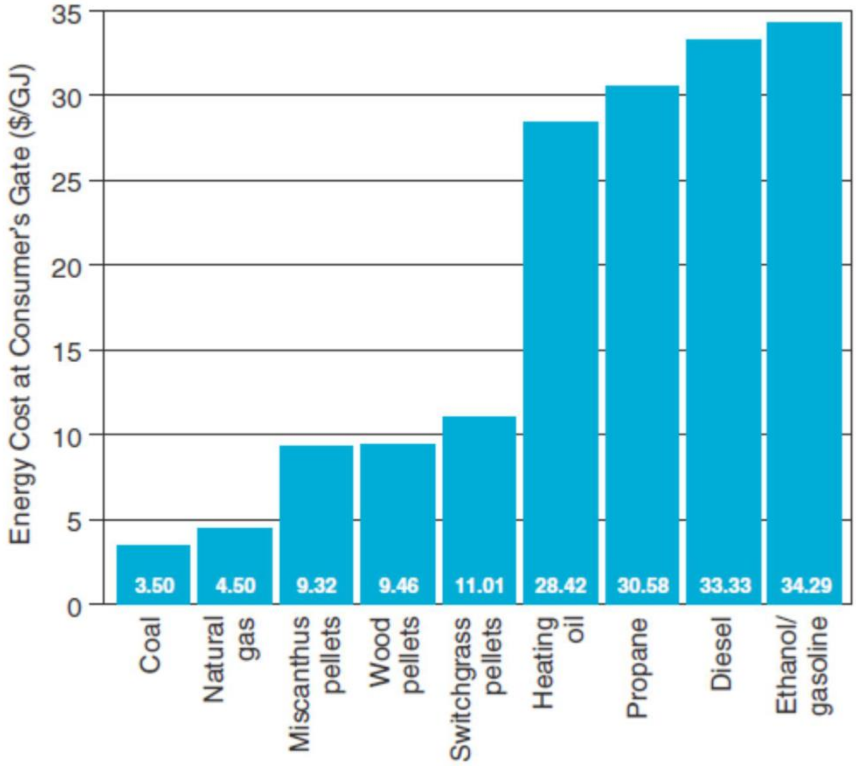

Figure 21. Cost to the consumer for bioenergy from purpose-grown biomass pellets and other energy sources in Ontario, Canada.

Even though oil prices are expected to rise again, the economic argument for bioenergy as the primary product derived from biomass is difficult to make in many parts of Canada. In its recent energy forecast to 2040, the National Energy Board projected modest growth of electricity from biomass, increasing from 2.2 GW in 2014 to 3.8 GW in 2040. By 2040, both wind and solar energy are expected to exceed biomass with, respectively, 19.4 and 5.0 GW capacity in 2040. The majority of additions, 84% of the total 45 GW additions, are expected to be in the form of natural gas, wind or and hydro facilities (National Energy Board 2016). Therefore, the focus of the agricultural residue use in Southwestern Ontario has been placed on deriving higher value, non-energy products from biomass with bioenergy being produced from process residues.

5 Supply chain development

5.1 Logistical analysis of current supply chains

5.1.1 Denmark

Straw is baled in the field and transported for intermediate storage at the farm or energy utility. Straw used in larger CHP plants is delivered by road in the form of 500 kg bales. Despite more than 20 years of experience in increasing supply-chain efficiencies, inefficient road transport is still an issue in Denmark. Because of the low density of straw bales, road transportation is volume-constrained and trucks transport only one-third of their load capacity. Development of densified bales has not led to significant breakthrough on the operational level. Recently German machine manufacturer Krone has developed machinery to pelletize straw directly in the field (http://landmaschinen.krone.de) to densify the straw resource and reduce subsequent handling cost. The machine, however, has a must lower capacity than traditional balers.

5.1.2 USA

The cellulosic biofuel industry is still in its infancy; currently producing less than 1 million gallons (3.8 million litres) of cellulosic ethanol per year, and current practice may not represent that of a fully evolved industry. At this point in the U.S., the cellulosic biofuel industry relies on a vertically integrated feedstock supply system where agricultural residues are procured through contracts with local growers, harvested, locally stored, and delivered in low-density form to the nearby conversion facility. The vertically integrated supply system without active quality control measures has been demonstrated to work in a local supply context within high-yield regions (e.g., the U.S. Corn Belt). However, scaling up the biorefinery industry will require increasing feedstock quantities at decreasing costs and active quality control.

5.1.3 Canada

The logistics of harvest, baling, storage, transport, and pre-processing corn stover are currently being evaluated in Southwestern Ontario. This is a particularly promising region of the country with very productive agriculture, excellent transport links, demonstrated innovation capacity, and clusters of related industries and supportive communities. As such it is being seriously examined for the development of cellulosic sugars and other bio-products including bioenergy from agricultural residues. Millions of hectares of grain corn are grown in rotation with soybeans and winter wheat in this region. In 2015, grain corn yields averaged 10.67 tonnes per hectare (170 bushels per acre) and furnished three ethanol plants and one corn refiner. Work has been underway since 2010 to explore the feasibility of converting agriculture residues (mainly corn stover) and purpose grown crops into cellulosic sugars and other bio-products.

Industries along the supply chain are collaborating to support the implementation of a biorefinery. Work is underway on all fronts, including best management practices for stover removal, logistics design, economic modelling and technology assessment. Both existing ethanol producers and new technology companies are involved. Within a three to five year time horizon, at least one cellulosic sugar facility is expected to be in operation and new products are expected to be produced from corn stover.

The objective of the logistics work is to develop a practical scheme for providing a consistent supply of corn stover (or stover blended with wheat straw, switchgrass and Miscanthus) that:

- can be applied by agriculture producers under a variety of growing scenarios and weather conditions;
- satisfies the quality specifications of processors with minimal losses (or markets for lower quality material);
- arrives at a price point that is profitable and acceptable for all members of the supply chain; and
- does not have a detrimental impact on the following years' crop production.

As shown in Figure 22 harvest demonstration trials have been carried out with specialised high-density-baling equipment operating in a two-pass system. A number of harvest practices that have been developed in Iowa in the USA are being reviewed for their applicability in southwestern Ontario. It is critical that feedstock costs are kept low for the bio-processor while still providing sufficient financial incentive for agricultural producers to commit to harvesting a portion of their stover on a long-term basis.

Figure 22. Corn stover harvest demonstration at Woodstock Outdoor Farm Show (September 2014).

Work is ongoing to identify the management practices and harvesting systems best suited to this area. For example, in this region, corn harvest is carried out last in the year because corn can withstand frost conditions much better than soybeans. Current thinking is that a two pass system will be predominantly adopted as the moisture content of the stover could be too high during grain harvest. Care will be required to avoid picking up inorganic material during stover collection. Spring stover harvest has also been tested to provide flexibility to deal with poor fall harvest conditions and make better use of equipment and human resources. To meet the volumes requirements of 250,000 dry tonnes per year, sufficient stover supply could be derived from a mixture of fall and spring harvest. Such information has resulted in a more accurate and lower cost estimate for collected stover that is based on real farm trials with experienced equipment suppliers.

Equally important is longer term work to determine the impacts of stover removal on soil health. While much work has been carried out on corn removal for silage operations, partial removal for bioenergy or bioproduct uses is a new practice. Given that changes in soil indicators are slow and there is a wide variability in the soil types in this region, an interim harvesting protocol will be required to ensure that environmental sustainability is being addressed with a caveat to be reviewed every few years or as new information is uncovered.

In February 2016, Comet Biorefining announced the location of its cellulosic sugar plant in this region. Approximately 23,000 tonnes of dextrose and 33,000 tonnes of co-products would be produced from 60,000 tonnes of corn stover and wheat straw. This high purity dextrose could be subsequently converted into bio-based chemicals, such as succinic acid, or cellulosic ethanol. In total, 19 technologies were reviewed for their potential to support an attractive business case. With a real buyer, an efficient and sustainable feedstock supply chain must now be designed.

5.2 Operational challenges to realizing potential

There are a number of challenges to realizing the mobilization potential of agricultural residues for bioenergy and biorefining applications, including the following.

- **Feedstock cost:** The cost of delivered agricultural residue can represent close to 50% of the operating cost of a biorefinery, ultimately affecting the economic viability of the value chain.
- **Feedstock (bulk) density:** Unprocessed agricultural residues have relatively low bulk densities that translate into high transportation costs and limit the volume that can be collected.
- **Economic sustainability:** Residue harvest should not negatively impact the core business of agricultural producers, i.e. production of quality grains and oilseeds for food and feed. Numerous agriculture producers in a given region need sufficient financial incentive to harvest their stover, and to be convinced that there will be no short- or long-term reduction in the productivity of their land.
- **Environmental sustainability:** Absence of guidelines and best management practices, as well as long term soil studies that provide validation of these practices, on the amount of residue (from what soil type and under what conditions) that must be retained without impacting soil health.
- **Feedstock quality:** Processors require a consistent supply of feedstock of a known feedstock quality. Agricultural biomass is inherently heterogeneous in nature and subject to degradation, resulting in a range of feedstock quality. Specifications and tolerances must be clear, and markets are needed for off-spec residue.
- **Feedstock availability:** Crop residue availability (in quantity, quality, and cost) is subject to changing biophysical factors. Climate and weather fluctuations can positively and negatively affect yields and impact the timing of harvest. While conventional feedstock supply systems are well adapted to supply biorefineries in local supply context within high biomass yield regions, they could encounter issues in some years due to inclement weather (e.g., drought, flood, heavy moisture during harvest, etc.). These supply uncertainties tend to increase the risk, which could limit the biorefinery concept from being broadly implemented.
- **Market uncertainty:** Biomass supply and demand is subject to changing market factors (e.g. fluctuating markets for primary products such as corn and wheat, competing uses, and prices of alternative raw material). Even in highly productive agricultural areas, supply and demand, costs and prices can be unpredictable. As is the case for grain production, markets need to exist for residue that does not meet the quality requirements of the downstream processor.
- **Weak framework conditions:** Absence of a stable policy framework for investments, e.g. constant feed-in rates, duration of renewable energy and biofuel mandates, market for carbon, valuation of GHG reductions from bio-based systems, etc. and dedicated strategies that support new value chain development from R&D through commercialisation.
- **Investment gridlock:** Chicken and egg situation that impedes investment, i.e. processors want to build a facility if there is a guaranteed, consistent supply of crop residue while residue providers want a commitment from a processor. Residue processors seek flexibility with respect to feedstock procurement and can appear to be indifferent to

the type of feedstock as long as quality and cost specifications are met. On the other hand, agriculture producers need assurances that there will be buyers for their residue before making significant investments.

- **Other:** Barriers typical of an emerging industry including a lack of information and misinformation, perception of high risk, little commercial experience, need for market acceptance, etc.

Current bioethanol and biorefinery supply chain systems where feedstocks are procured through contracts with local growers, harvested, locally stored and delivered in low-density format to conversion facilities can only partially address these issues. Further optimization of the agricultural residue supply chain is required for large scale mobilization.

5.3 Opportunities to increase supply chain efficiencies

Currently, the U.S. cellulosic biofuel industry relies on a vertically integrated feedstock supply system, often referred to as the conventional system, where feedstock is procured through contracts with local growers, harvested, locally stored, and delivered in low density format to the nearby conversion facility (Figure 23). These conventional systems were designed to support traditional agricultural and forestry industries. The conventional system has been demonstrated to work in a local supply context within high yield regions (e.g., the U.S. Corn Belt or southeast forest lands). However, scaling up the biorefinery industry will require increasing feedstock volumes at decreasing costs. The strategic goal of the U.S. Department of Energy's Bioenergy Technologies Office (BETO) is to meet a \$88 (in US$_{2011}$) per dry tonne delivered on-spec feedstock cost at the throat of the conversion facility (including grower payment and logistics) in support of reaching a \$0.79 per litre of gasoline equivalent (LGE) delivered fuel target by 2022 (DOE 2013). Targets are generally iterated between advancements in feedstock logistics and the development of more robust conversion systems. But it remains unclear if a conventional system will allow for the current goal to be met.

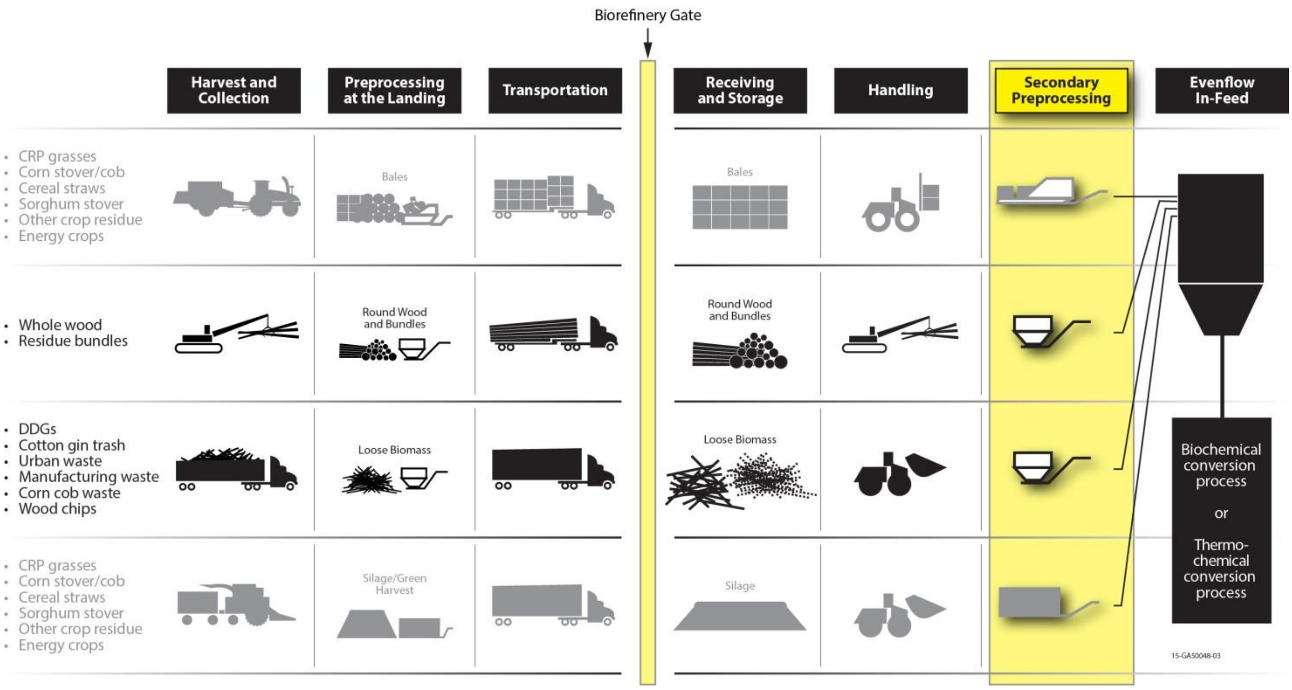

Figure 23. Schematic design of the conventional feedstock supply system (Lamers et al. 2015).

Different analyses (Hess et al. 2009, Argo et al. 2013, Jacobson et al. 2014, Muth et al. 2014) have shown that the conventional system fails to meet this supply cost target outside of highly productive regions and could encounter issues even in highly productive regions in some years due to inclement weather (e.g., drought, flood, heavy moisture during harvest, etc.). These supply uncertainties tend to increase the risk, which could limit the biorefinery concept from being broadly implemented.

The advanced uniform feedstock design system (Hess et al. 2009) introduces methods to reduce feedstock volume, price, and quality supply uncertainties. It is based on a network of distributed biomass pre-processing centres, so-called depots, which use one or several biomass types to generate uniform format feedstock 'commodities' (Figure 24). These commodities are intermediates with consistent physical and chemical characteristics that meet conversion quality targets and at the same time leverage the spatial and temporal variability in supply volumes and costs by improving flowability, transportability (bulk density), and stability/storability (dry matter loss reduction).

A fundamental difference between the two supply systems is that the conventional system relies on existing technologies and agri-business systems to supply biomass feedstocks to pioneer biorefineries and requires biorefineries to adapt to the diversity of the feedstock. On the other hand, the advanced system emulates the current grain commodity supply system, which manages crop diversity at the point of harvest and at the storage elevator, allowing subsequent supply system infrastructure to be similar for all biomass resources (Hess et al. 2009, Searcy and Hess 2010).

Previous comparisons between the two supply systems were focused on logistic costs (Argo et al. 2013, Muth et al. 2014). They concluded that the higher initial investments into pre-processing costs (depots) and more transportation activities increase average logistic costs, making a conventional system appear more attractive. On the other hand, advanced systems show lower cost variability and would enable other benefits, e.g., economies of scale at the biorefinery.

While pre-processing operations at the depot add costs to the feedstock supply system, they address many of the supply risks associated with the conventional system and create wider system benefits. A recent study translated several of these benefits into cost reductions per litre of gasoline equivalent (LGE) for the biorefinery operation (Lamers et al. 2015). Supply risk reduction (leading to lower interest rates on loans), economies of scale, conversion efficiency improvements, and reduced equipment and operational costs at the biorefinery outweigh the pre-processing costs involved in the depot operations. The authors found total cost reductions per LGE range between US$0.60 to US$0.34 for biochemical and US$0.44 to US$0.25 for thermochemical conversion pathways (Lamers et al. 2015). Naturally, these cost reductions appear on a systems level and may differ for the individual actors in the supply chain.

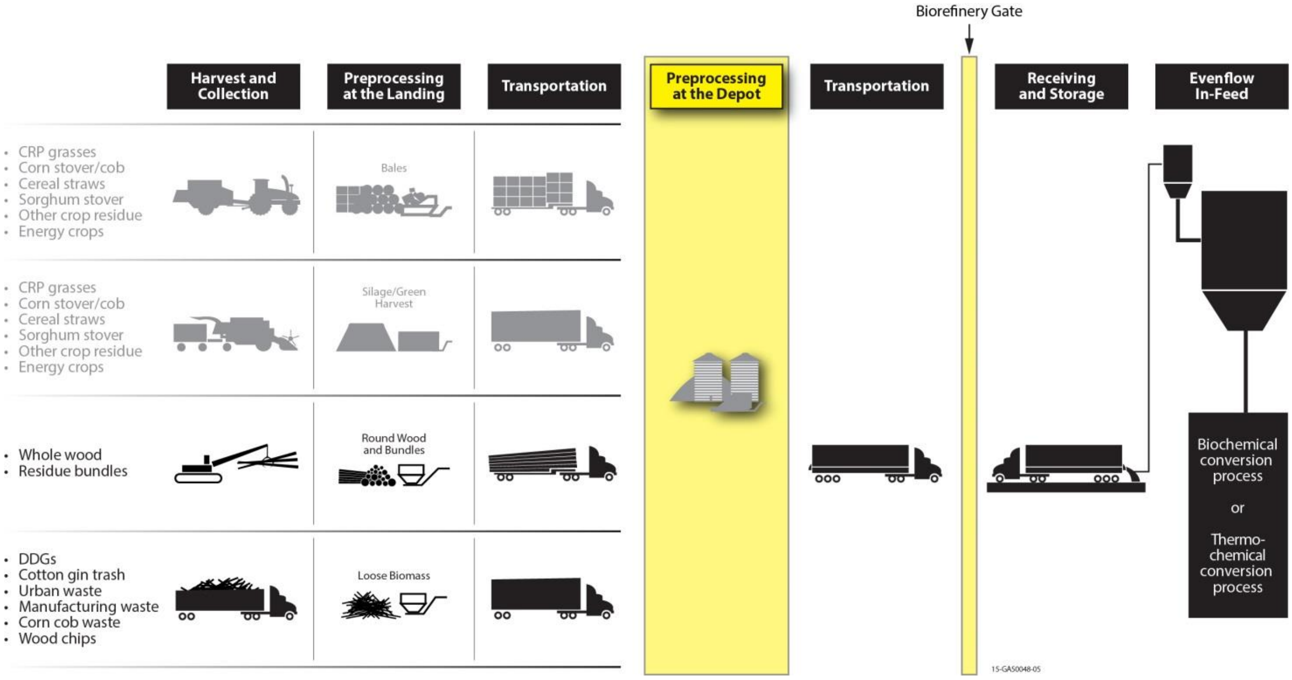

Figure 24. Schematic design of the advanced feedstock supply system (Lamers et al. 2015).

Depot systems, when matched with the appropriate mode of transportation, could help reduce temporal and spatial biomass variability and allow access to greater quantities of sustainable biomass (including stranded resources) within a cost target by decoupling the biorefinery from feedstock location. Reducing profitability risks could also help leverage the reluctance from the investment community to invest in larger facilities, enabling production economies of scale. The variability of feedstock supply to biorefineries is recognized as an investment risk by financial institutions. Reducing the variability of feedstock supply will reduce associated project risks which will be reflected in the annual percentage rate for financing biorefineries. Also, depots will reduce the handling infrastructure (for raw biomass in various formats) at the biorefinery, improve in-feed operations and thus reduce investment and operating costs. This should further reduce investment risks. While this comparison provides a first-of-a-kind holistic supply system perspective, future research is needed with respect to depot sizing, location, and ownership structures.

6 Sustainability

Defining and establishing metrics to effectively quantify sustainability is challenging, because there are many aspects of sustainability. Distinguishing the effects of bioenergy on the environment and society from the effects of alternative or baseline activities is difficult. Indicators can be useful tools for decision makers in policy and management if they provide practical guidance in an accepted way to quantify sustainability. While decision support tools can help in identifying indicators that are relevant for a particular system (Convertino et al. 2013), systematic approaches for selecting and using indicators are rare (Niemeijer and de Groot 2008, Lin et al. 2009). Ongoing efforts have developed what resembles a shopping list of potential indicators that cover different aspects of sustainability.

Five different indicator frameworks were reviewed to assess the sustainability of bioenergy: GBEP, ISO 13065, PROSUITE, LEEAFF and an approach developed for the U.S. Department of Energy. The frameworks are applied to the three country cases of mobilizing straw or corn stover to produce bioenergy, transportation fuels or bioproducts. The GBEP framework was applied to a Danish case, the GBEP, ISO 13065, PROSUITE and LEEAFF frameworks were evaluated for their suitability to evaluate a supply chain under development to a case in Ontario, Canada, and the U.S. approach is described. The results of the analyses are discussed jointly to identify opportunities and barriers for straw and stover based bioenergy or bioproducts under different conditions, including policy, biophysical, environmental, economic, and social contexts.

6.1 Sustainability goals of bioenergy

Sustainability ensures the environmental, economic, and social needs of the present generation without compromising the ability future generations to meet their needs (United Nations General Assembly 1987). It relates to the life cycle of products that replenishes resources and is constrained by human and environmental needs over the long term (Seuring and Müller 2008).

Environmentally, sustainability of the bioeconomy (including bioenergy systems) refers to the interaction of biophysical and ecological properties (e.g. soil conditions, surface and ground water quality and quantity, air quality, biodiversity, GHG emissions, and land productivity) (McBride et al. 2011) with environmental stressors, including human activities at several scales. Environmental sustainability may imply efficient use of natural resources, such as water (Juwana et al. 2012) and energy, and benign disposal of wastes (Sydorovych and Wossink 2008). Decisions about bioenergy management practices and the use of different feedstocks must consider variability of the ecoregions where bioenergy is produced.

Economically, sustainability of bioenergy encompasses the relative costs associated with the life cycle of a complete supply chain and all its elements. Economic sustainability means that cultivation, processing, distribution, and end-use costs to purchasers of bioenergy are competitive with other energy sources and that social equity is facilitated while avoiding the obligation of unfair burdens on any particular location, region, or demographic group. For producers, costs, benefits and risks must be found competitive or advantageous relative to alternative land use and energy options. Economic sustainability tends to improve when purchases of supplies for production and borrowed capital are reduced, cash flow is adequate to cover operational expenses on time, and profits increase (Sydorovych and Wossink 2008).

Socio-politically, sustainability of bioenergy implies fair access to energy and ecological resources and ensures that bioenergy production does not prevent people from secure access to food and fibre crops (Ewing and Msangi 2009) or disrupt livelihoods (e.g., employment, income, or safety) (Dale et al. 2013a).

The concept of sustainability also includes respect for workers' rights to equitable wages and working conditions, with safety as a primary goal. Human health and welfare implications of bioenergy are particularly important for marginal populations and developing countries, which rely on biomass as a primary fuel (Ewing and Msangi 2009).

6.2 Regulatory context for bioenergy sustainability

The regulatory context of bioenergy sustainability gives rise to specific priorities, which shape the definition of goals and objectives for analysis and choice of indicators. For example, requirements mandated by United States federal laws differ from regulations crafted by the European Commission[3].

[3] http://ec.europa.eu/energy/en/topics/renewable-energy/biofuels/sustainability-criteria

Title II of the U.S. Energy Independence and Security Act (EISA) of 2007 focuses on "energy security through increased production of biofuels" and defines reporting requirements for estimated environmental impacts of energy technologies (U.S. Public Law 110-140). EISA requires a life-cycle assessment of biofuel emissions, and the assessment must include direct emissions from bioenergy production as well as indirect emissions from land use change elsewhere in the world caused by the bioenergy production (Liska and Perrin 2009). Compliance with EISA requires measures of air, water, hypoxia, soil, pathogens, ecosystem health, biodiversity, and non-native vegetation. EISA mandated life cycle assessments must also consider trade of renewable fuels and feedstocks and environmental impacts outside the United States caused by biofuel production driven by the Renewable Fuel Standard (RFS). The RFS requires that transportation fuel sold in the U.S. contains a minimum of renewable fuels (Sissine 2007).

The California Air Resources Board (ARB) established a Low Carbon Fuel Standard (LCFS), with the goal of "a reduction of at least 10 percent in the carbon intensity of California's transportation fuels by 2020" (http://www.arb.ca.gov/fuels/lcfs/lcfs.htm). LCFS goals include a reduction of greenhouse gas emissions to 1990 levels by 2020, a reduction of the state's dependence on petroleum, and the creation of a market for clean transportation technology. The regulation assigns scores for the carbon intensity of different biofuel supply chains including corn and sugar cane ethanol, cellulosic ethanol from farmed trees, and from forest waste. The assignment is based on a modified version of the Global Trade Analysis Project model (CARB-GTAP) and life cycle assessment of energy use and greenhouse gas emissions using the CA-GREET model (http://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm), building on the GREET platform developed by Argonne National Lab.

The European Union is working to improve the sustainability of energy options across Europe (European Parliament and the Council 2009). The EU's Renewable Energy Directive (RED) and National Renewable Energy Action Plans (NREAP) has set a bioenergy target to be reached by 2020, aimed at ensuring security of supply, promoting technological development and innovation and providing opportunities for employment and regional development, especially in rural areas (European Parliament and the Council 2009). Aware of the implications for developing countries, the European Union intends that growth in biofuel markets will be of benefit to European producers and developing nations alike.

6.3 Identification of sustainability indicators for bioenergy

The demand for sustainability indicators has come from several directions. From life cycle assessment advocates, regulators and the climate change community there has been a focus on GHG emissions that often overshadow other environmental, social and economic aspects of sustainability. There has also been disproportionate focus on the "sustainability requirements" for bioenergy without adequate support to use comparable criteria on alternative energy sources and land management systems, e.g. agriculture. Furthermore, many people active in the development and promotion of sustainability standards are effectively stakeholders as employed researchers and consultants with own interests in a growing demand for modelling, certification, verification and related studies (e.g., LCA, Product Codes, chain of custody, and sustainability audits).

Acknowledgement of the need to establish sustainability indicators for bioenergy and associated measures has led to efforts to establish a standard suite of indicators. A suite of indicators can serve as a reservoir from which to compose subsets of indicators that meet specific goals. General agreement exists about the relevance of soil and air quality, water quality and quantity, greenhouse gas emissions, productivity, and biodiversity as categories of indicators of environmental sustainability (McBride et al. 2011). However, some indicators focus on management practices even though there is little scientific background to identify which practices are “sustainable.” Furthermore, most existing approaches use indicators that are numerous, too costly, very broad or difficult to measure (McBride et al. 2011, Dale et al. 2013a).

The host of standards and certification schemes for bioenergy sustainability can be categorized in many different ways. One characterizing variable is the object of analysis, which can range from a specific supplier to a national policy. An approach designed to show compliance with a certification scheme or demonstrate that a product is “fit for purpose,” will usually focus on a prescriptive set of indicators and documentation that must be prepared or presented to demonstrate that specific thresholds or targets are met. Other methods are designed to assess specific research questions related to the sustainability of processes, products, projects, policies and programs; these can be less prescriptive about documentation, are not necessarily concerned about threshold values, and focus more on replicable methods for data collection and analysis. Certification schemes and other sustainability assessment schemes can operate at different scales and be led by private or governmental entities.

The multi-stakeholder, international Roundtable on Sustainable Biomaterials (RSB) provides an example of a voluntary certification scheme. RSB is a private effort that brings together farmers, companies, non-governmental organizations, experts, governments, and inter-governmental agencies concerned with the sustainability in production and processing of biomaterials. The RSB has established a set of *principles* that describe “the general intent of performance”, and *criteria* representing “objectives of performance which are measurably operationalizing a principle”(Roundtable on Sustainable Biomaterials 2011). An RSB *indicator* reflects the “outcome specifying a single aspect of performance” or a specific measurement associated with a criterion (Roundtable on Sustainable Biomaterials 2011). RSB principles include compliance with domestic and international laws for bioenergy production; design and operation under transparent and participatory processes; mitigation of climate change; consistency with human rights; contribution to the social and economic development of local, rural, and indigenous peoples and their communities; maintenance of food security; avoidance of negative impacts on biodiversity, ecosystems, and areas of high conservation value; improvement or maintenance of soil health; optimization of surface and groundwater use; minimization of air pollution; cost-effective production; and maintenance of land rights. Guidance for compliance with principles and criteria is given by the RSB, such as recommending that areas of high conservation value are mapped, native crops be preferred, ecosystem functions and services for an area of biomaterial production are locally identified, buffer zones and ecological corridors are identified and protected.

As of 2 March 2015, the European Commission recognized the RSB and eighteen other voluntary schemes as acceptable ways to document compliance with its sustainability criteria (European Commission 2013). The approaches recognized by the EU must meet criteria related to GHG savings and land use, the latter to avoid disturbance to areas of high carbon stocks and biodiversity.

6.3.1 GBEP

The Global Bioenergy Partnership (GBEP) was established in 2007 to implement commitments taken by G8[4] in 2005. GBEP promotes bioenergy for sustainable development at the national level. GBEP is coordinated by the Food and Agriculture Organization of the United Nations (FAO) and includes 13 other international organizations (e.g. IEA, European Commission, IRENA, UNEP and

[4] The Group of Eight. A forum for the governments of eight leading industrialised countries. Members are Canada, France, Germany, Italy, Japan, Russia (suspended as of 24 March 2014), UK, USA and the European Union.

UNDP) and the world's major economies among its 23 member nations. The partnership focuses its activities in three strategic areas: 1) Sustainable Development; 2) Climate Change; and 3) Food and Energy Security. In June 2008 GBEP established a task force on sustainability to develop 'a set of global science based criteria and indicators regarding the sustainability of bioenergy' (GBEP 2011). GBEP developed a set of criteria and indicator categories (Hecht et al. 2009, GBEP 2011), and is working to have examples of experiences and best practices including benchmarks regarding the sustainability of bioenergy (Hayashi et al. 2014). GBEP indicator categories include environmental, social, and economic considerations Figure 25.

PILLARS GBEP's work on sustainability indicators was developed under the following three pillars, noting interlinkages between them:		
Environmental	**Social**	**Economic**
THEMES GBEP considers the following themes relevant, and these guided the development of indicators under these pillars:		
Greenhouse gas emissions, Productive capacity of the land and ecosystems, Air quality, Water availability, use efficiency and quality, Biological diversity, Land-use change, including indirect effects.	Price and supply of a national food basket, Access to land, water and other natural resources, Labour conditions, Rural and social development, Access to energy, Human health and safety.	Resource availability and use efficiencies in bioenergy production, conversion, distribution and end use, Economic development, Economic viability and competitiveness of bioenergy, Access to technology and technological capabilities, Energy security/Diversification of sources and supply, Energy security/Infrastructure and logistics for distribution and use.
INDICATORS		
1. Lifecycle GHG emissions	9. Allocation and tenure of land for new bioenergy production	17. Productivity
2. Soil quality	10. Price and supply of a national food basket	18. Net energy balance
3. Harvest levels of wood resources	11. Change in income	19. Gross value added
4. Emissions of non-GHG air pollutants, including air toxics	12. Jobs in the bioenergy sector	20. Change in consumption of fossil fuels and traditional use of biomass
5. Water use and efficiency	13. Change in unpaid time spent by women and children collecting biomass	21. Training and requalification of the workforce
6. Water quality	14. Bioenergy used to expand access to modern energy services	22. Energy diversity
7. Biological diversity in the landscape	15. Change in mortality and burden of disease attributable to indoor smoke	23. Infrastructure and logistics for distribution of bioenergy
8. Land use and land-use change related to bioenergy feedstock production	16. Incidence of occupational injury, illness and fatalities	24. Capacity and flexibility of use of bioenergy

Figure 25. The 24 sustainability indicators developed by GBEP (GBEP 2011).

To evaluate the feasibility of working with the indicators and enhance the practicality as a tool for policy making a number of so-called pilots have been conducted in Columbia (FAO 2014a), Indonesia (FAO 2014b), Germany (Köppen et al. 2014), Ghana (Hanekamp et al. 2013), Japan (Hayashi et al. 2014) and the Netherlands (NL Agency 2012).

6.3.2 International Standard, ISO 13065

Starting in 2009, experts from over 35 countries have been developing an international standard that communicates a common interpretation of sustainable bioenergy. The International Standard (ISO/DIS 13065) purpose and scope are as follows:

This International Standard specifies sustainability principles, criteria and indicators for the bioenergy supply chain to facilitate assessment of environmental, social and economic aspects of sustainability. It is applicable to:

The whole supply chain, parts of a supply chain or a single process in the supply chain.

To all forms of bioenergy, irrespective of raw material, geographical location, technology or end use.

This draft standard does not establish thresholds or limits and does not describe specific bioenergy processes and production methods, and compliance with this International Standard does not determine the sustainability of processes or products.

Use of this International Standard is intended to facilitate comparability of various bioenergy processes or products, and it can also be used to facilitate comparability of bioenergy and other energy options.'

Principles, criteria and indicators have been agreed upon in the areas shown in Table 6.

Table 6. Criteria and indicators of the ISO standard 13065.

Environmental	Social	Economic
Greenhouse gas (lifecycle)	Human rights	Economic sustainability
Water	Labour rights	
Soil	Land use rights and land use change	
Air	Water use rights	
Biodiversity		
Energy efficiency		
Waste		

The standard lays out what indicators should be addressed by an economic operator. In its present form, DIS 13065 follows the approach of asking how impacts related to a certain aspect are evaluated, what the impacts are and how the impacts are being addressed, etc. It appears to provide guidance on how sustainable bioenergy should be defined and lays out expectations for economic operators on what aspects should be identified and managed.

6.3.3 PROSUITE

PROSUITE (**PRO**spective **SU**sta**I**nability Assessment of **TE**chnologies) was an EU FP7 project aimed at developing rigorous and scientifically sound methodologies for assessing the sustainability of new technologies (Figure 26). New technologies, represented by four case studies, were evaluated over their whole life cycles from the perspectives of the three dimensions of sustainability. Building on environmental lifecycle assessment (LCA) methodology, a hybrid LCA model was developed for an integrated assessment that unites five major impact categories: human health, social well-being, prosperity, natural environment, and exhaustible resources.

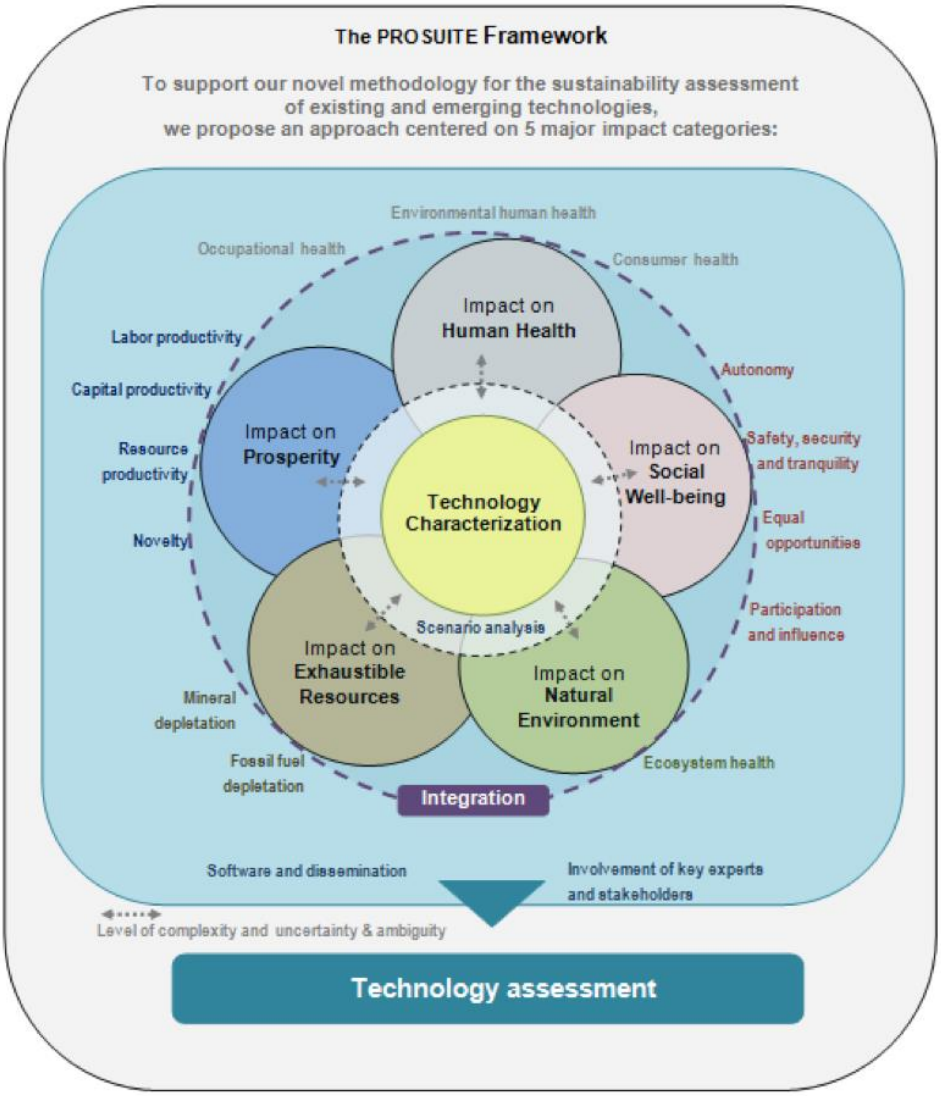

Figure 26. Schematic overview of the PROSUITE framework.

The output is presented in a user friendly manner for the five impact categories. Care must be taken to interpret the impacts correctly, i.e. some changes to more beneficial outcomes if they increase the impacts while others are more positive if they reduce impacts.

Unlike GBEP and ISO 13065, the PROSUITE sustainability framework is not specific to bio-based applications. A biorefinery case (Meester and Dewulf 2013) was one of four cases used to develop and test the framework, but in theory this framework could be used to assess any new technology. One of its main advantages is that the impacts are considered to be independent of one another – enabling for a robust, quantitative integration. This has been a serious challenge for sustainability evaluations, enabling apples to be traded-off between with oranges and pears.

6.3.4 LEEAFF

LEEAFF is a six category sustainability assessment framework designed to identify and communicate sustainability issues for the development and design of new biorefineries (Table 7). It was a work product of IEA Task 42 Biorefineries that evaluated different ways of assessing bio-based systems. As with the above-mentioned frameworks, LEEAFF also addresses the three pillars of sustainability. The issues are grouped into six categories that represent the questions most frequently raised when discussing new bioproducts industry development. As shown below many of the sustainability aspects (issues) are the same as the ones addressed in previous frameworks.

Table 7. Criteria and indicators of the LEEAFF framework.

Category	Sustainability issues
Land Use	Land ownership, land use conflicts, land use efficiency, food security
Environment	Impacts: Waste generation, greenhouse gases, air quality, water quality, water availability, soil health, loss of biodiversity,
	Benefits: Remediation services; carbon sequestration
Employment	Job creation, wages earned, education, new skills development
Acceptability	Landowner, company (economic operator), community, intra-industry, inter-industry, public; Health, noise, odour, well-being
Financial	Investment costs, operating costs, profitability, return on investment, markets for biorefinery products, incentives & subsidies, tax revenues
Feedstock & Inputs	Biomass availability (security of supply for processors), water supply, energy supply, renewable and non-renewable resource use, limiting inputs

The application of LEEAFF is intended to encourage users to think of sustainability from the start, and consider a project from a comprehensive 360° lens of relevant sustainability issues. As in the case for most sustainability assessments, LEEAFF is used to make a relative evaluation, i.e. compare the 6 aspects of new system to an existing or reference system. Its aim is to prompt users to identify what they know and don't know with respect to the sustainability questions that are asked by a variety of stakeholders including investors, suppliers, consumers, policy makers and the community. It can be used qualitatively, which can be particularly useful at the start of a project or when data are lacking. Whenever possible, users are encouraged to include quantitative data that is either determined through measurement or estimated by standardized methodology.

6.3.5 U.S. DoE Bioenergy Technology Office Sustainability Framework

Oak Ridge National Laboratory (ORNL), on behalf of U.S. Department of Energy Bioenergy Technologies Office (BETO), has been developing a framework and useful set of measurable and meaningful indicators as they relate to biofuel production. It entails a set of indicators that cover a broad set of environmental categories including soil quality, water quality, greenhouse gas emissions, air quality and productivity. In each of these categories a set of meaningful indicators was identified that can be measured and tracked over time (McBride et al. 2011). The recommendation is that sustainability should be applied across the entire biofuel supply chain. Figure 27 identifies the sustainability indicators as they apply to each of the supply chain components.

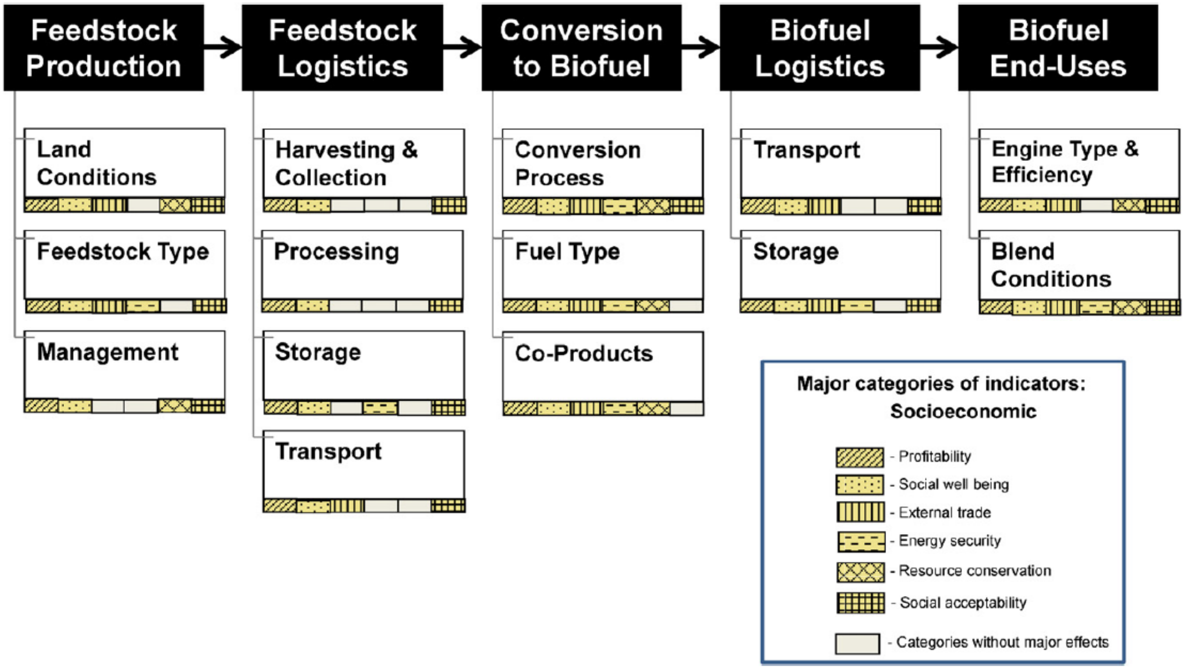

Figure 27. Application of sustainability indicators to different supply chain components (Efroymson et al. 2013).

ORNL has also developed a separate set of socioeconomic sustainability indicators (Dale et al. 2013a). The selection criteria for bioenergy sustainability is based on the availability of information about socioeconomic conditions for each category, on other efforts to identify sets of indicators, and on established criteria for selecting indicators (Figure 27). Dale and Beyeler (2001) analysed existing literature on indicator selection to identify key criteria:

- *practical* (easy, timely, and cost-effective to measure),
- *sensitive* and responsive to both natural and anthropogenic stresses to the system,
- *unambiguous* with respect to what is measured, how measurements are made, and how response is measured,
- *anticipatory* of impending changes,
- *predictive* of changes that can be averted with management action,
- *estimable* with known variability in response to changes, and
- *sufficient* when considered collectively (i.e., a suite of indicators integrates changes in socio-economic sustainability) (Dale and Polasky 2007).

Indicators meeting these criteria should allow users to set targets and create incentives for continual improvement toward more sustainable processes. Furthermore, indicators should provide comparable measurements of performance across different contexts where they will be applied. Additional standards apply to the data used to support indicator measurement, e.g., data validity, reliability, quality/uncertainty, timeliness, and representativeness.

A few of the other attempts to develop sustainability indicators, standards, or principles relevant to bioenergy include those of the Council on Sustainable Biomass Production (CSBP), Biomass Market Access Standards (BMAS), Keystone Alliance for Sustainable Agriculture, Sustainable Forestry Initiative, World Wildlife Fund of Germany, and Sustainable Biodiesel Alliance, as well as efforts that target particular feedstock crops such as sugar cane (e.g. Bonsucro-Better Sugarcane Initiative, Greenergy) and oil palm (e.g. Roundtable for Sustainable Palm Oil).

While forestry standards groups such as the Forest Stewardship Council (FSC), and the Sustainable Forestry Initiative (SFI) address sustainable forest management for production of any forest product, they do not require greenhouse gas emissions accounting and therefore need to link to another method or scheme to document compliance with GHG-related criteria.

Researchers have proposed less formal lists of sustainability indicators for bioenergy. McBride et al. (2011) suggested 19 indicators for environmental sustainability for bioenergy in six categories: soil, water, air, greenhouse gas emissions, biodiversity, and plant productivity. Evans et al. (2010) propose indicator categories of price, efficiency, greenhouse gas emissions, availability, limitations, land use, water use, and social impacts for electricity generation from biomass. Dale et al. (2013a) identified 16 socioeconomic indicators of bioenergy sustainability that fall into the categories of social well-being, energy security, trade, profitability, resource conservation, and social acceptability. Efforts like these are driven more by the need for consistent methods that could facilitate comparable, science-based assessments (Dale and Beyeler 2001) than by the need for compliance certification. While some indicators are commonly identified by experts (Buchholz et al. 2009) other frameworks present approaches for indicator selection that targets key components of the three pillars of sustainability (social, environmental and economic). Some emphasize quantifiable indicators, others emphasize qualitative targets, and others again stress documentation requirements to permit audit and verification. Some favour sustainability goals that may be more socially than scientifically determined. While most are working toward the development of a general set of indicators, there are no generally accepted frameworks for selecting goal-relevant and/or contextually meaningful indicators.

6.4 Framework for selecting and evaluating sustainability indicators

The following describes a framework (Figure 28) that guides indicator selection towards relevance to specific sustainability goals and the values that shape them, and to the objectives of the particular bioenergy sustainability analysis. The framework helps stakeholders to articulate their goals and values and to narrow the long list of potential indicators to those most useful in a particular situation. Determining what groups constitute relevant stakeholders and reach agreement of relevant goals among those groups is neither trivial nor easy. Diverse perspectives and groups have interests in the outcomes and implications of bioenergy projects (Cuppen et al. 2010). Use of the framework should increase the prospects for relevance to stakeholders (Rickard et al. 2007), facilitating the development of indicator sets that are well suited to stakeholder priorities.

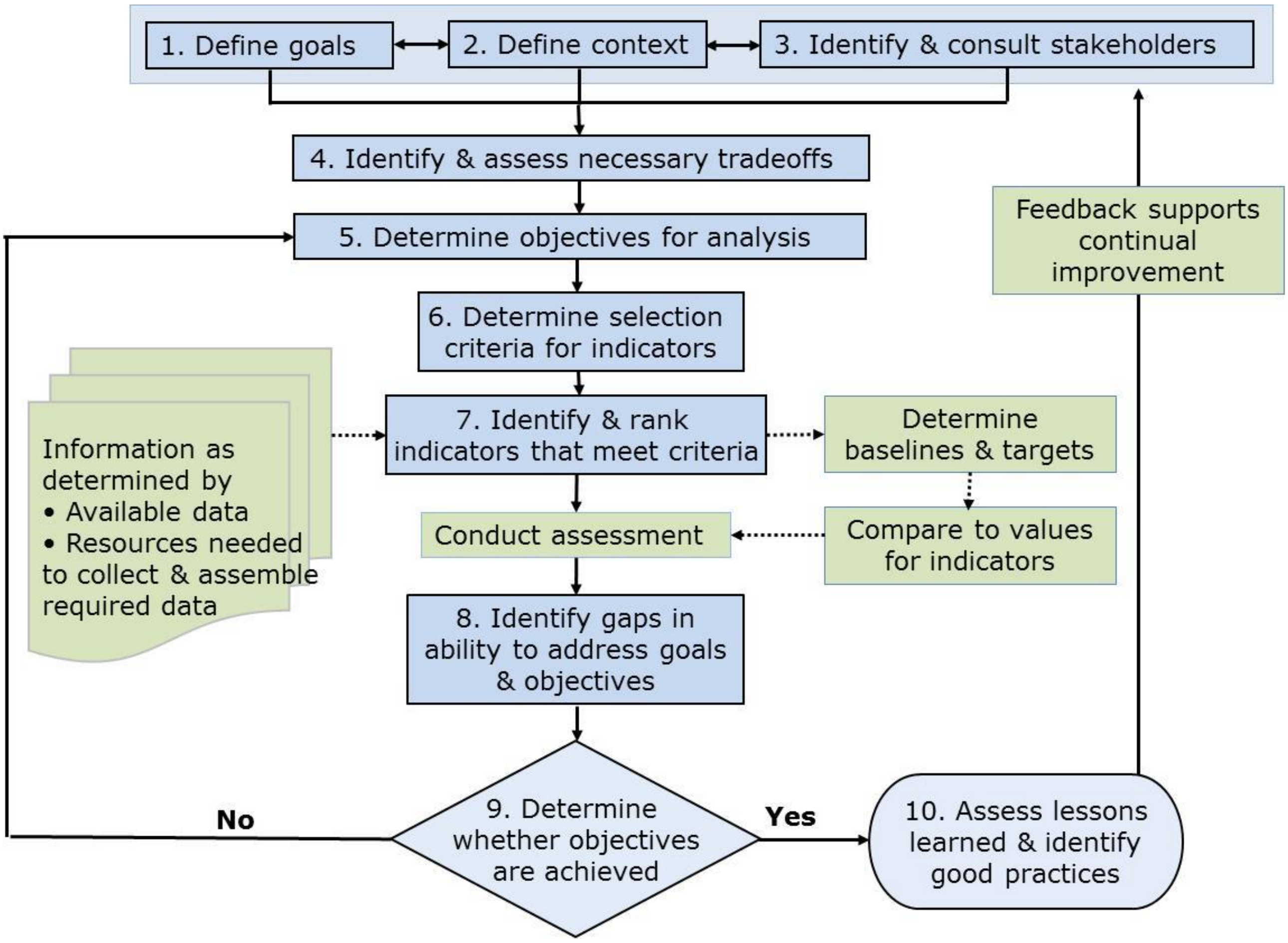

Figure 28. A framework for selecting and evaluating indicators of bioenergy sustainability. Steps for the framework are shown in blue; supporting components of the assessment process are in green. Note that steps 1, 2, and 3 interact and occur concurrently. Adopted from (Dale et al. 2015).

These aspects of the framework should be defined simultaneously, because discussions in one area inevitably raise questions in another. For example, an analysis of goals leads to questions about the context in which the goals are placed. Who the stakeholders are depends on context and how overarching goals are defined. The goals themselves vary in meaning for different stakeholders, and acceptability of trade-offs between goals depends on the stakeholders. Goals are value driven, and bioenergy sustainability indicators may be thought of as measures of those values (Turnhout et al. 2007). Because multiple communities (e.g., policymakers, scientists, industries, farmers, or particular sectors of the public) with differing priorities and values have a stake in bioenergy sustainability, an indicator selection process that ensures that values do not get buried beneath technical details is more likely to yield lasting results. Hence, the process of selecting indicators can be hindered by apparently conflicting differences among stakeholders. It is sometimes better to retain a larger set of indicators rather than to seek efficiency and exclude key stakeholder groups. In other situations, one stakeholder may impasse progress, and the larger group of stakeholders may move forward on the indicator selection process acknowledging that some concerns are not being addressed.

The steps in the framework depicted in Figure 28 are discussed in detail in appendix B.

6.5 Selecting and evaluating sustainability indicator frameworks

The different sustainability frameworks bear much similarity in terms of the ultimate goal of sustainable development, and what should be included in this concept. While the indicators are not identical, there is a common core set of environmental indicators, and much similarity between economic indicators. The greatest variation appears amongst the social indicators. What differ between the frameworks is intended user and application, and the resulting information, and the time and effort needed to complete an assessment.

At the start of the Inter-Task project, the intention was for all of the countries to use a common sustainability framework, namely GBEP. As the project progressed other frameworks were identified, and the three countries navigated towards different sustainability frameworks. All of the frameworks examined consider the three sustainability dimensions that is environmental, economic and social sustainability. A high level comparison of the frameworks, presented in Table 8 shows the frameworks to have very similar indicators. Most congruence can be found among the environmental indicators with all frameworks addressing climate change, air pollution, water use and pollution, soil health and biodiversity. Resource use is also included in all frameworks but in some cases it falls under the environmental pillar while in others it is seen as more of an economic matter. There is less congruence between the indicators that are grouped as being economic and social matters. This is mainly due to the scale of the application that the framework is targeted to assess, e.g. project level vs. national picture.

In general, GBEP and PROSUITE frameworks take a more macro level perspective than LEEAFF or the U.S. ORNL approach based on McBride et al. (2011) and Dale and Beyeler (2001). GBEP and PROSUITE better address issues specific to developing countries. Only ISO 13065 includes human rights, labour rights and water use rights. The ISEAL Alliance's 10 credibility principles for sustainability standards - sustainability (goals); improvement; relevance; rigour; engagement; impartiality; transparency; accessibility; truthfulness and efficiency - could be used to compare frameworks in a more thorough manner. As shown in Table 8 many of the LEEAFF sustainability indicators are the same or very similar to those of the other frameworks. The main differences are how the information is organized, i.e. the six impact categories, and that it provides useful information to stakeholders even when used in qualitative mode. LEEAFF can be used as a quick screening tool to scan what is known and not known, to compare different pathways, and to identify the vulnerable areas that should be addressed in the development process.

As discussed by (Dale et al. 2015), the goal of the assessment will be key to determining the most relevant sustainability indicators, and hence the most applicable framework for a particular assessment. One needs to know the user, the application and the type of desired output information as well as the effort and time needed to complete the assessment. Therefore some of the key initial steps in developing an effective framework for selecting and evaluating indicators include clearly defining sustainability and other goals and objectives for analysis, developing practical criteria for selecting indicators that relate to the goals, and applying the criteria to select indicators of bioenergy sustainability (Dale et al. 2015). Emphasis should be put on those indicators that contribute most to achieving identified goals. The iterative process facilitated by most frameworks, including the refinements based on stakeholders' involvement, contributes significantly to goal clarification, indicator development, and continual improvement in assessing the sustainability of bioenergy systems. Many challenges are associated with these steps. Ideally, the objectives for analysis should be defined only after potential synergies and trade-offs among stakeholder goals are considered. This is, however always challenging and becomes untenable at large scales.

Selecting indicators using a formal framework can

- contribute to stakeholders' understanding of sustainability and other goals,
- ensure that important stakeholder concerns and priorities are considered in the process of selecting indicators,
- develop an indicator set that is well-suited to the sustainability goals and objectives of the analysis, and
- yield a good cost-to-benefit ratio.

Also, for sound interpretation and confidence in the decision, there should be a common understanding of how much confidence or weight to place on the different indicator values. PROSUITE, for example, uses a pedigree matrix to rate the data and information on a scale of 1 to 5 with respect to their reliability, completeness, temporal correlation, geographical correlation and technological correlation.

While the frameworks reviewed propose how sustainability should be described, none of the frameworks bring the user to the point where it can be said that biomass to bio-product pathway X is more sustainable than pathway Y. They enable the comparison of how X and Y rate with respect to defined sustainability indicators, or can track progression of a pathway over time if time series data are available. This outcome might not be adequate for some who search for a more definitive result.

Table 8. Comparison of indicators of the different assessment frameworks in the three pillars of sustainability

Environmental	**GBEP**	**PROSUITE**	**LEEAFF**	**U.S. ORNL**
Greenhouse Gases	GHG lifecycle emissions	Impact on Natural Environment (climate change)	Change in CO_2e (CO_2, CH_4, N_2O) on lifecycle basis - decrease in value is positive; comparison with non-bio-based product - the lower value of bio-based product is positive	CO_2e (CO_2, CH_4, N_2O)
Air Quality	Emissions of non-GHG air pollutants, including air toxics	Ozone depletion, acidification, photochemical ozone formation)	Change in Criteria Air Contaminants or Emissions that are Locally of Concern	Tropospheric ozone; carbon monoxide; particulate matter
Water Quality	Pollutant loadings attributable to fertilizer and pesticide application; pollutant loadings attributable to bioenergy processing	Impact on freshwater environment (climate change, eutrophication, eco-toxicity); impact on marine environment (eutrophication, eco-toxicity)	Change in Regulated Water Quality Parameters for surface water and ground water; Quality parameters that are of local concern	Stream nitrate concentration; stream phosphorus concentration; Stream suspended sediment concentration; Stream herbicide concentration;
Soil Quality	% of land for which soil quality, in particular SOC is maintained or improved	Impact on terrestrial environment (land use)	Change in Soil Quality Parameters; Quality parameters that are of local concern; Soil erosion; Soil Organic Carbon; Soil Compaction; Nutrients Environmental Benefits; Soil remediation - reduction in soil contaminants in soil is positive; Ability of product to be bio-degraded or composted	Total organic carbon, Total nitrogen, Extractable phosphorus, Bulk density
Biodiversity	% of area of high biodiversity value converted to bioenergy production; % of area used for bioenergy production where invasive species are grown; % of area used for bioenergy production where conservation methods are used	Impact on terrestrial environment	Change in Biodiversity Indicators or Species that are Locally of Concern; increase in value over time is positive	Taxa of special concern (presence, habitat area)

Biomass Use	Annual harvest by volume and % of net growth or yield; % of harvest used for bioenergy		Biomass availability (yield, current and long term average and biomass consumption)	
Water Use	Volume of water withdrawn for feedstock production; volume of water withdrawn for bioenergy production	Impact on freshwater environment; impact on marine environment	Water availability (current and long term average) and water consumption)	Storm flow; minimum flow; Consumptive use (agriculture, biorefinery)
Non-Renewable Resource Use		Impact on mineral depletion; Impact on fossil depletion	Fossil fuel consumption; consumption of other major non-renewable resources	Resource conservation (Depletion of non-renewable resources; Fossil energy return on investment)
Acceptability		Social well-being (Autonomy; Equality; Safety, Security, Tranquillity; Participation and Influence) and Human Health	Company; Industry (intra); Industry (inter); Community; Consumers; Risk Tolerance	Social acceptability (Public opinion; Transparency; Stakeholder participation; Risk of Catastrophic event)
Land Use and Land Use Change	% of total land area used for bioenergy; Biomass sources of bioenergy; Net annual rates of land conversion		Land use efficiency, land use change	
Allocation and Land Tenure	% of land used for bioenergy production allocated via (1) legal instrument or domestic authority; (2) due process is provided and procedures are followed for determining land title	Social well-being	Land ownership, land use conflicts, unresolved land claims	
Labour rights	Social	Social well-being: Autonomy (child labour, forced labour)		
Food security	Effects of bioenergy use and production on the price and supply of a food basket			Social well-being (Change in food price volatility)
Change in income	Change in income from wages paid in bioenergy sector and net income of self-employed households from the sale, barter and own consumption of bioenergy	Social well-being: Equality (regional income inequalities; global inequalities)		Social well-being (Household income)

Employment in bioenergy	Net job creation; total number of jobs in bioenergy sector; % of jobs adhering to recog-nized labour standards	Social well-being: Safety, Security and Tranquillity (total jobs; knowledge intensive jobs)	Job creation, job retention, job type	Social well-being (Full time equivalent jobs)
Unpaid labour	Change in unpaid time spent by women and children to collect biomass			
Access to bioenergy	Total amount and % of increased access to modern bioenergy; total number and % of house-holds and businesses using bioenergy			
Mortality and Disease Attributed to Indoor Smoke	Change in mortality and burden of disease attributable to indoor smoke			
Occupational injury, illness, fatalities	Incidences of occupational injury, illness and fatalities in the production of bioenergy in relation to other sectors	Impact on Occupational Health	Occupational Health and Safety	Social well-being (Work days lost to injury)
Productivity	Measured as (1) productivity of bioenergy feedstock; (2) processing efficiencies; (3) amount of bioenergy per ha per year; (4) production cost per unit of bioenergy	Impact on Prosperity: (Labour productivity; Capital productivity; Resource productivity; Impact on novelty)	Resource efficiency, energy efficiency	Above ground net primary productivity
Net Energy Balance	Ratio of energy used in bioenergy value chain over energy used in other energy value chains		Energy efficiency and GHG lifecycle emissions	
Gross Value Added	Gross value added per unit of bioenergy produced; gross value added as % GDP			
Economic Sustainability		Impact on Prosperity (Micro analysis - CAPEX, OPEX and End of Life Expenditure, Direct and Indirect Labour)	Investment costs; Return on investment; Net present value Wages; Taxes Incentives, Subsidies	Return on investment; Net present value

Macroeconomic Impact		Impact on Prosperity (Macro analysis - Pervasiveness, Import Dependency, Structural Index, Financial Risk, Capital Productivity, Labour Productivity, Resource Productivity, Novelty, GDP)		
Market Demand		Impact on Prosperity (Macro analysis): includes market analysis and assessment of novelty	Demand growth for bio-products; existing or new products; existing or new markets; potential threats	External trade (trade volume, terms of trade)
Change in Consumption of Fossil Fuels	% substitution of fossil fuels with bioenergy; % replacement of traditional biomass use with modern bioenergy	Impact on Exhaustible Resources (impact on fossil depletion)	Fossil fuel consumption; energy consumption; % renewable energy	
Training and requalification of workforce	% of trained workers in the bioenergy sector workforce; % of re-qualified workers		Education level, New Training, Job retention	
Energy diversity	Change in diversity of total primary energy supply		Energy type, % renewable	Energy security (Energy security premium; Fuel price volatility)
Infrastructure and logistics for distribution of bioenergy	Number and capacity of routes for critical distribution systems			
Capacity and flexibility of use of bioenergy	Ratio of capacity for using bioenergy with the actual use; flexible capacity that can use bioenergy or other types of energy			

6.6 Governance issues to meet sustainability criteria and facilitate mobilisation

Additional economic and social opportunities arise, together with environmental concerns when crop residues are collected. This includes particularly issues related to the soil, for example conservation of soil organic matter and nutrients, soil erosion and water runoff, wind erosion, soil water issues.

6.6.1 Natural resource policy and regulation in the agricultural sector

In the EU, the cross-compliance principles of the Common Agricultural Policy (CAP) were introduced in 2003. Cross-compliance is a mechanism that links agricultural subsidies with the farmers' compliance with basic standards concerning the environment, food safety, animal and plant health, animal welfare, and maintaining land in good agricultural and environmental condition (Europan Commission 2009). It varies among Member States in which form the requirements have been implemented; in Denmark 105 requirements have been formulated under the cross-compliance requirements (Ministeriet for Fødevarer 2015).

Except for straw recommended as an option for mandatory bedding in animal farming, only one of the EU cross-compliance requirement concerns straw in prohibiting its burning in open fields. The requirement contributes to fulfilling overall criteria such as protection against soil erosion, and maintenance of soil organic matter and soil structure. In the U.S. and some parts of Canada, excess crop residues can be burned to facilitate seeding. However, this is the exception rather than the rule, and permits are required. The Province of Ontario, the location of the Canadian case study, has a ban on open burning. As in Europe, most crop residues are chopped and reincorporated into the soil.

Agricultural producers in the United States generally are subject to only few mandatory conservation measures (Endres 2010), but agricultural policies do include incentives to set aside lands for conservation purposes. *The Conservation Reserve Program* (CRP), established by the 1985 Farm Bill, is for example the largest conservation program in the United States by acreage and expenditures. Later programs focus more on conservation through management practices, and it has become an option to participate in "working lands" environmental enhancement programs such as the *Conservation Security Program* (CSP, initiated with the 2002 Farm Bill, with substantial changes in 2008), The *Environmental Quality Incentives Program* (EQIP, initiated 1996), and the *Agricultural Management Assistance* (AMA). Other such programs have existed, for example *The Wildlife Habitat Incentives Program* (WHIP), which was repealed in 2014, with parts of its contents rolled into EQIP. The *Biomass Crop Assistance Program* (BCAP), introduced with the 2008 Farm Bill, and reauthorized with modifications by the 2014 Farm Bill, provides direct financial support for energy biomass cropping, and require sustainable practices in both agriculture and forestry (Endres 2010). These programs, however, do not specifically address crop residue removal.

In Canada, agriculture producers are encouraged to have environmental farm plans which identify their specific environmental risks and outline their mitigation plan. Provincial and federal environmental regulations related to waterways, pesticide application, etc. must be adhered to.

6.6.2 Best management practices in the agricultural sector

In Denmark the extension services provide comprehensive information and advice on several issues around straw removal, including handling, logistics and economy. They also inform and advice about possible impacts on soil carbon contents, even if Best Management Practice guidelines (BMPs) have not yet been established. The basis for guidance to farmers is the so-called Dexter-index (the ratio between clay and soil carbon), which has been suggested as a way to assess when and where soil carbon contents are critical to maintenance of appropriate soil physical properties. It builds on the observation that SOM effects on soil physical properties depend on the size of the clay fraction of the soil, with SOM increasing significantly at a Clay/SOC ratio below 10 (Dexter et al. 2008).

Comprehensive BMPs for management of crop production have been elaborated in the U.S. and Canada by universities, extension services, and government bodies, such as the U.S. Department of Agriculture (USDA), often in collaboration. Such BMPs commonly address residue management as a measure of soil conservation (e.g. USDA Natural Resources Conservation Service and University of Wisconsin - Extension (2000), (Government of Alberta: Agriculture and Forestry 2004). Crop residue harvesting is rarely considered in these BMPs, but scattered specific guidelines do exist that explain the conservation issues that need to be considered (Wortmann et al. 2012). No quantitative guidance is given on the amount that can be removed in different conditions, and such assessments must rely on the farmers own experiences. In the future, more specific guidelines for the quantities of residue that can be harvested without soil degradation can perhaps be based on knowledge on functional relationships for example between soil loss and rain fall, runoff, slope steepness, soil erodibility, cover-management, slope length and supporting practices, or between wind erosion and soil erodibility, soil ridge-roughness, climate, unsheltered travel distance of wind across a field, and the vegetative cover (U.S. Department of Energy 2011).

Compensation measures are also addressed in guidance to farmers, both in Denmark and North America. Such measures include addition of organic matter with manure (Christensen 2002), even if this cannot reduce evaporation and trap snow like crop residue (Wortmann et al. 2012, Neary 2015). Another mitigation measure is the use of cover crops that can also replace carbon removals, improve water management and act to protect the soil against erosion and damage to soil structure (Christensen 2002, Wortmann et al. 2012, Neary 2015). Finally, an increased number of years with grasses/clover in crop rotation systems will also contribute to soil carbon conservation.

The European Bioeconomy Panel and the Standing Committee on Agricultural Research Strategic Working Group (EBP/SCAR 2014) generally considers that adoption of existing and new innovative best practices around the world has huge potential to increase productivity and thus the biomass supply, without increasing the demand for land. In this regard, crop residue harvesting may be a low-hanging fruit, if scientifically and practically sound BMPs for efficient and sustainable harvesting can be established.

In Canada, statistics are reported through the Farm Environmental Management Survey which tracks the use of no-till practices and recently the use of cover crops. Agricultural producers often use cover crops after harvesting a winter wheat crop. Many producers in Ontario are experimenting with the planting of cover crops prior to harvesting of soybeans and corn. In Ontario, 2016 marks the year of the 25th anniversary of the Environmental Farm Plan (EFP) which was developed as a producer risk assessment tool for environmental matters on farm landscape. Through government programming under Growing Forward, producers are incentivized to review and, if necessary, change their practices to achieve specific environmental outcomes. Since 2016, Ontario livestock sector is subject to nutrient management regulations covering storage and spreading of livestock manure.

The Canadian Grains Council initiated the Canadian Roundtable for Sustainable Crops (CRSC) in 2013 to address the growing global demand for sustainably produced grains, oilseeds and agricultural products. The CRSC is currently developing an Assurance Protocol that will be applied by the CRSC to verify on behalf of agriculture producers that grain grown in Canada will meet a set of core sustainability indicators. A metrics platform is being built that includes tools, datasets and pilot testing. The work is expected to be completed in 2018. All major exporting grain and food crops growers and grain handlers participate in the CRSC, as well as several ENGOs.

6.6.3 Regulation in the bioenergy sector

Apart from agricultural land management sustainability requirements are emerging in energy regulation. The U.K. was first in establishing a regulatory scheme that requires carbon and non-carbon sustainability of both transportation biofuels (Renewable Transport Fuels Obligation (RTFO), electricity and heat (Renewables Obligation (RO), Domestic and Non-domestic Renewable Heat Incentive (RHI). The environmental principles and criteria of the RTFO include ecosystem carbon conservation (above and belowground stocks), biodiversity and soil conservation, sustainable water use, and air quality, while the social principles include workers' and land rights.

The EU followed with the Renewable Energy Directive in 2009 (European Parliament and the Council 2009), which include sustainability criteria for transportation and liquid biofuels. These criteria address greenhouse gas emission (GHG) savings, biodiversity and prohibition of conversion of land with high carbon stocks, and compliance with cross-compliance requirements of CAP. Similar to the cross-compliance principles from agriculture, energy producers receive subsidies only if they show compliance with sustainability criteria/conservation requirements. In the U.S., the Renewable Fuels Standard (RFS) mandates that transportation fuel sold in the United States contains a minimum volume of renewable fuel. RFS include minimum threshold requirements for GHG emission reductions, but no non-carbon requirements (Endres 2010, U.S. Environmental Protection Agency 2015)

In Europe, the documentation that sustainability criteria are met relies on a meta-standard approach, where various verification measures can be used; sometimes in combination. The exact requirements for verification depend on the specific legislation, but may include reporting GHG balance using provided calculation tools, private certification, or similar documentation assessed from case to case (Endres 2010, Stupak et al. 2016). The verification of compliance with CAP takes place through CAP legislation that again relies on a large complex of other legislation for implementation and documentation.

Energy from crop residues relatively easily fulfil threshold values for GHG emission reductions (21–58 % for cereal straw), but there are critics claiming that current methodologies, e.g. of the EU Renewable Energy Directive, do not adequately take account of impacts on soil carbon stocks, and that this may shift emission reductions from positive to highly negative (Whittaker et al. 2014).

In North America, initiatives such as the Clean Power Plan in the U.S. and climate change planning at the state-province levels in both countries are expected to clarify the role of biomass, how biogenic emissions are to be accounted for and the criteria that need to be met for soil carbon sequestration.

6.6.4 Barriers to regulatory oversight of bioenergy and the bioeconomy

Bioenergy production involves numerous sectors, ranging from waste production, land management, energy production and transportation. In most countries these policies and regulations are shared by different Ministries who are responsible for agricultural, forestry, environment, energy, manufacturing, and regional economic development. With the increasing emergence or shift to the use of crop residues in integrated and cascading production of various biomaterials, biochemicals and different bioenergy forms, even more sectors become involved. The oversight of these new bio-economic value chains become highly complex, with relevance and probably overlap of existing regulation from different sectors (Det Nationale Bioøkonomiudvalg 2014, EBP/SCAR 2014). This increases the need for comprehensive coordination among sectors and the associated ministerial responsibilities. Sometimes the regulation of one sector might unintentionally prevent policy goals from being achieved in another sector, with consequences in relation to deployment of the bio-economy.

A survey in Denmark (NaturErhvervstyrelsen 2015) identified such regulatory barriers, including application requirements when introducing new technologies (Algae - 'blue' biomass), and classification of residue/waste products may hinder new uses (waste from meat production - 'red' biomass), including use of waste products for soil amendment Barriers in energy legislation includes the absence of mandated use of second generation biofuels (straw – 'yellow' biomass), with the National Bioeconomy Panel recommending a mandated blending requirement of 2.5%, valid until 2030, to kick-off a hesitating bio-refining industry, that is currently seeking to develop their business potentials in other countries. Other legislation with strict requirements to organization and municipal participation in heat production projects furthermore makes it difficult to obtain loans for investments with state or municipalities guarantees. This kind of challenges likely exists also in other countries.

Part of the challenge is developing a bio-economy based on sound and sustainable environmental, social and economic principles that are well aligned for all biomass and all its end-uses. Especially, legal requirements for certain biomass production systems in the land use sector should not depend on an end-use that does not influence the biomass production. It is also important that there is level competition on sustainability parameters for those products with which the bio-economy competes (Det Nationale Bioøkonomiudvalg 2014), even if it may still be desirable to have private regulatory mechanisms for showing excellence in sustainability performance above other actors in the market, in order to meet different consumer priorities.

The verification of biomass sustainability continues to be a challenge (Stupak et al. 2016). The European Bioeconomy Panel and the Standing Committee on Agricultural Research Strategic Working Group recognize the value of existing regulation and certification systems to document sustainability of the biomass, but also consider that creating more of the same may not be the best way forward (EBP/SCAR 2014). In line with approaches being developed e.g. by the U.K. and the private certification system *Sustainable Biomass Partnership* (SBP), they propose that a system for issuing certificates of origin from so-called *Sustainable Biomass Regions* are established. They consider that a regional/urban approach may be more useful for further promoting and ensuring sustainable forestry, agriculture and marine/aquatic practices. Like others, they suggest that the approach can reduce costs and administrative complexity and ease commitment of primary producers, while at the same time being able to account for shifts in demand and divergent natural or social circumstances and needs.

With respect to agricultural residues, they are a by-product of grain production and dedicated for bioenergy production. That is agriculture producers are managing their land to grow the grain crop to meet the requirements of the global wheat or corn markets. Food and feed companies are increasingly requiring evidence of sustainable production, and a number of schemes have emerged (e.g. Unilever, Cargill, etc.). It is envisioned that the end result will be market-driven, end-user requirements for best management practices to meet a number of environmental and social indicators. At present, residue removal is not explicitly described in these emerging schemes for sustainable agriculture. There is growing unity among world scale retailers and food service providers to adopt meaningful sustainability criteria that are both suitable for their supply chains as well as supporting public policy on governments' commitments to meet GHG targets and other environmental goals.

7 Case studies - Sustainability analysis of bioenergy supply chains

This section presents three case studies of sustainability analysis of bioenergy supply chains based on agricultural residues. The case on Denmark covers the use of straw for combined heat and power production (CHP) and bioethanol and applies the GBEP framework. The U.S. case generically describes the application of the framework developed by Oak Ridge National

Laboratory. Lastly the Canadian case looks at the use of corn stover for high value bio-products and bioenergy.

7.1 Cereal straw for CHP and bioethanol in Denmark

The case study on Denmark applies the GBEP methodology to evaluate two different supply chains: 1) cereal straw for combined production of heat and electricity (CHP), which has been an operational business case for more than 20 years, and 2) cereal straw for 2nd generation ethanol production, which has taken place on demonstration scale since 2009.

10 of 24 sustainability indicators were selected for the study. Indicators were omitted for reasons of lack of sufficient data (indicators 6, 16, 19, 21, 23 and 24) or lack of relevance to the specific context (indicators 3, 5, 8, 9, 10, 13, 14, and 15). See Figure 25 above for a description of the indicators. The three pillars of sustainability are not equally represented in the analysis; there is an overweight of indicators from the environmental and economic pillars.

In line with the GBEP methodology the geographical scope is the nation of Denmark (excluding the Faroe Islands and Greenland). With regards to the temporal scope the methodology is expanded to calculate, where possible, a development in indicator values instead of a value for a specific year. The GBEP methodology does not apply threshold values or specific targets for each indicator, and we find the development in indicator values more informative than specific values. For this analysis the reference year is 2000 and the period of interest the following 10-12 years.

7.1.1 Indicator 1: Lifecycle GHG emissions

Indicator 1 quantifies lifecycle greenhouse gas emissions from bioenergy production and use. This quantification is based on a review of current literature. A number of LCA studies have been made, which include scenarios relevant to this evaluation.

A recent consequential LCA with the functional unit of 1 kWh of electricity from straw fired CHP (Nguyen et al. 2013a) found an energy output of 1005 kWh electricity and co-product output of 8.7 GJ heat per ton straw. GHG emissions (GWP) were assessed to 0.35 kg CO_2eq kWh_{el}^{-1}. Fossil reference scenarios yielded 0.976 kg CO_2eq kWh_{el}^{-1} with coal as fuel, and 0.423 kg CO_2eq kWh_{el}^{-1} with natural gas as fuel (Table 9). The marginal benefit of straw to CHP is 0.626 kg CO_2eq kWh_{el}^{-1} when displacing coal and 0.073 kg CO_2eq kWh_{el}^{-1} when displacing natural gas. Nguyen et al. (Nguyen et al. 2013a) also looked at the attribution of GHG emissions (and other impacts) to different processes in the straw to CHP supply chain and found that straw removal and the subsequent reduction in soil carbon is the main contributor. The utility company Vattenfall (Vattenfall 2013) has made an LCA based product declaration of various energy production systems in the Nordic countries. The straw to CHP production system is based on data from one of the largest straw fired plant in Denmark (Amagerværket). Vattenfall use the same functional unit 1 kWh electricity) as (Nguyen et al. 2013a) but apply an attributional LCA methodology and different system boundaries. GHG emissions are assessed to 0.1 kg CO_2eq kWh_{el}^{-1} i.e. considerably lower than (Nguyen et al. 2013a). An explanation for this large difference may be found in methodological approach (consequential vs. attributional LCA), but probably the main reason relate to changes in soil carbon that was not included in the Vattenfall study. Straw removal and subsequent changes in soil carbon accounts for approximately 80% of GWP in Nguyen et al. (2013a). Another recent LCA study including a straw to CHP supply chain (Parajuli et al. 2014) corroborate the findings of (Nguyen et al. 2013a) in terms of attribution of GHG emissions to soil carbon loss being the main contributor. The findings on GHG emissions are not directly comparable between the two studies as one has electricity from GHP as functional unit (Nguyen et al. 2013a), while the other has heat from CHP as the functional unit (Parajuli et al. 2014).

For the second scenario in this assessment, straw to ethanol, Møller et al. (Møller et al. 2014) and Slentø et al. (Slentø et al. 2010) find straw to ethanol capable of reducing GHG emissions by 33% relative to the fossil reference, petroleum based gasoline. The assessment is based on consequential LCA but the system boundaries are not comparable to the straw to CHP study by (Nguyen et al. 2013a) as changes in soil carbon is disregarded. GHG emissions are estimated to 0.202 kg CO_2eq MJ_{Etoh}^{-1} for straw to ethanol and 0.304 kg CO_2eq MJ_{Etoh}^{-1} for the fossil reference (Slentø et al. 2010). The benefit of displacement is 0.102 kg CO_2eq MJ_{Etoh}^{-1}.

As input to the GBEP analysis, data from the most comprehensive LCA reports were used, i.e. Nguyen et al. (2013a) for straw to CHP and Møller et al. (2014) for straw to ethanol (Table 9).

Table 9. GBEP indicator values for indicator 1, life cycle greenhouse gas emission.

Indicator	Name	Unit	Reference year	Straw to CHP			Straw to EtOH		
				Value	Change	Change yr^{-1}	Value	Change	Change yr^{-1}
1	GHG emissions	kg CO_2eq kWh_{el}^{-1}	~2010	0.35	-	-			
		Kg CO_2eq MJ_{Etoh}^{-1}	2008				0.202	-	-

7.1.2 Indicator 2: Soil quality

Indicator 2 quantifies the percentage of land for which soil quality, in particular in terms of soil organic carbon, is maintained or improved out of total land on which bioenergy feedstock is produced.

Straw left in the field is partially oxidized and most of the carbon stored in straw is eventually released to the atmosphere. The fraction of carbon immobilized and stored in the soil is estimated to between 15% (Christensen 2004) and 21.3% (Petersen et al. 2013) in a 20 year perspective. Correspondingly impaired soil carbon sequestration caused by straw removal is estimated to 57 - 86 kg C per ton of straw (15% MC) removed (Christensen 2004, Olesen et al. 2012, Petersen et al. 2013). Other studies that include changes in soil carbon from straw removal in Denmark assume amounts in the above range. Nguyen et al. (Nguyen et al. 2013a, Nguyen et al. 2013b) assume impaired soil carbon sequestration to 80 kg C per ton straw removed, Parajuli et al. (Parajuli et al. 2014) assume 39 kg C per ton straw removed, but in a 100 year time perspective. Tonini et al. (Tonini and Astrup 2012) assume 90 kg C per ton straw removed. However the assumption by Tonini et al. (Tonini and Astrup 2012) build on Austrian agricultural data.

The amount of straw harvested for energy purposes has increased from 1.061 million tonnes in the reference year 2000 to 1.737 million tonnes in 2012 (Figure 29). The area affected by straw removal for energy has increased as well (Figure 30) and data on harvest intensities for the last 12 years do not suggest a significant change in the amount of straw harvested per area unit (Figure 29).

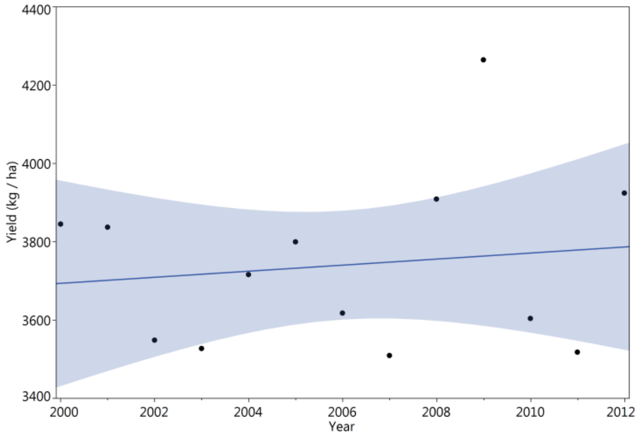

Figure 29. Harvest intensities of straw to energy purposes in Denmark 2000 - 2012. Data from (Danmarks Statistik 2015). The weak trend (blue line) in increased harvest intensities over time is not significant (shaded area indicate 95 % confidence interval).

In 2012 straw removal affected additionally 185,000 ha in comparison to the reference year 2000. This area makes up 42% of the current area, where straw removal for energy takes place. As such 58% of the current area harvested has not changed status since 2000. As the harvest intensity hasn’t changed significantly in the period 1997-2012 the area already in utilization in 2000 is assumed having the same status in 2012 as in 2000.

The total amount of soil carbon lost due to energy production in 2012 is estimated to 99.5 - 148.7 thousand tonnes C (Figure 30).

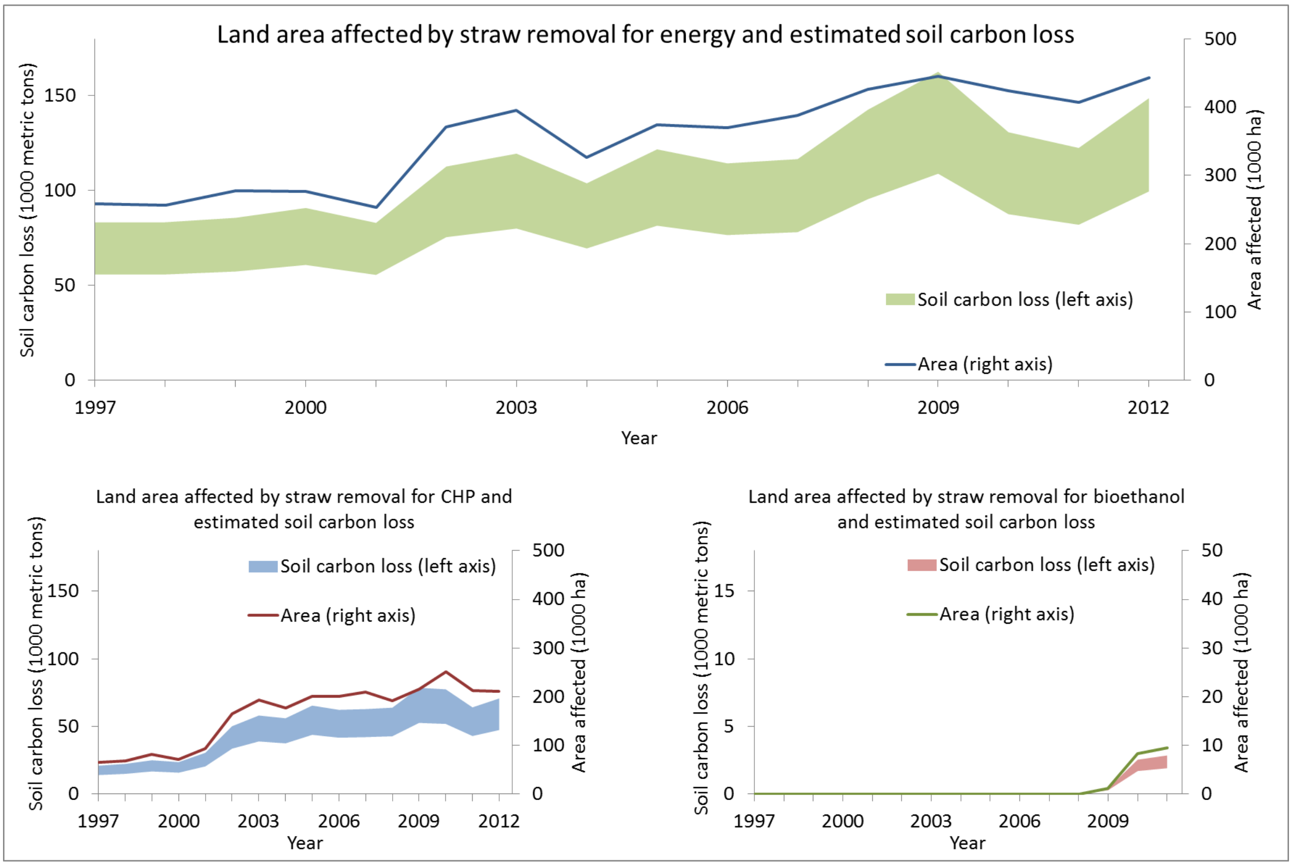

Figure 30. Area affected by straw removal (lines) and estimated loss of soil carbon (shaded areas) as a consequence of energy production from cereal straw in total (upper left display), to CHP (lower left display) and for bioethanol (lower right display). Notice that the Y-axis scale on the lower right display is 1/10 of the left displays.

The agricultural statistics does not contain information whether harvest intensities of straw depend on the subsequent use of straw for e.g. CHP or district heating. Assuming they do not, the fraction of straw for energy used for CHP in 2000 corresponds to straw from 71,700 ha (26%) of the total amount of straw used for energy. In 2012 the corresponding figures were 210,700 ha (48%). Of the 210,700 ha currently harvested for CHP production, 71,700 ha (34%) has not changed status (Table 10).

For bioethanol production the figures started from zero hectares in 2000 and to arrive at 8,353 ha (2.0%) being harvested in 2011. As such all of the current area changed status and the indicator value becomes 0%.

Table 10. GBEP indicator values for indicator 2, soil quality.

Indicator	**Name**	**Unit**	**Reference year**	**Straw to CHP**			**Straw to EtOH**		
				Value	**Change**	**Change yr^{-1}**	**Value**	**Change**	**Change yr^{-1}**
2	Soil quality	%	2012(*11*)	34	-	-	*0*	-	-

7.1.3 Indicator 4: Non-GHG emissions to air

Indicator 4 quantifies emissions of non-GHG to the air from bioenergy production systems; ideally attributed to 4.1) feed stock production, 4.2) processing/conversion, 4.3) transportation and 4.4) use. Quantification of this indicator is to some extent hampered by data availability and only the overall supply chain (indicator 4) and sub-indicator 4.2 (processing/conversion) is quantified (Table 11). Primary data sources are green accounts for individual plants, which are available to the general public for most plants. Due the operating conditions and configurations of individual plants only a very limited number of green accounts can be used. Some plants co-combust straw together with other feedstock and emissions attributable to the straw feedstock cannot be identified. Other plants operate a number of boilers in parallel with their straw fired boiler, but report emissions for the plant in total; thus emissions attributable to straw firing cannot be identified.

Secondary data sources can be technology catalogues (Danish Energy Agency 2010, Danish Energy Agency and Energinet.dk 2012, Energistyrelsen 2013, Evald et al. 2013) or LCA studies on these particular production systems (Nguyen et al. 2013a, Vattenfall 2013). While these data are more generic and constitute averages over time and across operators and as such do not report variability in space and time, they may be more robust estimators of an emission than a single entry in a single green account.

For straw to CHP a number of references are available. The utility company Vattenfall (Vattenfall 2013) reports emission to air from straw to CHP (primary data). Data are based on LCA work on one plant (Amagerværket) in Denmark: 0.36 g SO_2 kWh_{el}^{-1} and 1.13 g NO_x kWh_{el}^{-1}. Nguyen et al. (2013a) estimate (secondary data) non-GHG emissions to air for the total supply chain of 680 g SO_2/tonnes straw (0.61 g SO_2 kWh_{el}^{-1}), 1900 g NO_x /tonnes straw (1.91 g NO_x kWh_{el}^{-1}), 1.92 g PM_{10}/tonnes straw (1.91 mg PM_{10} kWh_{el}^{-1}), and 1.48 g $PM_{2.5}$/tonnes straw (1.48 mg $PM_{2.5}$ kWh_{el}^{-1}).

The Danish Energy Agency (Danish Energy Agency and Energinet.dk 2012) report (secondary data) emissions relating to straw conversion (indicator 4.2) of CHP to 49 g SO_2/GJ_{fuel} (0.61 g SO_2 kWh_{el}^{-1}) and 125 g NO_x/GJ_{fuel} (1.55 g NO_x kWh_{el}^{-1}).

For the total life cycle of straw to ethanol production the Danish Energy Agency (Energistyrelsen 2013) report non GHG emissions to air of 2 g SO_2 MJ_{Etoh}^{-1}, 429 g NO_x MJ_{Etoh}^{-1}, and 1.7 g particles MJ_{Etoh}^{-1}.

Table 11. GBEP indicator values for indicator 4, non-greenhouse gas emissions from the total supply chains and processing step in the supply chains.

Indicator	Name	Unit	Reference year	Straw to CHP			Straw to EtOH		
				Value	Change	Change yr^{-1}	Value	Change	Change yr^{-1}
4	Non-GHG emissions, supply chain	g SO_2 kWh_{el}^{-1}	2010	0.36-0.61	-	-			
		g NO_x kWh_{el}^{-1}	2010	1.13-1.91	-	-			
		mg PM_{10} kWh_{el}^{-1}	2010	1.91	-	-			
		mg $PM_{2.5}$ kWh_{el}^{-1}	2010	1.48	-	-			
		g SO_2 MJ_{EtOH}^{-1}	2020				2	-	-
		g NO_x MJ_{EtOH}^{-1}	2020				429	-	-
		mg PM MJ_{EtOH}^{-1}	2020				1700	-	-
4.2	Non-GHG emissions, processing	g SO_2 kWh_{el}^{-1}	2010-15	0.61	-	-			
		g NO_x kWh_{el}^{-1}	2010-15	1.55	-	-			

7.1.4 Indicator 7: Biological diversity in the landscape

Indicator 7 quantifies the area and percentage of lands of high biodiversity value converted to bioenergy production (7.1), area and percentage of lands where recognized invasive species are cultivated to bioenergy (7.2) and area and percentage of lands, where nationally recognized conservation methods are used. Bioenergy production from agricultural residues in Denmark is a part of industrialized and highly mechanized agriculture. It is believed not to have implications for areas of high biodiversity value (7.1). Straw used for energy is predominantly based on cereal species (wheat and barley), which aren't considered invasive in Denmark (7.2). As straw production and harvest is part of the agricultural practice it takes place on land under active management i.e. not under nature conservation (7.3). All sub-indicators are summarised under the overall indicator 7 (Table 12).

The impact categories included in the GBEP framework must be broad to cover the national scope. On a finer scale biodiversity impacts of straw removal are likely to occur as straw removal can be seen as an intensification of land management (Pedroli et al. 2013).

Table 12. GBEP indicator values for indicator 7, biological diversity in the landscape.

Indicator	Name	Unit	Reference year	Straw to CHP			Straw to EtOH		
				Value	Change	Change yr^{-1}	Value	Change	Change yr^{-1}
7	Biological diversity	Ha	2000	0					
			2012	0	0	0	0	0	0
		%	2000	0			0		
			2012	0	0	0	0	0	0

7.1.5 Indicator 11: Change in income

Indicator 11 quantifies wages paid for employment in the bioenergy sector (11.1) and net income from sale, barter or own consumption of bioenergy products (11.2).

Based on a selling price of straw of DKK413 tonne^{-1} straw[5] (€55.4) Dubgaard et al. (2013) find that increased mobilisation of straw generates positive income for the farmer in the order of DKK159 tonne^{-1} straw (€21.3). Compensatory measures to re-sequester carbon in soils reduce the economic benefit for the farmer to DKK82 tonne^{-1} (€11) (Table 13).

Taking into consideration taxes and economic incentives to further mobilisation of straw it is also found to be of economic benefit to the energy consumer (DKK258 tonne^{-1} straw), to the utility sector (DKK269 tonne^{-1} straw), while the state loses income worth DKK339 tonne^{-1} straw (ibid.).

Table 13. GBEP indicator values for indicator 11, change in income.

Indicator	Name	Unit	Reference year	Straw to CHP		
				Value	Change	Change yr^{-1}
11	Change in income	€ tonne^{-1} straw	2013	11-21.3		

7.1.6 Indicator 12: Jobs in the bioenergy sector

Indicator 12 quantifies net job creation as a result of bioenergy production and use.

National statistics do not identify bioenergy as a sector in Denmark. The bioenergy supply chains studied here directly affect the agricultural, transportation and utility sectors, and indirectly affect

[5] All economic values in this section are expressed as net present value in 2013 of a straw mobilization campaign running from 2013 to 2042.

a number of sectors as machinery production, service and maintenance, oil-refineries, engineering and construction.

Since 2008 The Eur'ObservER has reported annually on jobs in renewable energy production in the European Union. The supply chains evaluated here cannot be separated from other supply chains in the EurObserv'er reports. Employment figures (Figure 31) express full time equivalents of the economic activity in the sector and do not directly express the number of jobs created.

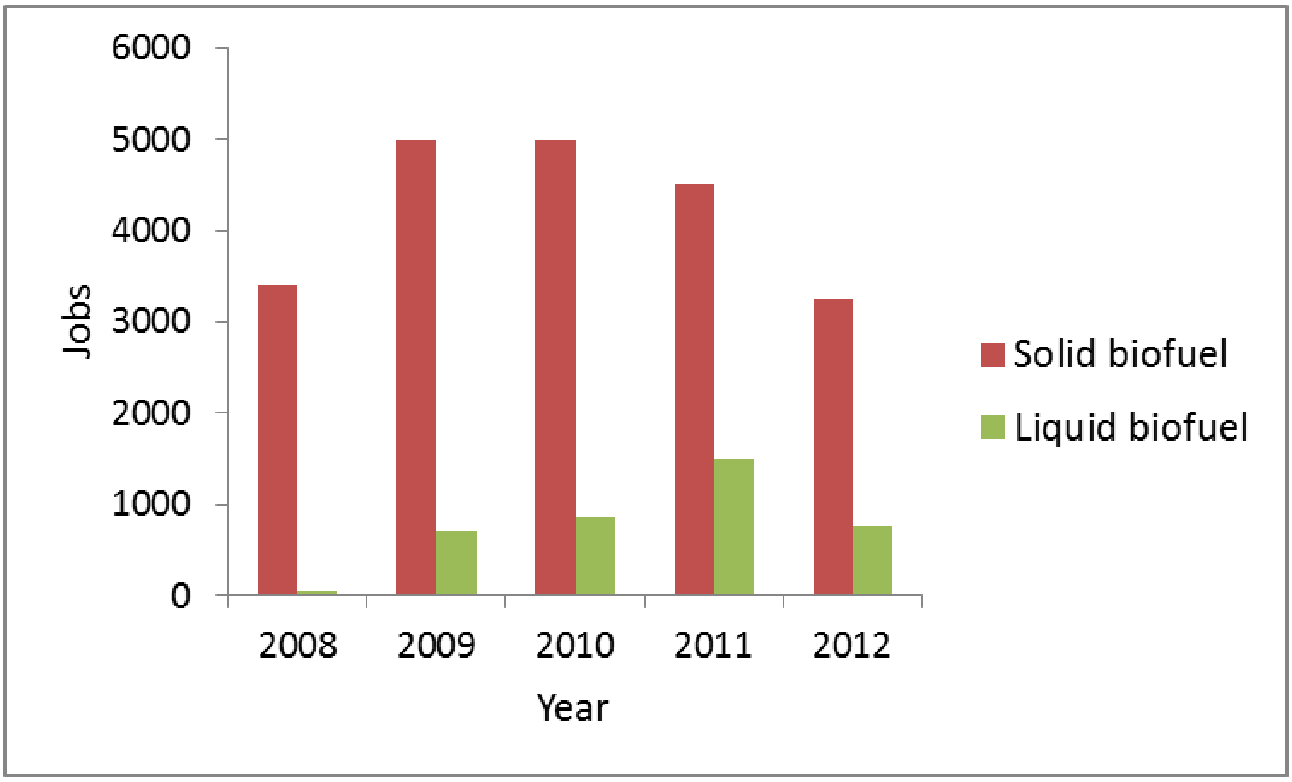

Figure 31. Jobs in the solid bioenergy and liquid biofuel sectors in Denmark 2008-12. Based on (EurObserv'ER 2009, EurObserv'ER 2010, EurObserv'ER 2011, EurObserv'ER 2012, EurObserv'ER 2013).

7.1.7 Indicator 17: Productivity

Indicator 17 quantifies productivity in primary feedstock production (17.1), in the conversion of biomass feedstock to energy services by mass (17.2) and area (17.3), and finally quantifies production cost per unit of bioenergy.

7.1.7.1 Sub-indicator 17.1: Feedstock productivity

The national average productivity of cereal straw for energy has remained fairly constant over the last 12 years (Figure 29). In 2012 the national average amount of cereal straw collected for energy was 3.9 tonnes per hectare (3.3 tonnes dry biomass). There are geographical differences across the country accounting for a variation of approximately ± 15 % on average. In the reference year 2000 3.8 tonnes (3.2 tonnes dry biomass) were collected per hectare for energy. There is no evidence of an increasing trend in productivity over time (Figure 29), and the average amount of straw harvested for energy over the 12 year period is 3.74 tonnes ha^{-1} (Table 15).

7.1.7.2 Sub-indicator 17.2: Processing productivity by mass

The first purely straw fired CHP plant started operation in 1989 and at the end of 2010 9-10 plants were in operation (Sander and Skøtt 2007). Basic operation characteristics and nominal efficiencies are listed in Table 14 below. For comparison the installed electricity generation capacity on thermal plants was 8,160 MW in 2013 (Table 15).

Table 14. Straw capacities, operation characteristics and efficiencies of straw fired plants in operation in Denmark .The conversion efficiency of co-combustion plants expresses the total efficiency of all fuels combined.

Plant	Year in operation	Capacity	Co-combustion	Steam temp.	Steam pressure	Electricity capacity	Electricity efficiency	Total efficiency
		t straw yr^{-1}		^{o}C	bar	MW		
Haslev	1989 -	26,000	-	455	67	5.0	0.19	0.88
Greenaa	1992 -	40,000	Coal	505	92	19.6	0.22	-
Rudkøbing	1990 -	14,000	-	450	60	2.6	0.22	0.89
Slagelse	1990 -	30,000	-	450	67	11.4	0.25	0.89
Masnedø	1996 -	40,000	Wood chips	522	92	9.0	0.25	0.88
Ensted	1998 - 2010	120,000	Wood chips	510	210	-	0.41	0.92
Maribo	2000 -	45,000	-	540	93	10.6	0.29	0.88
Avedøre	2001 -	150,000	Nat. gas, oil, wood pellets	545	310	275.0	0.49	0.94
Studstrup	2005 -	130,000	Coal	540	250	700.0	0.42	-
Fynsværket	2009 -	150,000	-	540	110	35.0	0.33	0.93

Co-combustion of straw is applied in a number of plants to reduce the corrosion by combustion reactants. The relatively high mineral content of straw leads to corrosion and clogging of heat exchangers. These effects can be reduced through co-combustion with a 'purer' fuel or by reducing the steam temperature. Nominal plant efficiency in terms of electricity generation efficiency has generally increased over time primarily as a function of increased steam temperature (Carnot principle).

Production statistics for individual plants using straw made available by the Danish Energy Agency mirror to some extent the information given in Table 14. Biomass use efficiency, expressed as the weighted total fuel efficiency (Figure 32) show an increasing trend from 2000 to 2012, indicating that the utility gained from the straw resource is increasing.

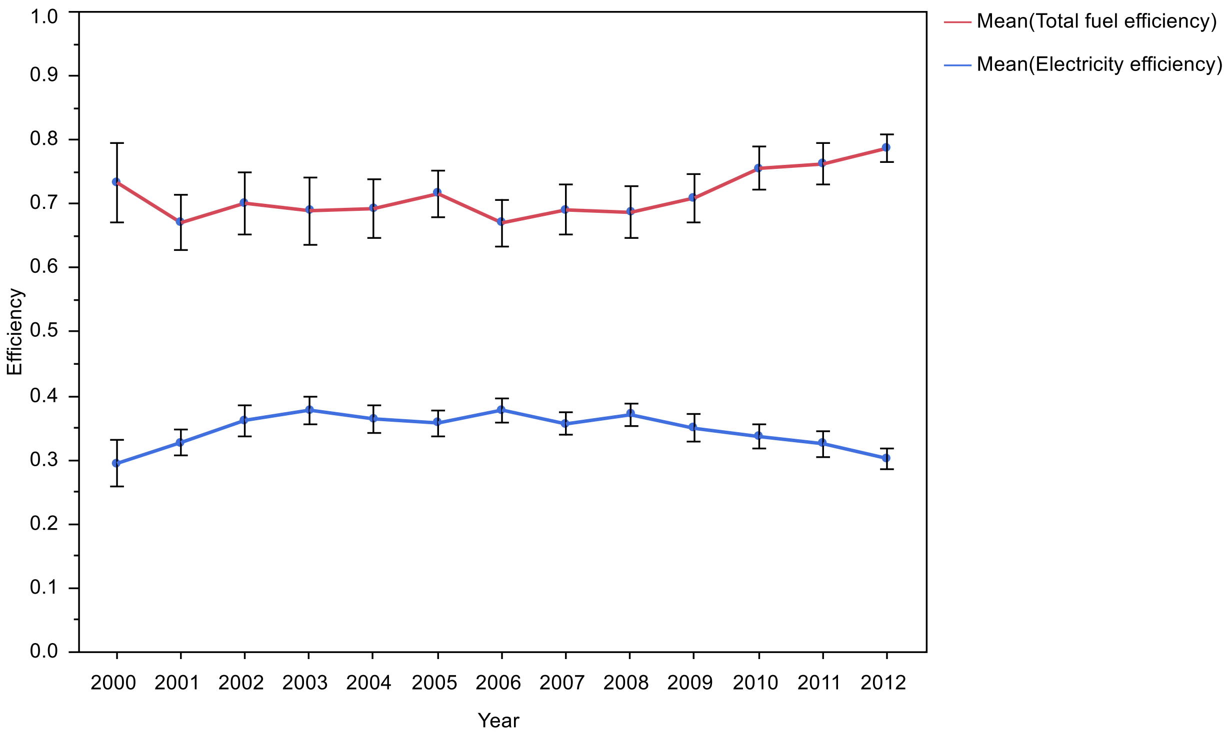

Figure 32. Weighted mean total fuel efficiency and electricity generation efficiency of CHP plants in Denmark using straw as fuel. Mean values are weighted with the individual plants total production of heat and electricity as the plants differ greatly in annual production. Error bars indicate one standard error from the mean.

Ethanol production was not in operation in 2000. Based on the current development of the Inbicon plant it can be estimated that one tonnes of straw can be processed to 4,000 MJ ethanol (Larsen et al. 2012, Evald et al. 2013).

7.1.7.3 Sub-indicator 17.3: Processing productivity by area

The development in area based productivity of CHP production is a function of plant efficiency only as feedstock productivity is assumed constant. In 2000 the average electricity output from straw fired plants corresponded to 4,667 kWh_{el} ha^{-1} and the total energy output to 48,800 MJ_{total} ha^{-1}. In 2010 the productivity had increased to 5,583 kWh_{el} ha^{-1} and 49,900 MJ_{total} ha^{-1} respectively.

The 2010 area based productivity of ethanol production is estimated to 14,960 MJ_{EtOH}/ha (Table 15).

7.1.7.4 Sub-indicator 17.4: Production cost

The Danish Energy Agency (Danish Energy Agency and Energinet.dk 2012) estimates the initial investment cost of straw fired CHP plants to €4-5.8 million per MW in capacity. Small plants with a capacity of 8-10 MW have the highest relative investment cost, while medium sized plant, with capacity of 10-50 MW fall in the lower end of the cost spectrum. Operation and maintenance cost are estimated to €40,000/MW/year (fixed) and €6.4/MWh (variable) (Danish Energy Agency and Energinet.dk 2012). Fuel costs are a significant part of the production costs, and for straw the price paid by the utility company has increased from €3.7 GJ^{-1} in 2000 to €5.0 GJ^{-1} in 2011 measured in real prices (Dansk Fjernvarme 2012).

For bioethanol production the total cost for a Inbicon plant type is estimated to ~€0.9 $liter^{-1}$ EtOH for plants located in North-Western Europe (Larsen et al. 2012) corresponding to ~€0.043 MJ_{EtOH}^{-1} (Table 15).

Table 15. GBEP indicator values for indicator 17, productivity.

Indicator	Name	Unit	Reference year	Straw to CHP			Straw to EtOH		
				Value	Change	Change yr^{-1}	Value	Change	Change yr^{-1}
17.1	Feedstock productivity	$t\ ha^{-1}\ yr^{-1}$	2000	3.8			3.8		
			2012	3.9	ns	ns	3.9	ns	ns
17.2	Processing Productivity by mass	$kWh_{el}\ t^{-1}$	2000	1,249					
			2010	1,490	241	21.9			
		$MJ_{total}\ t^{-1}$	2000	13,050					
			2010	13,340	290	26			
		$MJ_{EtOH}\ t^{-1}$	2010				4,000		
17.3	Processing Productivity by area	$MJ_{el}\ ha^{-1}$	2000	4,667					
			2010	5,583	916	83,3			
		$MJ_{total}\ ha^{-1}$	2000	48,807					
			2010	49,892	1,085	99			
		$MJ_{EtOH}\ ha^{-1}$	2010				14,960		
17.4	Production cost	$EUR\ MJ_{EtOH}^{-1}$	2010				0.043		

7.1.8 Indicator 18: Net energy balance

Indicator 18 evaluates the net energy ratio of bioenergy supply chains in individual process steps 18.1) production, 18.2) processing into bioenergy feedstock, 18.3) bioenergy use or 18.4) for the whole supply chain.

1.1.1.1 Sub-indicator 18.2: Processing (harvest)

Energy consumption for straw collection (baling and handling) is estimated to be 53.2 - 81.8 MJ/ton straw (Dalgaard et al. 2001) including combustion of the diesel itself and energy for extraction, refining and distribution. An average is suggested to be 65.4 MJ/ton straw (Dalgaard et al. 2001), which is also applied in newer studies (Nguyen et al. 2013a, Nguyen et al. 2013b). The average net energy ratio is calculated as 1-(65.4/14,500 [6]) = 0.995. Data is not available to support an assumption on significant development over time (Table 16).

1.1.1.2 Sub-indicator 18.3: Use

Resource use efficiency, expressed as the straw capacity weighted average, has increased from ~0.31 in the reference year 2000 to ~0.37 in 2010 (Figure 32). The total efficiency has increased slightly in the same period from 0.90 to 0.92.

Bio ethanol production on cereal straw came into demonstration scale operation in 2009 with the Inbicon plant in Kalundborg. Demonstrated energy efficiency developments over time are not available. The conversion efficiency on plant level is estimated in a recent study made for the Danish Energy Agency (Evald et al. 2013). Assuming C6 fermentation they find an energy ratio (energy out/energy in) of 0.74. A study made on the demonstration plant reports an energy balance on the plant to 0.71 (Larsen et al. 2012). Considerable efficiency gains are expected in future plant due to process development of pre-treatment, increased dry matter content and enzyme efficiency (Table 16).

1.1.1.3 Sub-indicator 18.4: Life cycle energy balance

A number of life cycle based energy balance studies have been made on bioethanol production on agricultural residues in Denmark. Results are difficult to compare due to methodological differences, assumption and system boundaries. Of particular importance is the energy values

[6] Lower heating value of straw is 14,500 MJ $tonnes^{-1}$.

attributed to different inputs and by-products. If straw is considered a waste product and not attributed an initial energy value (Slentø et al. 2010) then a life cycle energy balance may exceed parity. Also the feedstock transformation during processing and fermentation may yield by-product with improved characteristics that in turn may displace more energy intensive products. E.g. the lignin residue from straw pre-treatment is a more valuable fuel per energy content that straw due to the lower mineral content and higher energy density. Hedegaard et al. (2008) found the LCA energy balance of the Danish IBUS concept based on corn stover to be 0.74. Bentsen et al. (2009), providing worst case scenarios, showed energy balances of wheat straw to ethanol production to be 0.36 (0.29-0.45) assuming C6 fermentation and 0.42 (0.33-0.51) assuming fermentation of C6 and C5 sugars. The study by Bentsen et al. (2009) is methodologically different than others referenced here as it uses an area of land as functional unit and not a quantity of fuel or distance driven on that fuel (Table 16).

Table 16. GBEP indicator values for indicator 17, productivity.

Indicator	Name	Unit	Reference year	Straw to CHP			Straw to EtOH		
				Value	**Change**	**Change yr^{-1}**	**Value**	**Change**	**Change yr^{-1}**
18.2	Net energy balance, harvest	Ratio (0-1)	2000	0.995			0.995		
			2012	0.995	0	0	0.995	0	0
18.3	CHP, electricity		2000	0.31					
			2010	0.37	0.06	0.005			
	CHP, total		2000	0.90					
			2010	0.92	0.02	0.002			
	EtOH, total (C6)		2015				0.74		
18.4	CHP electricity		2010	0.94					
	EtOH, C6		2005				0.74		

7.1.9 Indicator 20: Change in fossil fuel consumption

Indicator 20 quantifies the change in consumption of fossil fuels and traditional use of biomass caused by deployment of (modern) bioenergy.

Although this indicator should be applicable to industrialized supply chains and countries, the indicator is methodologically weak on a national scale. On project or plant level i.e. in retrofitting a plant from a fossil feedstock to biomass the immediate displacement effect may be quantified. However, changing feedstock may change the selling price of energy products from the plant and in turn change the capacity factor and thus the experienced displacement. York (2012) has demonstrated that deployment of renewable energy sources doesn't displace fossil resources one to one measured in energy content, and Mathiesen et al. (2009) demonstrate the uncertainties in identifying marginal energy technologies in LCA work. Ripple effects as described predominantly account for electricity production as electricity is traded within and across borders. In district heating production the displacement effect is more easily assessed as heat customers (usually) haven't got alternative supplies.

Not only have the amounts of straw used for energy changed over time. Also the use pattern has changed (Figure 33). Initially straw was used for individual heating of farm buildings and houses. The advent of energy policies encouraging or even mandating the use of biomass for energy has shifted the balance towards distributed energy generation rather than individual. The use of straw for individual heating would normally displace fuel oil, while straw for district heating would displace natural gas, oil or wood. In CHP production straw would normally displace natural gas, coal or other renewable energy sources.

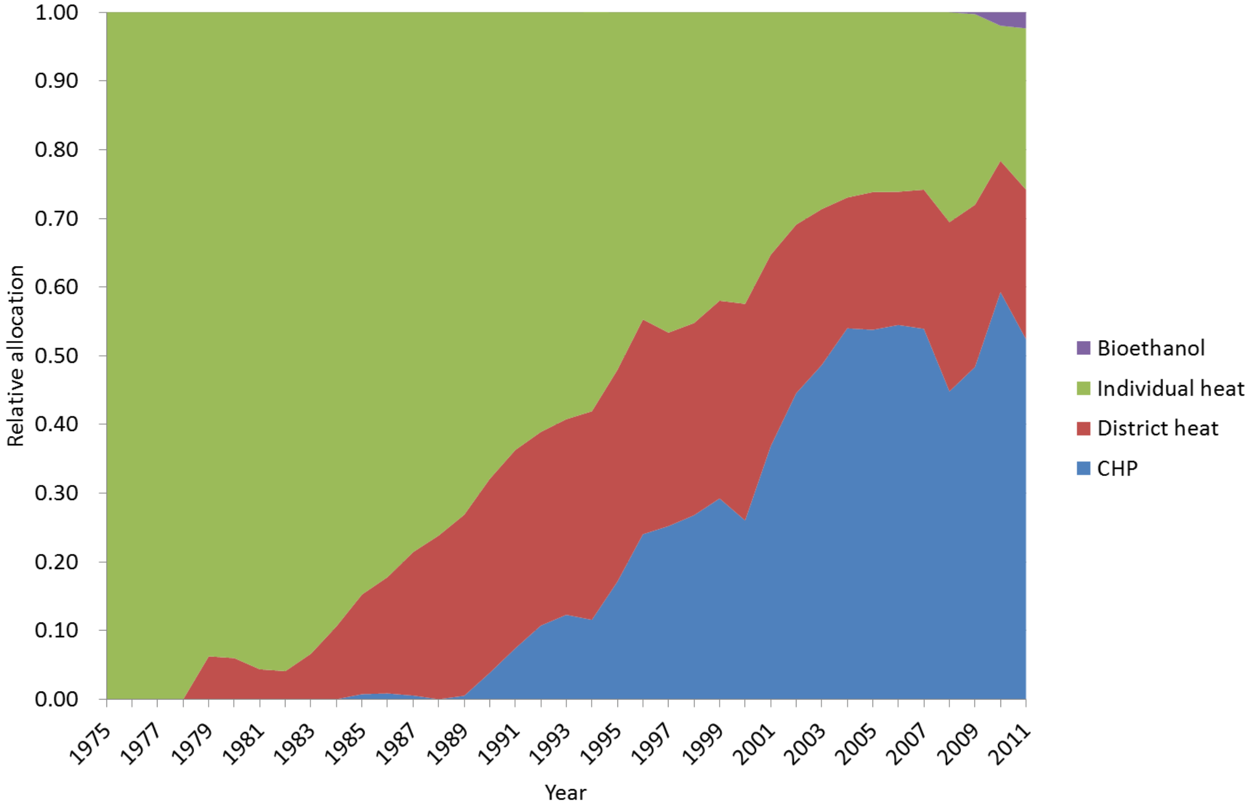

Figure 33. Pattern of straw allocation to energy purposes over time from 1975 to 2011.

As a part of the Danish government's most recent climate and energy strategy (Regeringen 2011) a comprehensive analysis of the economic impact of a number of greenhouse gas mitigating initiatives for agriculture has been conducted (Dubgaard et al. 2013). The analysis builds on the assumption that additionally 350,000 tonnes straw from 100,000 ha could be used for CHP. The direct displacement effect of deploying that amount (5.08 PJ) is calculated to 4.44 PJ coal, 0.51 PJ natural gas and 1.27 PJ wood chips (ibid.). Due to differences in electricity generations efficiency between these fuels a side effect of deploying 350 kilo tonnes straw for CHP is a reduced electricity production of 1 PJ (the reason that 5.08 PJ straw displaces 6.22 PJ other fuels) that must be compensated by e.g. trade, power plants in condensation mode run on natural gas or coal, or wind power. What actually compensates 1 PJ electricity depends on the hour to hour dynamics of the electricity grid.

Regarding ethanol production the fossil displacement can be reasonably assumed to be petroleum based gasoline, however, the displacement ratio is somewhat debated. The energy density of ethanol is lower than of gasoline, but the octane number is higher enabling the use of higher compression rates in engines designed for ethanol. Slentø et al. (2010) find that deployment of 2nd generation bioethanol based on wheat straw reduce the use of fossil resources by 33.5 MJ per kg ethanol produced. Hedegaard et al. (2008) assume a one-to-one displacement of gasoline from bioethanol based on energy content.

7.1.10 Indicator 22: Energy diversity

Indicator 22 measures the change in diversity of total primary energy supply due to bioenergy. As a generalized measure of diversity of the energy supply, the normalized Herfindahl index (HHI*) is applied.

$$HHI^* = \frac{\sum_{i=1}^{N} MS_i^2 - \frac{1}{N}}{1 - \frac{1}{N}},$$

with MS = market share of individual agents and N = the number of agents. HHI is traditionally used in economic sciences to describe competition or concentration in a market. Values close to 1 indicate monopolistic situations with one or few dominating agents, here energy supply sources. Values close to 0 indicate a market with equally strong agents, here understood as high levels of energy diversity. The steady decrease in HHI* show a general trend towards a more diversified energy supply in Denmark (Figure 34). The Dutch GBEP study reports a HHI* of the Dutch energy supply of 0.37 in 2010 (NL Agency 2012). In comparison the Danish energy sector HHI* was 0.21 in 2010.

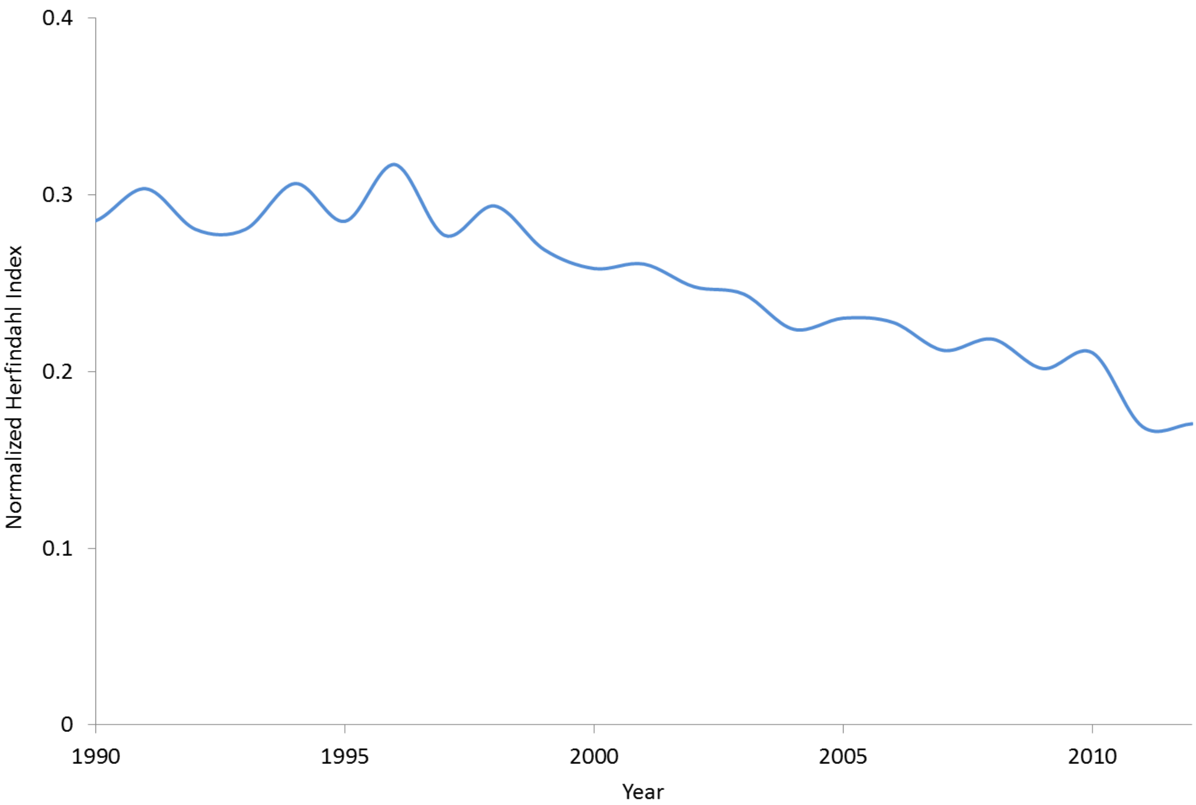

Figure 34. Normalized Herfindahl index of the Danish energy supply from 1990 to 2012. Data from national energy statistics (Energistyrelsen 2016).

The Danish energy supply has changed significantly over time due to strong development in off shore oil and natural gas production after the oil crises in 1973 and 1978-79, and to a political desire to develop a renewable energy sector and support energy self-sufficiency since 1986. Until the mid-1990s coal and oil held strong positions in the Danish energy supply (Figure 35). In later years the penetration of natural gas and a diversity of renewable sources e.g. wind, biomass and waste incineration has increased. The diversity index is calculated as supply = production + import - export of 41 energy carriers in the national energy statistics aggregated to 12 categories relative to total primary energy supply (TPES). Stock changes have been disregarded.

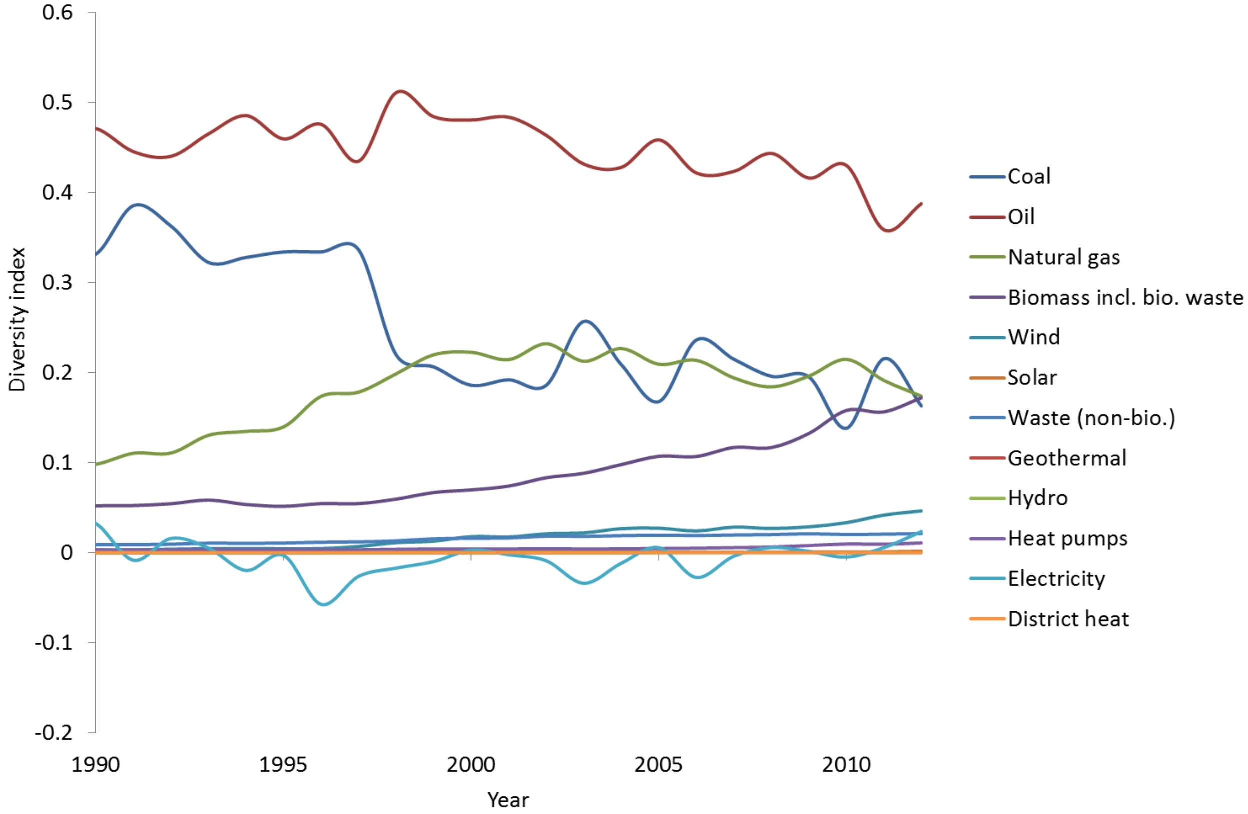

Figure 35. Diversity index of 12 supply sources to the Danish energy mix 1990-2012. Data from (Energistyrelsen 2016)

Since the late 1990s the diversity index of bioenergy has increased almost constantly (Figure 36), but biomass covers a lot of different sources. Figure 36 shows that the diversity index of straw to energy has increased from 0.014 in the reference year 2000 to 0.028 in 2010, and with a subsequent decrease to 0.022 in 2012 (Table 17), while other biomass sources compiled has shown a diversity index increment from 0.055 in 2000 to 0.150 in 2012. Energy from imported wood pellets is one of the main contributors to biomass' increased index. The corresponding indices for the scenarios evaluated here are for straw to CHP 0.004 in 2000 and 0.010 in 2012, and for straw to bioethanol 0.0 in 2000 and <0.001 in 2011 (Figure 36) (Table 17).

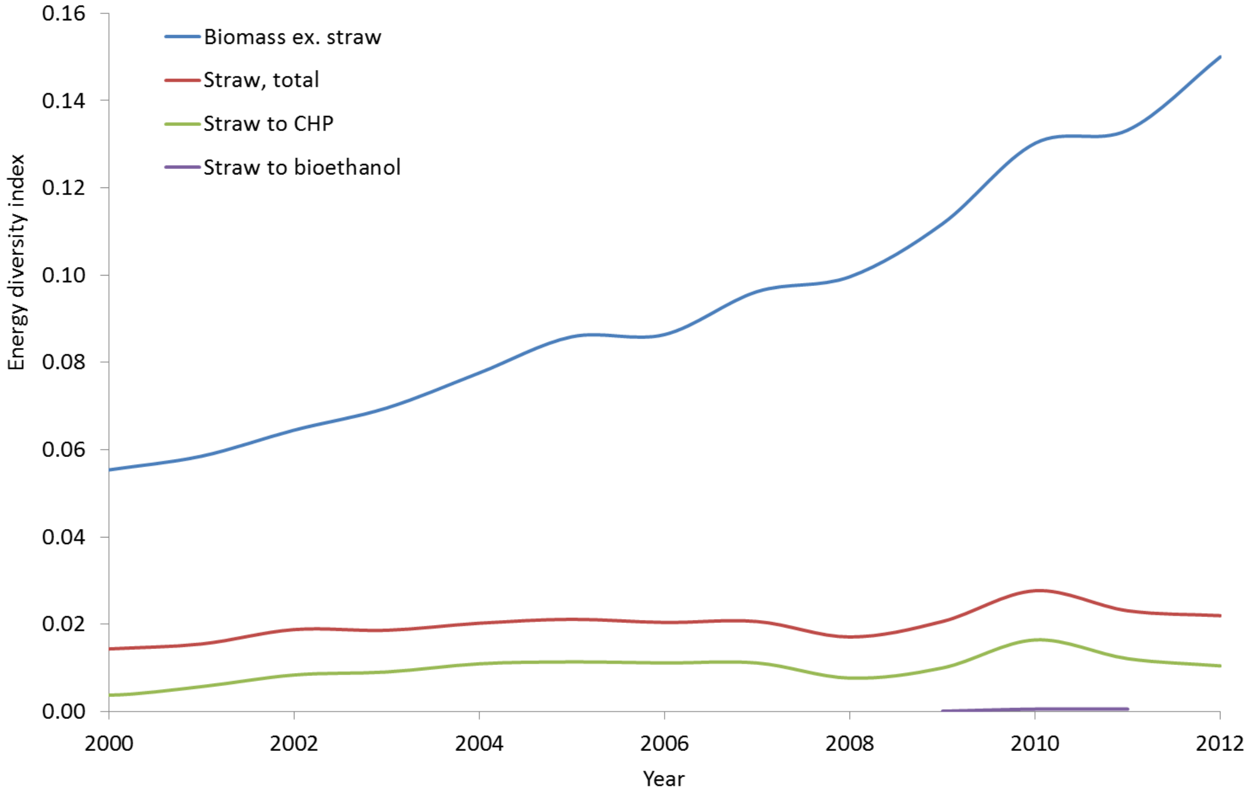

Figure 36. Energy diversity index of biomass, straw, straw to CHP and straw to ethanol in the Danish energy supply.

Table 17. GBEP indicator values for indicator 22, energy diversity.

Indicator	Name	Unit	Reference year	Straw to CHP			Straw to EtOH		
				Value	Change	Change yr^{-1}	Value	Change	Change yr^{-1}
22	Energy diversity	Index (0-1)	2000	0.0037			0		
			2012	0.0105	0.0068	5.23E-04	0.0009	0.0009	6.92E-05

7.1.11 Discussion

Based on the GBEP analysis of straw to energy supply chains it can be summarized that straw used for CHP or ethanol can reduce GHG emissions, improve income generation for the rural population, reduce the use of fossil fuels and increase the diversity of the national energy supply. The critical point from a sustainability point of view is the potential impact on soil carbon derived from straw harvest. Straw harvest will in most cases lead to loss of soil carbon, which again can reduce soil productivity and friability (Dexter 2004, Schjønning et al. 2012). To sufficiently ensure environmental sustainability large scale deployment of straw to energy should be based on locally adapted best management practices.

The analysis does not allow for a direct comparison between the use of straw for CHP or for ethanol. The result indicate that the energy efficiency and GHG benefits is better using straw for CHP. Such a conclusion, however, does not take into consideration differences in energy quality between different energy carriers (Bentsen and Felby 2013) (2nd law efficiency).

7.1.11.1 Evaluation of the assessment framework

Gamba and Toop (2013) evaluated the application of the GBEP framework, based on ongoing work in the pilot studies and found the following for the framework in general.

- Attribution of data to bioenergy is challenging, especially since data may be monitored already, but not specifically related to bioenergy (e.g. data related to agriculture or jobs).
- The appropriate geographical scope of the indicator is not always clear, especially when data crosses country boundaries (e.g. a watershed) or involves imported feedstock. For individual indicators, it should be explained when and how imported feedstock, intermediates and bioenergy carriers should be included.
- Further guidance would be valuable on how to deal with data gaps and how to reduce the uncertainty of the indicators.
- Some indicators were found to be too focused on agricultural feedstock, or lacking in specific details on how to treat, for example, residue feedstock.

7.1.11.2 Data availability

Data availability or the lack of same is a key constraint in sustainability assessments. This case study is based only on data already gathered and made available, no new data were generated. To meet the methodological requirements of the GBEP framework data should ideally relate to a national scale and be based on measurements/experiments, censuses, surveys or national statistics. For this case study a number of otherwise relevant indicators had to be omitted due to the lack of relevant data. Lack of data is predominantly attributable to bioenergy not being a specific sector in the Danish economy. E.g. for indicator 12, jobs in the bioenergy sector, jobs related to bioenergy would be a subset of jobs in industry (machine manufacturing), agriculture (production and harvest of residues), transport and the utility sector (energy generations and distribution). To illustrate the different scales and origins of data used in this case study we developed a data quality barometer (Table 18) for the data included.

Table 18. Origin and scale of data used in the analysis of GBEP indicators.

Data from measurements, national statistics, censuses, surveys	
Data from technology catalogues, life cycle assessments, analyses	
No data available	
Not included, considered irrelevant to the context	

Scale **Indicator**	**Operation**	**Region**	**National**	**Global**
1. GHG emissions				
2. Soil quality				
3. Harvest level of wood				
4. Non-GHG emissions to air				
5. Water use efficiency				
6. Water quality				
7. Biological diversity in the landscape				
8. Land use and land use change				
9. Allocation and tenure of land for bioenergy				
10. Price and supply of a national food basket				
11. Change in income				
12. Jobs in the bioenergy sector				
13. Change in unpaid time spent by women and children				
14. Bioenergy used to expand access to modern energy services				
15. Change in mortality and burden of disease attributable to indoor smoke				
16. Incidence of occupational injuries, illness and fatalities				
17. Productivity				
18. Net energy balance				
19. Gross value added				
20. Change in fossil fuel consumption				
21. Training and requalification of work force				
22. Energy diversity				
23. Infrastructure and logistics for distribution of bioenergy				
24. Capacity and flexibility of use of bioenergy				

7.1.11.3 Methodology issues and suggestions

This case study highlights to some degree the same methodological challenges in using the GBEP framework as reported by Gamba and Topp (Gamba and Toop 2013).

Attribution of environmental impacts to a specific supply chain is challenging when analysing a multiple input-multiple output system. There are a number of ways to allocate environmental burdens to co-products either by value, mass, energy or economic driver. In consequential life cycle assessments the allocation challenge is diminished through system expansion (allocation issues are moved from the centre to the periphery of the analysed production system). However, only a few of the GBEP indicators builds on a life cycle approach.

The import/export challenge also reported by (Gamba and Toop 2013) was not an issue in this case study as straw is not subject to cross border trade in Denmark. Everything used has a Danish origin. Including wood chips and wood pellets in the analysis would have highlighted the challenge. Import of wood pellets has increased over the years and in 2013 imported wood pellets made up 95% of the total supply. The corresponding figure for wood chips was 34%. Wood pellets and chips are sourced from more than 20 different countries on different continents (Bentsen and Stupak 2013) making it very difficult and time consuming to acquire relevant and covering data for the national supply of these resources.

The GBEP framework does not operate with indicator specific thresholds or targets to be met. By not having thresholds the GBEP framework seems applicable and relevant to wide variety of national and regional situations. Specific thresholds may be relevant to only a limited political or geographical area and determination of a threshold cannot be based on science alone. On the downside the numerical value of an indicator bears little relevant information in itself. Even though the methodology is well defined and described there is a considerable methodological operating space for the analysts making comparisons between GBEP studies in different countries and regions questionable. One solution to overcome this potential lack of relevance and information could be the approach applied in this assessment providing a development over time of indicator values.

7.2 USA

The situation in the U.S. is different from Denmark in that there is little tradition for using agricultural crop residues for energy purposes. Still a lot of research and information is available to assess sustainability issues for crop residue to energy supply chains. An assessment of U.S. agricultural residue potential with the GBEP indicator list was not available at the time of writing. Research has been done at U.S. level to define categories for indicators of environmental and socioeconomic sustainability (McBride et al. 2011, Dale et al. 2013a, Efroymson et al. 2013). The respective core indicator set has been applied to a case study with switchgrass, but not yet to agricultural residues. At the same time, soil quality aspects have been analyzed as part of other studies (Muth and Bryden 2013).

7.2.1 ORNL framework on environmental and socioeconomic sustainability

The ORNL framework identifies a number of quantitative indicators of environmental sustainability of bioenergy, along with associated management pressures and environmental effects expected to be captured by each indicator (Table 19) (McBride et al. 2011).

Table 19. Environmental indicators for bioenergy sustainability and associated management pressures and environmental effects to be captured by each indicator (McBride et al. 2011).

Category	Indicator	Units	Related management pressures	Potential related environmental effects	Reference that discusses methods used to collect data
Soil quality	1. Total organic carbon (TOC)	Mg/ha	Crop choice, tillage	Climate change, N mineralization, humification, water holding capacity, infiltration, CEC	Doran and Jones (1996)
	2. Total nitrogen (N)	Mg/ha	Crop choice, tillage, N fertilizer application, harvesting practices	Eutrophication potential, N availability	Bremner and Mulvaney (1982)
	3. Extractable phosphorus (P)	Mg/ha	Crop choice, tillage, P fertilizer application, harvesting practices	Eutrophication potential, P availability	Olsen et al. (1954) and Mehlich (1984)
	4. Bulk density	g/cm^3	Harvesting practices, tillage, crop choice	Water holding capacity, infiltration, crop nutrient availability	Doran and Jones (1996)
Water quality and quantity	5. Nitrate concentration in streams (and export)	Concentration: mg/L; export: kg/ha/year	Crop choice, % of residue harvested, tillage, N fertilizer application	Eutrophication, hypoxia, potability	Eaton et al. (2005)
	6. Total phosphorus (P) concentration in streams (and export)	Concentration: mg/L; export: kg/ha/year	Crop choice, % of residue harvested, tillage, P fertilizer application	Eutrophication, hypoxia	Eaton et al. (2005)
	7. Suspended sediment concentration in streams (and export)	Concentration: mg/L; export: kg/ha/year	Crop choice, % of residue harvested, tillage	Benthic habitat degradation through siltation, clogging of gills and filters	Eaton et al. (2005)
	8. Herbicide concentration in streams (and export)	Concentration: mg/L; export: kg/ha/year	Crop choice, herbicide application, tillage	Habitat degradation through toxicity, potability	Eaton et al. (2005)
	9. Peak storm flow	L/s	Crop choice, % of residue harvested, tillage	Erosion, sediment loading, infiltration	Buchanan and Somers (1969)
	10. Minimum base flow	L/s	Crop choice, % reside harvested, tillage	Habitat degradation, lack of dissolved oxygen	Buchanan and Somers (1969)
	11. Consumptive water use (incorporates base flow)	Feedstock production: m^3/ha/day; biorefinery: m^3/day	Crop choice, irrigation practices, downstream biomass processing	Availability of water for other uses	Feedstock production: calculated from flow measurements. Biorefineries: reported total water withdrawn used as proxy
Greenhouse gases	12. CO_2 equivalent emissions (CO_2 and N_2O)	kg C_{eq}/GJ	N fertilizer production and use, crop choice, tillage, liming, fossil fuel use throughout supply chains	Climate change, plant growth	Spreadsheet models (e.g., GREET; Wang, 2002), with various submodels
Biodiversity	13. Presence of taxa of special concern	Presence	Crop choice, regional land uses, management practices	Biodiversity	Various methods exist depending on taxa selected
	14. Habitat area of taxa of special concern	ha	Crop choice, regional land uses	Biodiversity	Various methods exist depending on taxa selected; for one approach see: Turlure et al. (2010)
Air quality	15. Tropospheric ozone	ppb	Fossil fuel use in production and processing, quality and mode of combustion of biofuel	Human health, plant health	Combination of sources and methods necessary, for example: EPA Mobile Source Observation Database, Community Multiscale Air Quality model (for example: Appel et al., 2007), reports from biorefineries, collation of vehicle use with emissions data per fuel type (for example: Gaffney and Marley, 2009)
	16. Carbon monoxide	ppm	Fossil fuel use in production and processing, mode of biofuel combustion	Human health	
	17. Total particulate matter less than 2.5 µm diameter ($PM_{2.5}$)	µg/m^3	N fertilizer application, fossil fuel use in production and processing, mode of biofuel combustion	Visibility, human health	
	18. Total particulate matter less than 10 µm diameter (PM_{10})	µg/m^3	Fossil fuel use in production and processing, other agricultural activities, solid biomass combustion	Visibility, human health	
Productivity	19. Aboveground net primary productivity (ANPP)/yield	g C/m^2/year	Crop choice, management practices	Climate change, soil fertility, cycling of carbon and other nutrients	Grasslands: Scurlock et al. (2002). Forests: Clark et al. (2001)

Table 20 below identifies the various socioeconomic categories and the measurable indicators that apply.

Table 20. Socioeconomic sustainability indicators of the ORNL framework (Dale et al. 2013a).

Category	Indicator	Units
Social well-being	Employment	Number of full time equivalent (FTE) jobs
	Household income	Dollars per day
	Work days lost due to injury	Average number of work days lost per worker per year
	Food security	percent change in food price volatility
Energy Security	Energy security premium	Dollars /gallon biofuel
	Fuel price volatility	Standard deviation of monthly percentage price changes over one year
External trade	Terms of trade	Ratio (price of exports/price of imports)
	Trade volume	Dollars (net exports or balance of payments)
Profitability	Return on investment (ROI)	Percent (net investment/initial investment)
	Net present value (NPV)$_2$	Dollars (present value of benefits miinus present value of costs)

Category	Indicator	Units
Resource conservation	Depletion of non-renewable energy resources	MT (amount of petroleum extracted per year)
	Fossil Energy Return on Investment (fossil EROI)	MJ (ratio of amount of fossil energy inputs to amount of useful energy output
Social acceptability	Public opinion	Percent favorable opinion
	Transparency	Percent of indicators for which timely and relevant performance datra are reported
	Effective stakeholder participation	Number of documented responses to stakeholder concerns and suggestions reported on an annual basis
	Risk of catastrophe	Annual probability of catastrophic event

Some proposed indicators are more complex and costly to measure than others but it is believed that these costs become manageable if broad agreement to focus on a limited set of measures can be reached. Collectively, the proposed suite of socioeconomic and environmental indicators forms a hypothesis of how effects on sustainability may be assessed. We submit that this suite of indicators could serve as a starting point to be adapted as necessary to address priorities for assessment in a specific place and time. The next step would be to test this hypothesis in diverse bioenergy systems and a variety of locations. The list of potential indicators should be reassessed as new information, technologies or data-collection techniques come online (Dale et al. 2013a).

7.2.2 SMAF for assessment of soil quality under residue management

Soil erosion is consistently identified as a critical process for soil quality. Significant loss in productivity and soil quality will occur if soil erosion losses consistently exceed soil formation rates. The USDA Natural Resources Conservation Service (NRCS) has developed standard approaches and tools for evaluating soil erosion levels to compare to established tolerable loss levels at the soil survey map unit scale. This project has incorporated the NRCS methods into the integrated framework, and all targets will include criteria that restrict simulated soil erosion levels to less than established tolerable soil loss levels.

In addition to soil erosion, soil quality is represented by a range of biological, chemical, and physical indicators of soil health. In collaboration with partners in the DOE Regional Biomass Feedstock Partnership it was determined that for this milestone the more appropriate and comprehensive soil quality evaluation approach is the Soil Management Assessment Framework (SMAF) (Andrews et al. 2004). Table 21 below represents the soil quality indicators and scoring criteria that are included in the SMAF tool.

Table 21. Soil quality indicators related to environmental, management, and productivity goals used in SMAF. Adapted from (Andrews et al. 2004).

Soil Function	**Indicator** [a]	**Criteria for Selection of Indicator** [b]	**Reference for use as a Soil Quality Indicator**
Biodiversity and habitat (environmental goal)	MI	Large spatial area of interest	(Bongers 1990, Linden et al. 1994, Blair et al. 1996)
	qCO_2	Environmental management goal or C change assessment	(Gregorich et al. 1994, Sparling et al. 1997)
Filtering and buffering (waste management and environmental goals)	D_b	Manure management goal	(Larson and Pierce 1991, Doran and Parkin 1994, Arshad et al. 1996)
	Test P	Environmental goal or manure applied	(Harris et al. 1996)
	TOC	Always suggested under this function	(Larson and Pierce 1991, Doran and Parkin 1994, Elliott et al. 1994, Sikora et al. 1996)
Nutrient Cycling (all goals)	MBC	C change assessment or alternative to PMN	(Gregorich et al. 1994, Turco et al. 1994, Rice et al. 1996)
	PMN	Always suggested under this function	(Doran and Parkin 1994, Needelman et al. 1999)
	Soil pH	Always suggested under this function	(Doran and Parkin 1994, Karlen et al. 1996, Smith et al. 1996)
	Test P	Organic amendment comparison or southern region + productivity goal	Listed Above
Physical Stability and Support (environmental and productivity goals)	AGG	Always suggested under this function	(Arshad et al. 1996, Harris et al. 1996, Karlen et al. 1996)
	D_b	Clay texture + practice comparison	Listed Above
	Soil pH	Arid region	Listed Above
Resistance and Resilience (all goals)	Soil Depth	Environmental or productivity management goal	(Arshad et al. 1996, Grossman et al. 2001, USDA-NRCS 2001)
	TOC	Comparisons over time or C change assessment or organic amendment comparison	Listed Above
Water Regulations (all goals)	AWC	Always suggested under this function	(Larson and Pierce 1991, Lowery et al. 1996)
	D_b	Tillage comparison	Listed Above
	EC	Arid regions or manure management goal	(Smith et al. 1996)
	SAR	Selected in arid regions	(Andrews et al. 2002a, Andrews et al. 2002b)
	Soil pH	Arid region or manure management or fertilizer comparison + water quality.	Listed Above

[a] – MI, nematode maturity index (used as an endpoint measure instead of a MDS indicator, see text); qCO_2, metabolic quotient (a proportion of soil respiration and microbial biomass); D_b, bulk density; test P, soil test P; TOC, total organic C; MBC, microbial biomass C; PMN, potentially mineralisable nitrogen (aerobic incubation); AGG, macro-aggregate stability; AWC, available water capacity; EC, electrical conductivity; SAR, sodium absorption ratio.
[b] – When the stated criteria are met under a given function, the corresponding indicator is suggested as a potential minimum data set component.

While the SMAF database contains in excess of eighty indicators for determining soil quality as related to function, eleven of these indicators are of principal interest for communicating the achievement of landscape management targeted towards residue availability or the production of dedicated energy crops. Locally managed indicators include soil pH, potentially mineralized nitrogen (PMN), and soil test phosphorus (test P), and are to a large extent determined by a land manager's agronomic practices. The relationship between each of these indicators is complex as the level of interaction between the three is high, and respect must be paid to each if management of one is to be undertaken. For example, soil pH impacts the availability of nutrients and activity of microorganisms which in turn limits a plant's productivity and the soil's ability to cycle organic matter and minerals. Acidic nitrogen fertilizers lower the soil's pH, and the potential to mineralize nitrogen from the soil's N-pool is determined by pH dependent biotic and abiotic factors. Phosphorus management must be balanced with nitrogen management, as the ratio of P to N available to a plant heavily impacts plant productivity and pollution risks. Counterproductive feedback between these factors dictates that proper balancing is critical to maintain soil health and site productivity. Because of this, active management is required on a site specific basis.

Secondary indicators focus primarily on soil physical and chemical properties. As with the locally managed indicators, many of the secondary indicators interact with one another. In a broad sense, the physical properties of water stable aggregation (AGG), plant-available water holding capacity (AWC), and soil bulk density (D_b) are appropriately discussed within the context of one another. Soil bulk density is the measure of a soil's mass within a specified volume, typically represented as g cm^{-3}, and is representative of soil compaction. Furthermore, depending on soil texture (composition of sand, silt, and clay) the bulk density of a soil will influence the soil's pore space which, in addition to its importance in gas exchange, is important in terms of infiltration rate and water holding capacity. An increase in soil bulk density decreases free air space in the soil, limiting gas exchange, root growth, and water relations. On the latter, water holding capacity is the measure of the quantity of water contained in a soil that is available for plant uptake (that is, not too tightly bound to soil particles due to an unfavourable fraction of micro-pores versus macro-pores as would be the case in a compacted soil). Reduction of a soil's plant-available water holding capacity increases the likelihood of plant desiccation in xeric conditions and may require additional management or resource use to maintain productivity. The stability of aggregates in a soil is indicative of the soil's organic carbon quantity and quality, as healthy soils with biotic decomposition of organics promotes the formation and stability of aggregates. The presence of aggregates in turn influences both the soil bulk density and water holding capacity; as large pore spaces are created that allow water infiltration and absorption of moisture into the aggregates themselves. Poor soil health related to these three indicators poses an interesting challenge, as poor bulk density, low aggregates, and low water holding capacity will result in poor stand production and increased rill and sheet erosion, but the most easily applied remedy to reducing soil compaction is tillage; which increases the soil's susceptibility to wind erosion. In whole, the proper management of these secondary indicators is ultimately reflected in soil erosion potential.

Soil chemical properties being classified as secondary indicators include electrical conductivity (EC), microbial biomass carbon (MBC), and sodium absorption ratio (SAR). The ability of a soil to conduct electricity is a common measure often used to describe soil physical properties (i.e., soil texture and moisture) and chemical characteristics (i.e., soil organic carbon, salinity, and pH). In a healthy soil system, electrical conductivity is greater in soils with smaller particles sizes (a greater fraction of clays versus sand) and thus inferences can be made to the soil's water holding capacity, pore space, and organic content. However, the sodium absorption ratio of a soil can have a great influence on soil EC, as sodium is highly conductive. A high sodium absorption ratio (a comparison of sodium ions present in a soil to those of calcium and magnesium) may develop in irrigated soils and is often associated with poor soil structure, inference with plant-water uptake, and reduce the soil's microflora. To this extent, the quantity of soil carbon derived from fungus and bacteria is reduced in a poor quality soil. In addition to a decreased pool of nutrients that would be provided by fungal biomass, the reduced microbial community will not provide the benefits of nutrient cycling and turnover (largely nitrogen availability that results from the breakdown of detritus by fungi) to the same magnitude as in a healthy soil system.

As discussed the soil quality indicators included in the SMAF are comprehensive, but they can be organized hierarchically for the targets developed in this report. For the purpose of setting soil sustainability targets, two primary indicators have been chosen: soil erosion and total organic carbon (TOC). Although soil erosion is not handled by SMAF, all of the locally managed and secondary indicators discussed have an impact on a soil's erosion potential. By focusing sustainability goals on a soil erosion factor, the influence of an immense amount of soil quality indicators is built-in to the processes' objective, focusing primarily on physical indicators. Total organic carbon is similar in nature and largely encompasses a great deal of influence from soil biological and chemical properties. With these interactions noted and respected, the development of soil quality targets will rely strongly on the primary indicators and will incorporate the secondary indicators as a means of quantifying the long-term benefits of energy crop production.

7.3 Canada

Currently there is no crop residue to energy/bioproduct business case in operation in Canada, but a lot of interest in developing such. In contrast to Europe the development of business cases in Canada is driven by the business it-self, farmers, farmer organisations and biorefineries.

The sustainability assessment work of the Canadian case of the partial harvest of corn stover in an existing agricultural area of Southwestern Ontario and conversion into biochemicals and coproducts, that could include bioenergy, began by reviewing the GBEP framework. A GBEP suitability assessment was completed by representatives of the Ontario Federation of Agriculture, La Coop fédérée and Agriculture and Agri-Food Canada in October 2013. The results, shown in Table 22, note, as in the Denmark case, that some of the GBEP indicators were not relevant. Also, the GBEP framework would have to be applied at a much smaller, regional scope, instead of national, for the results to be meaningful. Finally, many of the GBEP indicators apply to "land on which bioenergy is produced". As agriculture residues are produced as a by-product of grain production and they are not dedicated crops, this raised the question of what should the appropriate geographic area be for sustainability assessment where a portion of a managed land system is used for bioproducts.

Table 22. Evaluation of the GBEP framework's applicability in a Canadian context with corn stover as feedstock for liquid fuel and bio-materials.

Environmental pillar		GBEP Indicators	Corn Stover Canadian Case
1	Lifecycle GHG emissions	Lifecycle greenhouse gas emissions from bioenergy production and use	YES; could be quantified using GHGenius (nationally accepted methodology)
2	Soil quality	Percentage of land for which soil quality, in particular soil organic carbon, is maintained or improved	YES - very important indicator; modelling of change in soil organic carbon at SLC; soil organic carbon and particulate organic matter measured over the long term.
3	Harvest levels of wood resources	Annual harvest of wood resources by volume and as a percentage of net growth or sustained yield, and the percentage of the annual harvest used for bioenergy.	YES; ag residue harvest rates known (once operational); crop yield data; stover yield calculate from grain yield and harvest index.
4	Emissions of non-GHG air pollutants, including air toxics	Emissions of non-GHG air pollutants, including air toxics, from bioenergy feedstock production, processing, transport of feedstocks, intermediate products and end products.	YES (particulate matter emissions related to feedstock harvest and baling at SLC); YES (regulated air emissions for processing); Refer to provincial air regulations and emissions permit.
5	Water use and efficiency feedstocks per unit of bioenergy output, disaggregated into renewable and non-renewable water sources.	Water withdrawn from nationally determined watershed(s) for the production and processing of bioenergy feedstocks.	ZERO - the ag land under question is not irrigated.
		Volume of water withdrawn from nationally determined watershed(s) used for the production and processing of bioenergy.	YES; once operational; Refer to water intake permit and regulations.
6	Water quality	Pollutant loadings to waterways and bodies of water attributable to fertilizer and pesticide application for bioenergy feedstock cultivation.	Not possible to estimate at a farm scale nor to allocate to specific crop; risk of water contamination by N can be modelled for SLC polygon; risk of P contamination can be modelled by watershed that has more than 5% agriculture; risk of surface water contamination by pesticides in SLC polygon.
		Pollutant loadings to waterways and bodies of water attributable to bioenergy processing effluents.	YES; once operational; processing operations would be required to be below regulated discharge standards; Refer to operating permit.

7	Biological diversity in the landscape	Area and percentage of nationally recognized areas of high biodiversity value or critical ecosystems converted to bioenergy production.	ZERO; agricultural land is used, there is no land conversion; index of habitat capacity available by SLC polygon
		Area and percentage of the land used for bioenergy production where nationally recognized invasive species, by risk category, are cultivated.	ZERO; agricultural land is used, the crops grown on this land (corn-soybean-winter wheat) are not invasive species
		Area and percentage of the land used for bioenergy production where nationally recognized conservation methods are used.	ZERO; agricultural land is used; information on tillage practices, integrated pest management, etc. would have to be collected.
8	Land use and land-use change related to bioenergy feedstock production.	Total area of land for bioenergy feedstock production.	ZERO; agricultural land is used; land is used for grain and oilseed production; the primary markets for the grain are food and feed; there is no dedicated bioenergy feedstock production.
		Percentages of bioenergy from yield increases, residues, wastes and degraded or contaminated land.	YES; sources of biomass could be identified and quantified, once operational.
9	Allocation and tenure of land for new bioenergy production	Percentage of land – total and by land-use type – used for new bioenergy production where: a legal instrument or domestic authority establishes title and procedures for change of title; the current domestic legal system and/or socially accepted practices provide due process and established procedures are followed for determining legal title	ZERO; in this case, no agricultural land is converted to bioenergy production
10	Price and supply of a national food basket	Effects of bioenergy use and domestic production on the price and supply of a food basket, which is a nationally defined collection of representative foodstuffs, including main staple crops	Not relevant; Market Basket Measure (MBM) thresholds are available for rural communities and small communities under 30,000 for each province; It would not be possible to see the effect of use of biomass for bioenergy or bio-products on the MBM.
11	Change in income	Contribution of the following to change in income due to bioenergy production:	
		wages paid for employment in the bioenergy sector in relation to comparable sectors;	Yes - once operational; data more likely accessible at the sector (vs project) scale.
		net income from the sale, barter and/or own consumption of bioenergy products, including feedstocks, by self-employed households/individuals.	No; unlikely to collect information from self-employed households/individuals.

12	Jobs in the bioenergy sector	Net job creation as a result of bioenergy production and use, total and disaggregated (if possible) as follows: 1) skilled/unskilled; 2) temporary/indefinite. Total number of jobs in the bioenergy sector and percentage adhering to nationally recognized labour standards.	YES; once operational; could collect info on types and numbers of jobs created Sector level information needed; bioenergy or bioproducts would have to be identified as a stand-alone sector that would be tracked
13	Change in unpaid time spent by women and children collecting biomass	Change in average unpaid time spent by women and children collecting biomass as a result of switching from traditional use of biomass to modern bioenergy services.	Not applicable
14	Bioenergy used to expand access to modern energy services	Total amount and percentage of increased access to modern energy services gained through modern bioenergy.	Not applicable
		Total number and percentage of households and businesses using bioenergy.	Although possible, if data sources are available; Indicator is not considered relevant to the regional case study
15	Change in mortality and burden of disease attributable to indoor smoke	Change in mortality and burden of disease attributable to indoor smoke from solid fuel use, and changes in these as a result of the increased deployment of modern bioenergy services, including improved biomass-based cook stoves.	Not applicable
16	Incidence of occupational injury, illness and fatalities	Incidences of occupational injury, illness and fatalities in the production of bioenergy in relation to comparable sectors.	YES; once operational; but likely only at the sector level.
17	Productivity	Productivity of bioenergy feedstocks by feedstock or by farm/plantation.	YES; biomass yield information can be calculated from grain yield using harvest index.
		Processing efficiencies by technology and feedstock.	YES; processing yield should be available once operational; however information might be treated as business confidential.
		Amount of bioenergy end product by mass, volume or energy content per hectare per year.	YES; could be calculated from yield info.
		Production cost per unit of bioenergy.	YES; production costs will be available once operational; information will likely be confidential to business.
18	Net energy balance	Energy ratio of the bioenergy value chain (as a whole and individual stages) with comparison with other energy sources.	Can be calculated as part of GHG lifecycle assessment.
19	Gross value added	Gross value added per unit of bioenergy produced and as a percentage of gross domestic product.	YES; once operational; gross valued could be calculated, but likely business confidential.

20	Change in the consumption of fossil fuels and traditional use of biomass	Substitution of fossil fuels with domestic bioenergy.	Not applicable for a new operation; Could be calculated for an existing facility if fossil fuel were substituted with bioenergy.
		Substitution of traditional use of biomass with modern domestic bioenergy measured by energy content.	Not applicable; assume 100% modern energy use in Canada.
21	Training and re-qualification of the workforce	Percentage of trained workers in the bioenergy sector out of total bioenergy workforce.	YES; once operational; employee training records for operation.
		Percentage of re-qualified workers out of the total number of jobs lost in the bioenergy sector.	YES; once operational; potentially available for the facility; more readily available at the sector scale.
22	Energy diversity	Change in diversity of total primary energy supply due to bioenergy.	YES; energy mix of operation; source of purchased electricity mix is variable.
23	Infrastructure and logistics for distribution of bioenergy	Number and capacity of routes for critical distribution systems.	YES; potential market outlets and distribution networks could be identified; but information would likely be business confidential.
24	Capacity and flexibility of use of bioenergy	Ratio of capacity for using bioenergy compared with actual use for each significant utilization route	YES; however market capture information would likely be business confidential
		Ratio of flexible capacity which can use either bioenergy or other fuel sources to total capacity.	YES; If data source could be identified; would be easier for bioenergy or biofuels.

As separate work, the Canadian team had been following the development of the international standard ISO 13065 on Sustainability Criteria for Bioenergy with the hope that this standard could provide a useful framework that had international recognition. However, the final product is a type of management standard that guides users on what sustainability indicators should be identified and addressed with a management plan. The principles, criteria and indicators provide high level guidance on what should be included in a sustainability assessment, and what indicators should be managed.

The EU's FP7 framework supported a very ambitious integrated sustainability assessment project called PROSUITE. The development of PROSUITE and its application to bio-based projects was also followed to see if it would be useful tool for the assessment of new bio-product pathways. PROSUITE builds on a life cycle approach and brings together many sustainability indicators for an integrated assessment and discussion of trade-offs. It requires a fairly specific, quantified understanding of the new technology as well as a reference system for comparison. Such technology and process details were not yet available for the Southwestern Ontario case study, so PROSUITE could not be used but it could serve as a valuable tool when such information is available.

The LEEAFF framework, used in qualitative mode, was found to be the most practical tool to provide a holistic view of the corn stover to bio-chemicals value chain that is being explored. Table 23 provides a summary of the information provided by value chain stakeholders on each of the 6 LEEAFF categories. A new system based on partial corn stover removal added to corn grain harvest was compared with an existing corn grain only harvest. The exercise showed that neither system was without some issues or sensitivities. A corn stover system could likely provide benefits for some categories of sustainability, such as land use efficiency, broad acceptability, GHG emission reduction, and employment. However, the corn stover feedstock supply chain would have to be financed, built and optimized. The technology would have to be shown to be financially profitable at scale, and there are unknowns to address regarding nutrient addition and long term soil health.

This 360° lens perspective developed by stakeholders can be used to further develop the discussion on sustainability, and set goals and priorities. This qualitative assessment provides stakeholders with a first sense of the project viability from the perspective of 6 aspects - land use, environmental impacts and benefits, employment needs, acceptability, financial impacts and investment needs, and feedstock availability. It can be used to collectively build a new value chain that incorporates a comprehensive concept of sustainability from the start, potentially increasing the level of shared comfort with this new project.

In the early stages of development, a LEEAFF assessment helps to clarify what is not known and needs to be addressed. As quantitative information becomes available it can be added to the LEEAFF assessment. The framework respects the multi-dimensionality and complexity of sustainability, and encourages simultaneous development of understanding in each of the six aspects.

Table 23. LEEAFF Sustainability Framework: Corn Stover to Bio-products Value Chain.

Impact Category	**Description**	**Evaluation of Partial Corn Stover Harvest for Production of Bio-chemicals and Bioenergy**
Land Use	Issues related to the land used for biomass feedstock production including land ownership, historical land use and land use change, current land use conflicts, land use efficiency, and broader context questions such as food security.	Use of existing agricultural land for feedstock production; Increased land use efficiency; Logistics need to be developed so the operation does not impact current grain production. No land use change is anticipated; Corn yields are continuing to increase; Expansion of corn acreages (on existing ag land) is possible in the eastern Canada clay belt and in the crop-growing areas of the Prairie provinces.
Environment	Environmental impacts related to feedstock production and product including greenhouse gas emissions, air emissions, water emissions, soil sustainability, biodiversity Environmental benefits: carbon sequestration, remediation	Anticipated benefits: Fewer GHG emissions are released from ethanol derived from corn stover when compared with grain-derived ethanol (Tools: GHGenius LCA, HOLOS); general rule applies for almost all bio-products, but GHG reduction depends on the specific biochemical and product it replaces Partial stover removal could include P removal and mitigate water pollution in area Potential env issues: Loss of Soil organic matter, soil organic carbon Less nutrients (N, P, K) available to next year crop More Soil Compaction Additional Air Emissions (PM)

Employment	Issues related to all stages of the product lifecycle including job creation or retention, job type, wages, educational requirements, new skills development, employment equity	Additional employment is expected to occur in agricultural sectors; construction (temporary), manufacturing, and transportation sectors. Agriculture sector employment impacts: additional on farm labour and record keeping; additional soil sampling and env mgmt; stover harvest, storage and transport; equipment maintenance; stover cleaning and grading
Acceptability	Acceptability by all stages of the lifecycle including the company (internal), community, intra-industry, inter-industry, public; Risk Perception and Tolerance	Producer – YES - if it fits with farming operations; if it does not impact core business - production for food and feed markets; if it does not affect long term soil productivity ENGOs – Y or N; potential concern for soil erosion, long term soil productivity, and possibly biodiversity Public – Expect Y; preference for use of non-food biomass and no land use change; Government – expect Y; but unable to provide mandate as done for biofuels Investors – Lack of existing supply chain infrastructure for residue collection and storage + Lack of information on quality needs and cost + Lack of experience operating technology at commercial scale = Significant risk
Financial	Information on size of investment, operating costs, profitability and return on investment, projected markets for biorefinery products, government mandates, incentives & subsidies, tax revenues	Capital investment needed for feedstock collection and storage; Capital investment needed for cellulosic sugar facility; Agriculture Producer – potential for additional net revenue associated with partial stover removal; potential for greater yields in crops grown in the subsequent year Feedstock price point – still to be identified Technology to be proven at scale; risk Alternate markets for off-spec stover; Markets for the process co-products and by-products to be identified No dedicated programs or funding at this time; new programs expected for climate change, clean tech
Feedstock	Renewable and non-renewable resource use including biomass, water, energy and chemicals; supply and cost information	Sufficient residue volumes for biorefinery are theoretically available, with a good buffer; high density baling equipment has been identified and tested; the feedstock supply chain is not yet operational A producers cooperative has been formed to explore logistics, improve efficiencies to lower cost of production

8 Synthesis

High energy costs and societal and political goals for GHG mitigation and energy security have given rise to the mandate to use straw for heat and power production in Denmark. The first generation biofuels industry has since emerged, providing lower carbon transportation fuels. Concerns over land use, population growth and social equity, have led to greater interest in using crop residues from existing agricultural land. Investment in new technologies to deconstruct lignocellulose and convert its constituents into marketable products has given rise to new opportunities for the production of renewable energy, fuels and chemicals.

The technology for converting wheat straw and corn stover into liquid biofuels (primarily ethanol) has been under development for two decades. Both biochemical and thermochemical technologies have now reached commercial scale but are still more costly than first generation production. They need to be optimized and sufficient value needs to be derived from their co-products.

The three country reports cannot be directly compared as they differed with respect to the timing of the value chain development, the types of bio-based products they produce, and the frameworks used to assess their sustainability. Nevertheless the findings shared a lot in common. Economic sustainability is strongly influence by feedstock costs, energy prices and the frameworks supporting such development (i.e. existence of energy or environmental goals, mandates, programs, etc.). The current low fossil energy prices, and reduced cost of solar and wind energy installations make it hard to develop a business case for bioenergy (for electricity).

Regardless of the end-product, the removal of crop residue needs to be profitable for the agricultural producer and the processor or user of the residue, and not harm but hopefully benefit the environment. The risk of mining soil carbon has been identified as a priority area in all three countries. Locally adapted best management practices (BMPs) could be developed to guide the individual farmer on sustainable removal rates taking into consideration a number of other factors influencing soil quality as e.g. soil type, precipitation, crop rotation, agronomic and geological history, and management practices.

Also, society needs to recognize this development as a contribution to sustainable innovation and not as a potential danger.

The following sections summarize the constraints to further mobilization and ways to overcome these hurdles. This work will be elaborated on in the next triennium.

8.1 Constraints and barriers to further mobilisation

Kretschmer et al. (2012) identified five key types of barriers that currently affect the functioning of the straw supply chain, from agricultural producers on one end of the chain and the processors on the other end. These are:

- Underdeveloped markets (no existing supply chains) and lack of market information.
- The competing existing uses of straw.
- Lack of guidance on optimal use of straw as a soil improver and associated farming practices, to ensure that the utilisation is sustainable with regards to sustained soil quality and yields.
- Lack of infrastructure (experience, equipment, market etc.), and in some parts of the world, the skills to use the equipment.
- Variability of straw supply in quantity and quality from year to year and from region to region

Most of these factors reflect the early stage of development of crop residue use at a large scale (Kretschmer et al. 2012). In countries that have an abundance of forest biomass and large forest products industries, agricultural crop residue harvest and collection systems for bioenergy and/or bio-products are just being established. In addition to having the existing infrastructure for woody biomass harvest and collection, wood is generally a better fuel to convert into heat and power due to its lower ash content and fewer air emissions upon combustion. Therefore, there are technical as well as economic reasons for the later stage of development of agricultural residue supply for bioenergy in countries such as Canada.

Also, agricultural residues have competition from other biomass feedstocks such as municipal solid waste, and in the future, CO_2 in flue gas. Recently, INEOS and Enerkem have started up waste to energy production in North America. These facilities have their own feedstock challenges, but they are usually considered to provide greater overall environmental benefits when compared with agricultural or forest residues. Therefore, a hierarchy of biomass types exists with waste use generally followed by processing or crop residues that don't entail land use change.

8.1.1 Denmark

Cost: High feedstock costs are a main challenge to diversifying straw use for biorefining in Denmark (Jorgensen 2013). Straw is already extensively used in CHP, and with its low bulk density and high transportation costs competition from emerging supply regions is limited. With a strong market and limited suppliers, costs as high as DKK550 (~US$80) per tonnes are not uncommon.

Fuel quality: There are technical issues associated with straw use in CHP, including a high ash and mineral content that can cause corrosion of super heaters, slagging and fouling as well as deterioration of catalysts for NOx reduction. It is therefore a political challenge to encourage fuel source flexibility and the use of wood and other sources of biomass for CHP production in Denmark. According to the Biorefining Alliance (2012), a rapid shift to second generation biofuels will only be possible if Denmark institutes a mandatory blend to encourage supply chain development.

8.1.2 USA

On the production side, there are still difficulties with respect to the conversion technology, which have not yet been fully addressed for the industry to take off. Constant feed-in rates and feedstock quality have been identified by the pilot plants as critical parameters to maintain high conversion efficiencies and output rates. Biomass is inherently bulky, not homogeneous, difficult to transport, subject to degradation and susceptible to loss due to weather events. These barriers can only be partly addressed in the current feedstock supply chain design, where feedstock is procured through contracts with local growers, harvested, locally stored, and delivered in low density format to the conversion facility. These supply uncertainties tend to classify the biomass industry as a high risk investment and limit the biorefinery concept from being broadly implemented.

Feedstock cost and availability: The cellulosic biofuel industry is projected to be rooted in specific regions with concentrated resource supplies (e.g., high corn producing areas of the Midwest). Outside of these regions biorefineries may be prohibited in size and scale unless they are linked to a feedstock supply system that draws from a portfolio of resources.

Feedstock quality: Current feedstock supply chain systems only address feedstock quality indirectly through passive controls, e.g., resource selection and best management practices. The lack of feedstock homogeneity and quality however has proven to be a limiting factor for a continuous plant operation. Active quality control will be required in future, large-scale supply systems.

Economics and project finance: Probably the most critical barriers for the continuous expansion of the U.S. cellulosic biofuel industry are related to economics and project finance. The industry is seen as a high risk investment, partly due to technical barriers and policy uncertainty, but also in comparison to other possible investments (and thus opportunity costs for investors) and uncertainty about the projects' profitability.

Market uncertainty: Biomass supply and demand is subject to changing market factors (e.g. fluctuating markets for primary products such as corn and wheat, competing uses, and prices of alternative raw material). Even in highly productive agricultural areas, supply and demand, costs and prices can be unpredictable. As is the case for grain production, (companion) markets need to exist for crop residue streams that help establish supply chains which can support a growing biofuels industry.

Investment gridlock: There is still a chicken-and-egg situation that impedes investment, i.e., processors want to build a facility if there is a guaranteed, consistent supply of crop residue while residue providers require a more constant market demand, e.g., from a processor. Residue processors seek flexibility with respect to feedstock procurement and can appear to be indifferent to the type of feedstock as long as quality and cost specifications are met. On the other hand, agriculture producers need assurances that there will be buyers for their residue before making significant investments.

Framework conditions: Absence of a stable policy framework for investments, e.g., duration of renewable energy and biofuel mandates, carbon pricing, valuation of GHG reductions from bio-based systems, etc. and dedicated strategies that support new value chain development from R&D through commercialisation.

8.1.3 Ontario, Canada

Using agricultural residues for biorefining is an industry still very much in its infancy in Ontario. Until recently, the situation often referred to as the chicken and egg conundrum existed. Without reliable markets and a buyer of the crop residue, agricultural producers will not harvest their residues; and without a reliable source of biomass and offtake agreements, the investors will not take the risk. The recent announcement of Comet Biorefining to build a facility in this area makes the opportunity real.

Competing fuels and renewable energies: Affordable domestic energy sources such as natural gas, falling costs of wind and solar energy, and an abundance of woody biomass are all barriers to the development of bioenergy supply chains based on agricultural feedstocks. The focus in Southwestern Ontario is therefore on deriving chemicals and higher value products from crop residues.

Optimised supply chain (from field to the processor): An agricultural residue supply chain needs to be built, tested, and optimised. This will require capital investment, as well as BMPs for producers based on their soil types, tillage practices and rotations, and optimization work to lower the cost of production, etc.

Investment in Technology Scale-up and System Integration: Substantial investment is required to scale up the lignocellulosic conversion technology and to develop an efficient integrated biorefinery. Generally, this is done via a public-private partnership. Until recently there were few sources of public funding that directly targeted this type of investment. New clean tech and climate change funding could provide new opportunities.

Markets for Co-products: Marketable uses of the biorefinery co-products are needed to make a strong business case. This includes the valorization of hemicellulose, lignin and ash streams to become significant sources of revenue.

Lack of information: Other barriers typical of an emerging industry include a lack of information on such things as profit margins, market prospects, and how much residue to leave on different soil types to maintain long-term soil productivity.

8.2 Solutions for supporting further mobilisation of agricultural residues

Large-scale residue removal needs to make economic sense, be environmentally sustainable and fit with the agricultural practices in a given area. The residue supply needs to be off sufficient quality, consistent quantity and delivered at a cost that enables the processor to generate an acceptable profit to attract investment. The establishment of an agricultural residue supply chain that meets the criteria of diverse clients will require the following:

- A consistent and stable policy framework that supports investment in the bioenergy and products made from renewable biomass and wastes innovation continuum.
- The availability of credible and transparent knowledge on technologies, costs and sustainability aspects (e.g., for farmers, energy producers and other stakeholders along the supply chain).
- Developments in residue harvesting, transportation, processing that improve the efficiencies, and reduce the cost of bioenergy and bio-based products.
- Long-term feedstock supply contracts and offtake agreements (or mandates) for products to increase investor stakeholder confidence.
- Incentives for agricultural producers to bear the initial investment risk (e.g., grants, subsidies or credits for GHG offsets and energy security enhancements).
- Tools to provide confidence to processors (residue users) of consistent biomass supply, regardless of weather conditions.
- Best management practices for a variety of soil types and operating conditions that ensure crop residue removal is not detrimental to soil health over the long term.
- Credible sustainability guidelines that provide sufficient assurances but are not overly burdensome to agricultural producers.

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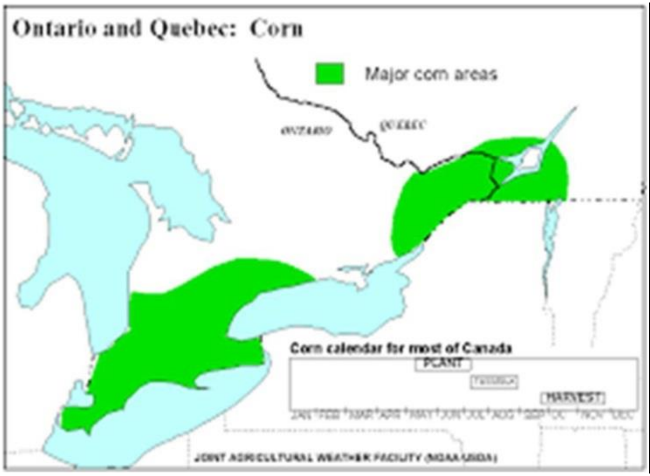
10 Appendix A - Canadian Regional Case: Southwestern Ontario

Charles Lalonde, CJ Agren Cosulting, Ontario, Canada

In Southwestern Ontario, a major agricultural region and the heart of the province's biorefinery research and development network, assessments show that the capacity and resources exist to support two integrated biorefineries based on a bio-facility processing volume of 250,000 to 300,000 dry tonnes of corn stover and wheat straw. Value-added products, such as biocomposites, bio-based chemicals and high quality animal feeds, are at the heart of the region's emerging bio-economy. Due to the availability of lower cost energy sources and other types of renewable energy, agricultural residues will most likely be converted in a regionally-based cascade manner where bioenergy is a co-product of the production of higher value bioproducts.



Southwestern Ontario is a region with both manufacturing industries and agricultural production that borders the US states of Michigan via the Great Lakes. It is also home to the corn grain processing plant – Ingredion (London, Ontario), three corn grain ethanol plants – Suncor St. Clair Ethanol Plant (Sarnia), Greenfield Specialty Alcohols (Chatham), Integrated Grain Processors Cooperative (Aylmer) and several biodiesel plants. The BioAmber bio-succinic acid plant has started operation

Figure A-1. Southwestern Ontario, Canada

10.1.1 Introduction

Southwestern Ontario has been identified as an area of high potential for the development of a corn stover supply chain for the following reasons:

It is an area of high corn yields (grain yields exceeding 150 bushels per acre) that could support supply of 500,000 tonnes per year; Corn grain yields have been increasing and expect to continue to grow, indicating that the supply of stover is also expected to increase over time; In typical years, there is no competing use for corn stover; Corn is grown in rotation with winter wheat that could provide an additional source of residue; Both switchgrass and miscanthus can be grown (with good yields) in this region and could provide an additional source of residue; Transportation infrastructure exist – road, rail and ship; Industrial infrastructure exists in terms of Sarnia-Lambton industrial Park; Sarnia is also headquarters of a bioproducts cluster (Bioindustrial Innovation Centre); Three first generation corn ethanol plants exist in the region.

People of Sarnia are committed to sustainable economic development (Bluewater Sustainability Initiative; past experience with petrochemical industry clean-up).

New conversion technologies and industrial development in the US have created interest in exploring partial stover removal for the purposes of producing bioenergy and/or bioproducts. From an operational perspective, some reduction in straw residue is believed to improve spring seeding operations as the soil can warm up more quickly. This could be particularly advantageous in areas where no till has been practiced for numerous years, especially as crop yields continue to increase. Some of the first questions that need to be answered are what is the future demand for bioenergy and or bioproducts, how much residue, of what quality, can be physically removed on a consistent basis, for what price can it be sold and how can residue removal be carried out so as not to effect the long term productivity of the soil.

The regional case study of a corn stover for bioproducts value chain under development in Southwestern Ontario follows. Much of this work has been led by the Ontario Federation of Agriculture (OFA) who has conducted studies on behalf of its agriculture producers to assess the potential to develop new corn stover supply chain to furnish an emerging bioenergy and bioproducts industry. Sustainable development has been at the core of this investigation, and entailed reviews of the conversion technologies, markets for bioproducts and bioenergy, biomass availability, agriculture producer interest and operational issues, and potential environmental impacts. These reports can be downloaded from: http://www.ofa.on.ca/issues/overview/biomass

10.1.2 Goal

The development of sustainable crop residue supply chains will need to address financial, operational, environmental and social aspects that can be both site and time specific. From a financial perspective, stover removal must be profitable for the agriculture producer and sufficiently affordable for the downstream processor to attract investment. The supply chain needs to deliver sufficient quantity at specified quality to the processor, and not negatively impact the agriculture producers operations, especially site productivity. From an environmental perspective, the quantity and frequency of straw removal from an area, that will not increase erosion or disrupt the carbon and nutrient balance, will depend on site specific factors such as soil type, topography and crop rotation. Finally, the new practice must be accepted by consumers and the broader public, and be seen to be sustainable.

While the feedstock supply chain needs to be sustainable, it is important to keep in mind that it is one part of a much larger system. That is, the whole value chain needs to be considered when discussing sustainability. What products are derived from the biomass and the societal context matter.

10.1.3 Historical Context

Past policy decisions of the Ontario Government to close down coal fired electricity generation by the end of 2014 resulted in interest on the part of agricultural producers to supply agricultural biomass as a replacement fuel. As two of the large coal fired facilities scheduled for closure were situated in South Western Ontario, an area coinciding with a major agricultural grain production, studies were initiated to assess the potential to supply a million tonnes of agricultural biomass to a local facility. In a study conducted by the University of Guelph (Kludze et al.) for the Ontario Federation of Agriculture (OFA), it was estimated that 5% of agricultural lands would need to be converted to miscanthus and switchgrass to generate the required amount of biomass.

Oo et al. examined where land could be available to grow purpose grown energy crops while mitigating impacts on food production. Based on a declining cattle population creating access to marginal pasture lands and availability of semi-dormant hay lands, Oo et al. estimated the availability of 350,000 ha, most of which is located in low grain producing areas. If all this land area were to convert to purpose grown biomass production, 3.3 million tonnes of agricultural biomass could be produced with sustainable carbon balance. In a study conducted for the OFA, the Delta Research Corporation reported on crop residue availability and characteristics for bioenergy use. The use of crop residue superimposed on food production creates a win/win scenario for producers and consumers as it eliminates competition for land use.

The OFA examined the competitive position of agricultural biomass as an energy source through combustion compared to other fuel sources. In a report to the OFA, Oo et al. concluded that biomass sources could not compete with natural gas as a fuel source in electricity generating stations. Biomass, however, could be used in regional settings where natural gas availability was non-existent and consumers relied on propane, electricity or transportation fuels as an energy source for heating. In instances where natural gas was not accessible, CHP units could become feasible to support industry. Obstacles to CHP units included the write-off of existing capital investments in heating systems ahead of schedule and knowledge of alternative biomass based systems. Accordingly, investment into new boilers based on biomass was impeded and has yet to materialize.

An alternative pathway to supplying energy to the marketplace is through conversion of agricultural residue, food waste and manures from livestock through anaerobic digesters into biogas which is then converted by generators to electricity for commercial distribution. Most of the technologies used in Canada originate from Europe, however Canada's biogas network is very small compared to the EU. Nevertheless, there are viable projects across the country and in 2013 these projects produced over 17 MW of electricity. There is also emerging opportunities to convert methane into transportation fuel.

Beginning in 2010, the developments of shale gas production in North America disrupted biomass supply opportunities as Ontario gained access to large quantities of natural gas delivered through existing pipelines at competitive prices to coal. Historically, coal represented the cheapest source of energy for electricity generating stations. In 2013, public policy in Ontario shifted in favor of establishing regional peak energy natural gas plants for electricity generation. These plants supplement base load and are situated along existing natural gas pipelines. Furthermore, during this period, purpose grown biomass was facing land use competition from grain crops due to record grain prices. Consequently, the development of the purpose grown biomass industry in Ontario for combustion purposes remains underdeveloped.

10.1.4 Commercialization of Lignocellulose Conversion

As the opportunity for residue to supply large scale power generation faded, crop residue sources were assessed to determine the feasibility of using agricultural biomass in smaller regional energy scenarios and other bioeconomy applications. This coincided with developments in the conversion of lignocellulose, in the form of agricultural residues, into advanced biofuels and valuable bioproducts.

With the commercialization of cellulosic ethanol technologies, opportunities now exist to convert crop residues into cellulosic sugars that can produce ethanol or bio-based chemicals. The profitability still needs to be shown and the US leads with three key cellulosic ethanol projects in the US Midwest.

The biochemical conversion processes used in these first commercial facilities currently combust the lignin co-product into bioenergy that is then used to operate the facility with excess energy sold as green power. Higher end uses are emerging for lignin, however obtaining consistent functionality remains a challenge. The development of lignin into higher end products will have a large positive impact on the economics of a facility. In the interim, using anaerobic digesters to convert lignin and bioprocessing residues through anaerobic digesters to electricity is a viable opportunity.

10.1.5 Development of a New Value Chain

Currently in Ontario, logistics supply models are not in place but are under active development. Value chain collaborative efforts are underway to support the implementation of a biorefinery in Southwestern Ontario. The diagram in Figure A-2 sets out a typical biorefinery to process cellulosic materials into sugars and biochemicals. It is important to cleanly separating the different components of lignocellulose (C5, C6 sugars and lignin) to support potential biochemical applications. The biochemical route, while more lucrative than ethanol production, has greater processing challenges compared to ethanol production based on the extraction of a C5 and C6 sugar blend and conversion using enzymes and biological cultures to produce ethanol.

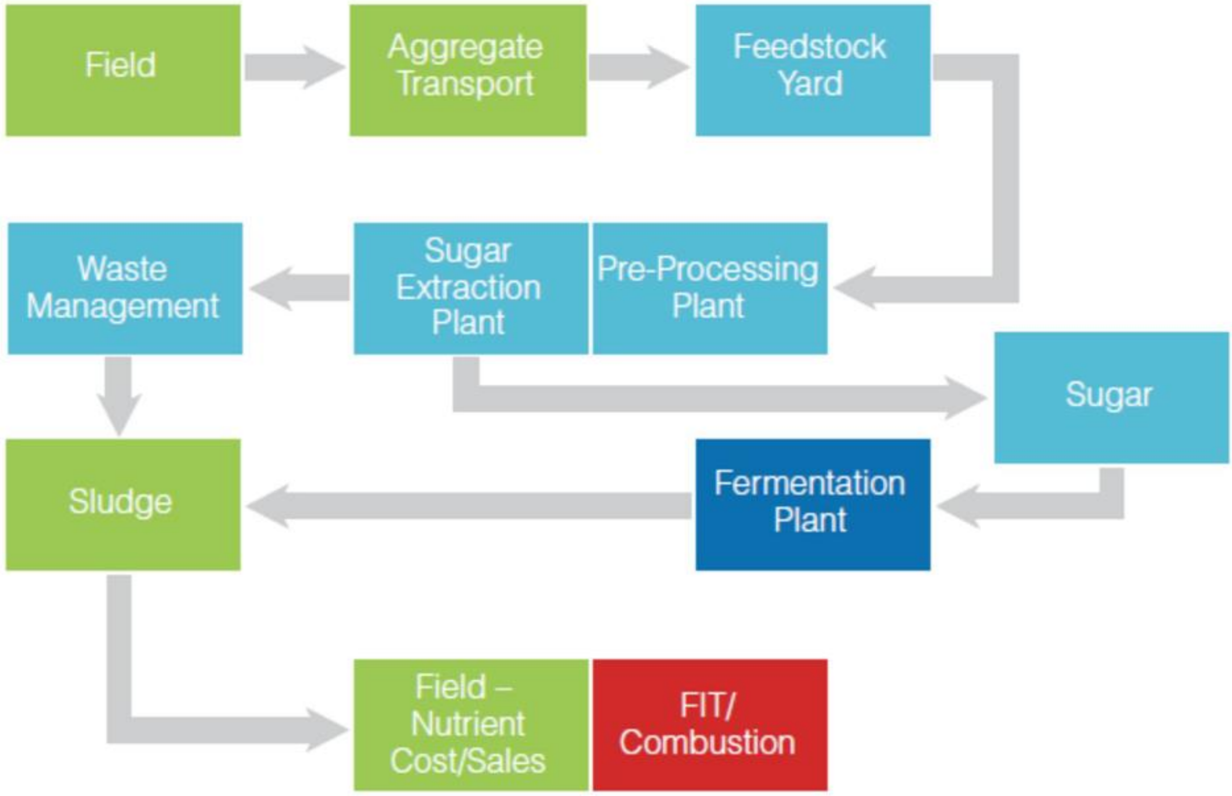


Figure A-2. Potential Cellulosic Sugar Value Chain (Duffy et al., 2013)

In 2014, two farm stover harvesting demonstrations and an informational seminar were delivered to interested agriculture producers to introduce harvesting protocols with the best of farm equipment available to handle cornstalks. Cost data were collected and used to update the business case on supply logistics using a model developed by Duffy et al. at the Ridgetown Campus, University of Guelph (2013). Further studies are underway to assess the efficiencies of various technologies to support a business case that includes: supply, storage, aggregation, transportation and multi-stage processing for cellulosic sugars.

The supply chain economics goes beyond providing cornstalk or wheat straw as a commodity. A commodity market implies that there is an ample supply for multiple end uses and a pricing mechanism based on supply and demand determines the end use. This does not exist for biomass and bioprocessors need to develop loyalty of supply by working closely with producers. Some agricultural producers would like to get paid on the basis of sugar yield rather than weight. These producers are interested in actively participating in biorefinery development as a means of securing a greater share of the value chain benefits. A producer co-operative model is under consideration.

For this pricing model to work, residue purchasing standards must be precise in order to calculate the value of the cornstalk supply based on sugar yields. These standards must specify moisture tolerance levels and ash content of the biomass. Producers expect the best of conversion technologies to recover the maximum available cellulosic sugars. The theoretical yields of hemi-cellulose, cellulose and lignin are shown in Figure A-3.

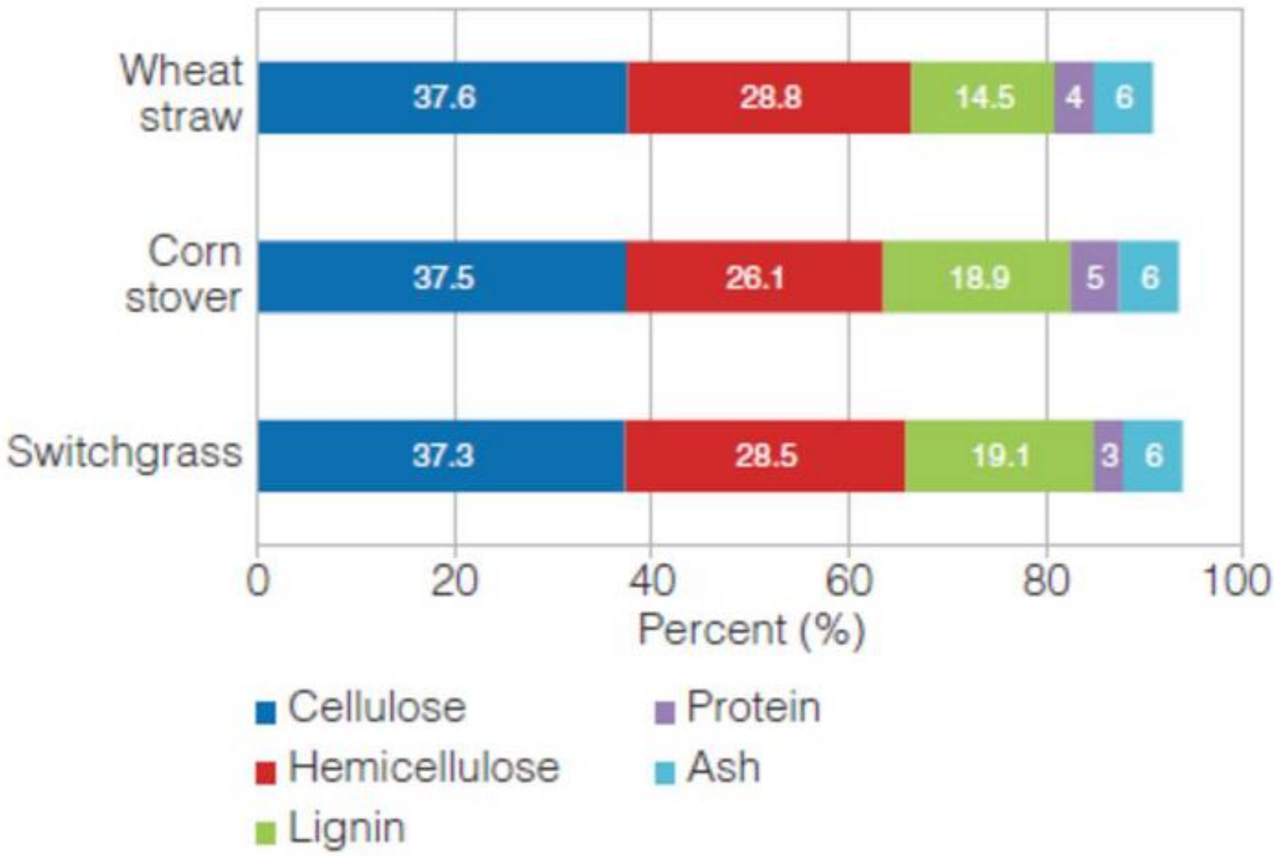


Figure A-3. Compositional breakdown of three types of biomass. (Lee et al., 2007)

Several bioprocessors in Ontario who are currently using corn grain for ethanol production or for food grade chemicals are currently looking at ways to add on or expand their existing processing facilities (based on corn grain) using cellulosic material. Provided financing can be accessed, at least one cellulosic sugar extraction facility could be operational within three to five years.

10.1.6 Biomass Supply

Oo et al. reported on the availability of sustainable cornstalk harvest in Southwestern Ontario based on feedstock availability within a 100 km of a potential facility. Sustainable crop harvest implied 25 % residue removal at a regional level. The methodology used to assess availability was based on the USDA assessment reported in the Billion Ton Challenge Report. Furthermore, it is recognized that individual producers will be able to harvest higher percentages if corn yields are in the 200 bu/ac range or if the producer utilizes livestock manure on the land.

As shown in Figure A-4, generally corn grain yields in the 4 counties are above 150 bushels/acre, similar to yields obtained in Iowa (USA).

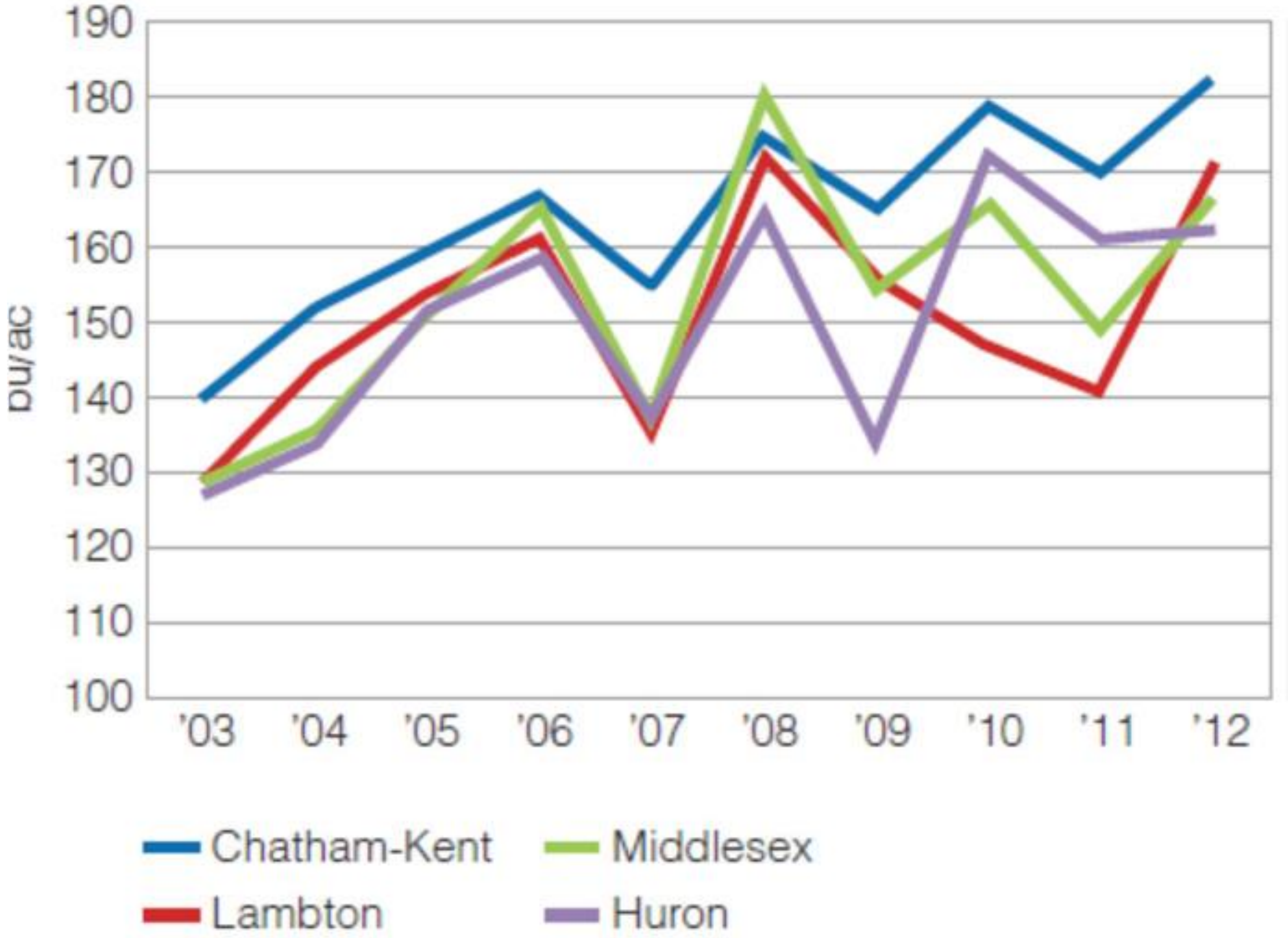


Figure A-4. Average annual corn yields by county.

Producers with higher corn yields are required to manage cornstalk residue more aggressively in order to prepare land for the following year crop. Excess residue impedes the yields for the following crop as the cornstalk layer insulates the soil from the sun and hence delays early spring planting. In addition, nutrients such as N and P are needed to decompose the cornstalk and compete with living plants for valuable nutrients. Hence yields are reduced. Accordingly, producers have expressed great interest in supporting a biorefinery with cornstalk harvesting.

Figure A-5 presents the crop acreages available in the four key grain producing regions of Ontario. A closer analysis of corn stalk availability was conducted on these four counties to determine sustainable harvest levels. The potential availability (dry metric tonnes) is shown in Figure A-6. Based on this analysis, Southwestern Ontario has the ability to support two biorefineries with an annual biomass supply in the order of 300,000 tonnes of corn stalks and wheat straw.

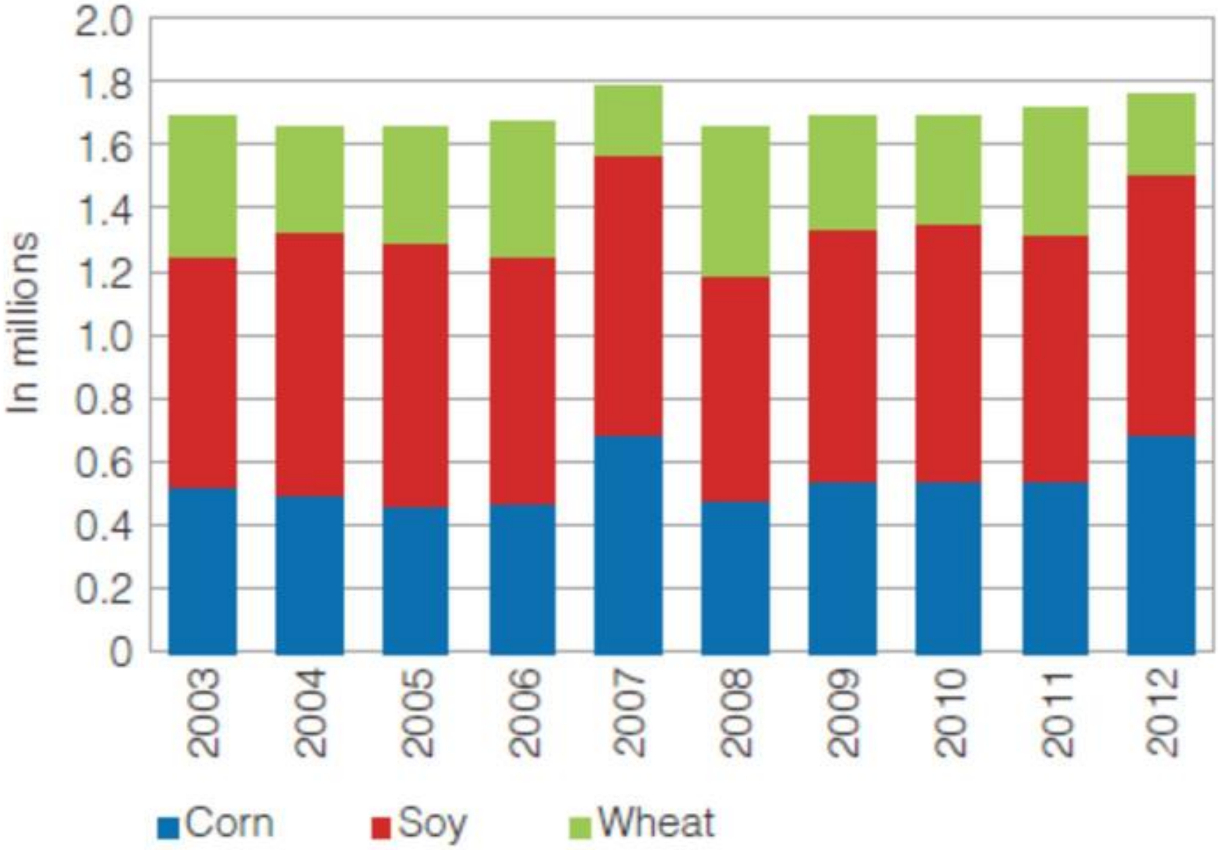


Figure A-5. Corn, soybean and wheat acres harvested in the 4 county region.

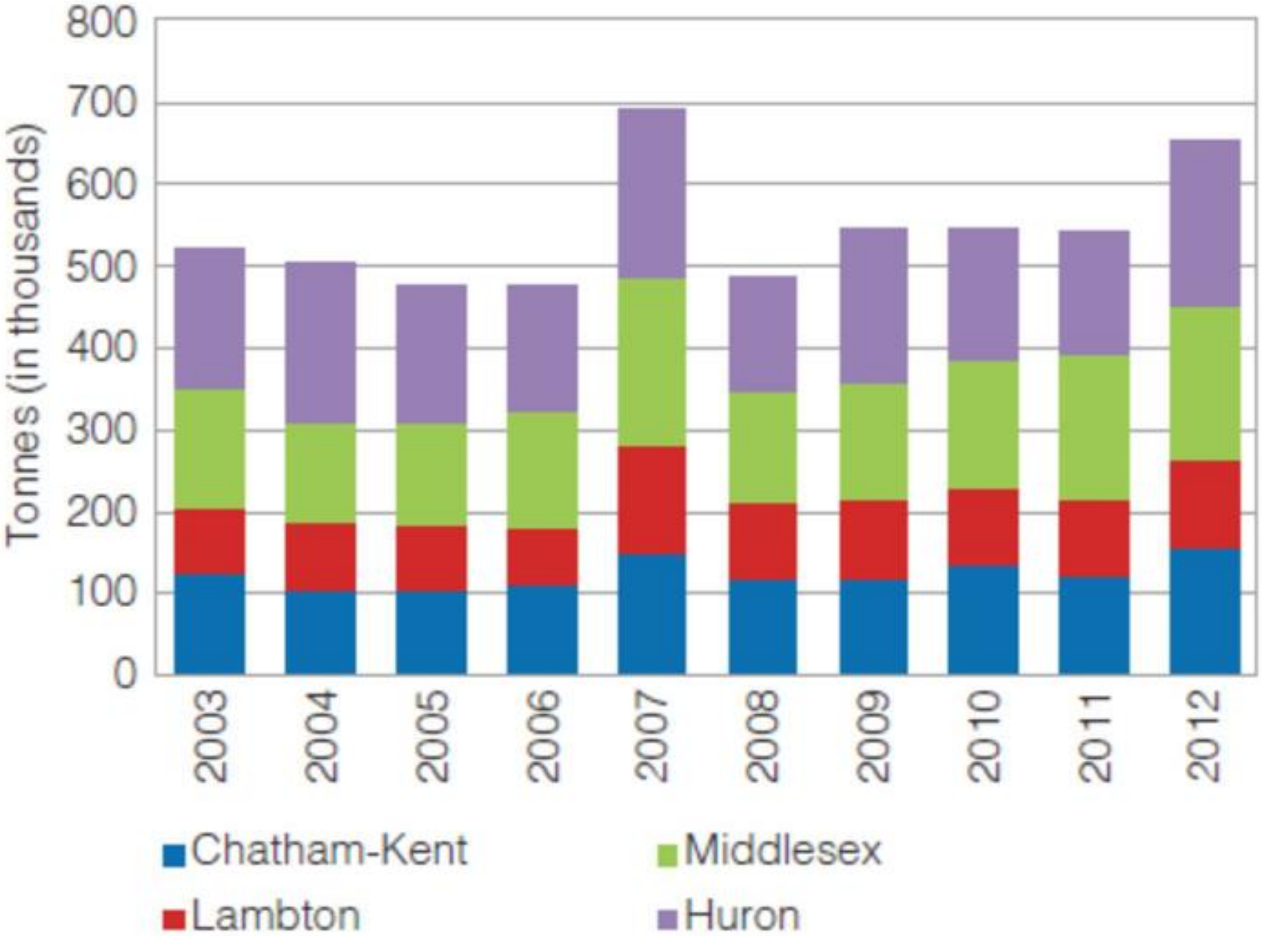


Figure A-6. Amount of sustainably harvestable corn stover (dry metric tonnes).

11 Appendix B - Framework for Selecting and Evaluating Sustainability Indicators

11.1.1 Define the goals

Goals for bioenergy projects or programs can include moving toward environmental, economic, or social sustainability targets; meeting regulatory or policy standards; conducting research; meeting expectations for land use; meeting logistical needs; or other goals (Figure 28).

Setting the goals is strongly determined by the stakeholders who are involved and the context of analysis. Different stakeholders often have different perspectives about goals and assessment scale. For example, a federal agency may target the sustainability of a nationwide deployment of bioenergy technologies. A farmers association might be interested in farm level price stability of a particular crop. A state agency may want to determine the suitability of different sites or land conditions for growing perennial crops, while industry may focus on profitability and compliance with regulations. Non-governmental organizations typically focus on specific interests of their communities and opportunities to increase support. Ideally an assessment would include all key stakeholders and would be led by an entity that all participants accept as impartial. The network of 22 Landscape Conservation Cooperatives (LCCs) across the U.S. is an example of multi-stakeholder participation to define goals in a structured environment. The LCCs are self-directed partnerships between federal agencies, states, tribes, NGOs, universities, and other entities that collaboratively define science needs and jointly address issues within in a defined geographic area.

11.1.2 Define the context

Context is important for prioritizing sustainability indicators for biofuels (Efroymson et al. 2013). This step in the framework includes identification of the socioeconomic, cultural, institutional, political, and regulatory environments and the spatial and temporal extent for consideration. For analyses at the regional or local scale, the context includes historical and alternative land uses. If a community has particular concerns about its prospects for economic development (e.g., a dominant industry has moved away from the community) or experience threats to its environment (e.g., water quality is poor), these concerns are part of the context of bioenergy sustainability and influence the goals. While the need to describe contextual details may seem obvious, failure to frame a particular situation in this way can result in unintended biases in the selection of indicators (Efroymson et al. 2013), such as spatial and temporal biases (Karlsson et al. 2007).

Context includes spatial and temporal scales and must be defined in conjunction with sustainability and other goals (Figure 28) because the scope of the goals determines the relevant spatial and temporal boundaries for the analysis. Consideration must be given to the geographic extent and the time periods encompassed by the sustainability analysis. Some indicator efforts can be designed to evaluate the status and trends of particular regions, watersheds, fuel sheds (areas providing feedstock), or national programs, while a global scope may be appropriate for some analyses, such as those designed to consider climate impacts, national or multi-national policies, and issues related to cross border trade and energy security associated with shifting from fossil energy to bioenergy. Many environmental analyses of bioenergy have used global-scale models to quantify impacts of e.g. indirect land-use change or climate change. The results are highly uncertain (Kline et al. 2011) and provide little useful guidance to decision makers on the trade-offs with the many other aspects of sustainability. Furthermore, questions about how and where to produce bioenergy, effects on welfare and the local influence are best considered at a regional, watershed, or fuel-shed scale and in accordance with the scale of investment and management decisions and where effects on many ecosystem and social parameters are more readily evaluated.

11.1.3 Identify and consult stakeholders

Stakeholders may be defined as individuals, groups, businesses or organizations that can affect or be affected by a process or project under consideration (definition adapted from ISO 13824; 2009). Some environmental organizations may take this concept even further by representing specific, often threatened, endangered or charismatic species as stakeholders. Some sustainability standards have indicators requiring that all stakeholders be "engaged", meaning that they are provided adequate opportunity to learn about and comment on the proposal, and that the parties responsible for the proposal demonstrate their responsiveness to legitimate issues raised by stakeholders. Establishing processes and providing evidence of free, prior and informed consent of local stakeholders is required by some sustainability certification standards and some developing countries that are exploring large bioenergy projects. E.g. in Mozambique with regulations for rural development and land leases.

Stakeholder values, perspectives, and information needs constrain the goals, time frame and underlying assumptions of the decision-making process (Johnson et al. 2013). A key concern is the determination of who decides about which stakeholders, sustainability goals, and issues are to be involved in indicator selection and who legitimately represents stakeholder groups. Who leads the process and applies this framework is crucial, and ideally the leader is recognized by all as a non-partial, honest broker. While land managers, policy makers, community organizations, and others with a stake in bioenergy sustainability could identify indicators that meet their own needs; these indicators are unlikely to lead to viable decisions unless other stakeholders are also offered the opportunity to articulate their own goals, and the cost and feasibility of measurement may require multiple stakeholders to be involved. Including diverse stakeholders early in the process is crucial (Jolibert and Wesselink 2012), because each represents a unique epistemic community and brings different values, priorities and meanings to the process of selecting indicators. While considerable emphasis is put on the credibility or scientific accuracy of indicators, it is equally important to address the legitimacy of indicators, which entails "the process of fair dealing with the divergent values and beliefs of stakeholders"(Rickard et al. 2007). As an example, farmers and scientists have differing perceptions of sustainability (Sydorovych and Wossink 2008), and also, scientists can have a different purpose in mind for indicators than decision makers (Turnhout et al. 2007). Some indicators tend to be dominated by the concerns and priorities of industrialized countries (Karlsson et al. 2007) or by specific agency mandates. If a project includes non-industrialized regions, stakeholders representing those regions should be involved. It is also important to acknowledge that the definition of credibility or scientific accuracy can vary, as cultural contexts vary, and as perceptions of expertise range from indigenous knowledge to Western notions of the scientific method (Wynne 1992). Consequently, a broad selection of stakeholder goals should be considered as part of indicator development (Schwilch et al. 2012).

Stakeholder goals may not be aligned but rather competing. Meeting regulatory requirements or guidance is a common obligation that may overlap with sustainability goals. In contrast, jobs, income generation, environmental protection and production targets often conflict or involve trade-offs among subsets of stakeholders. For example, a proposed project may improve incomes and enhance environmental conditions for some people while shifting burdens to others. Very importantly, stakeholder needs, goals and priorities are not static but change over time, and the context and individual conditions evolve over time.

11.1.4 Identify and assess necessary trade-offs

Whenever goals are articulated by multiple parties, it is likely that some goals may conflict, or resources may be inadequate to evaluate information pertinent to all goals. A transparent participatory process is recommended for assessing potential conflicts, negotiating trade-offs and making decisions (Dale et al. 2013a). Sustainability goals and requirements within one jurisdiction can compromise sustainability goals in another area (Acosta-Michlik et al. 2011). Similarly, focusing on one element of sustainability (e.g., environmental considerations) may jeopardize another aspect (e.g., social needs). If efforts to achieve one target, result in prohibitively high costs for bioenergy, then other environmental, social and economic sustainability targets are compromised. Similarly, if efforts to develop a profitable operation result in social and environmental costs, sustainability is also compromised. Trade-offs are often inherent when comparing goals associated with different bioenergy technologies (e.g., reducing carbon emissions versus reducing oil imports). Whereas some sets of indicators may be relevant to multiple goals (e.g., regulatory and sustainability goals), they may not be able to accommodate *all* goals.

11.1.5 Determine Objectives for analysis

The objectives for a particular sustainability analysis will determine its scope, spatial and temporal scales, relevant comparisons, and required data. Objectives flow from overarching goals but differ from them in defining the types of analyses that are conducted. Regulatory analyses may require comparisons between fuel types, comparisons to standards, or comparisons against baseline conditions or reference scenarios (Efroymson et al. 2013). As an example, the California Air Resources Board requires comparison of energy technologies. Assessments may be retrospective and focused on data collection and assimilation, or they may be predictive and be based on modelling. An objective may be to evaluate the long-term capacity of land to support yields under different management options. Assessments of trends may focus on a variety of ecosystem, economic, or social attributes. For example, Roundtable of Sustainable Biomaterials proposes two principles that require the assessment of trends through measurement or modelling: contribution to the social and economic development of local, rural, and indigenous peoples, and mitigation of climate change.

Scientists and policymakers often need to differentiate between effects resulting from bioenergy from effects resulting from previous or alternative activities. Hence, an objective for analysis is to determine baseline conditions, trends, and likely future developments. An option is to make informed projections based on historical and empirical evidence. This approach is, however, only feasible for those regions, where historical data are available for proposed indicators. Moreover, significant uncertainty always applies to future developments and to "alternative pasts." Adequate historic data are lacking for many aspects of environmental, economic, and social sustainability in many geographic regions. A business-as-usual reference scenario – assuming that current observed conditions continue into the future – may be preferred although it is a simplification, and could be more accurate than informed projections in some situations (Buchholz et al. 2014). A significant drawback to any informed projection is a reliance on behavioural aspects (Olander et al. 2006). For example, these comparisons do not allow effects to be attributed unambiguously to bioenergy where unanticipated but significant shifts in land or water management have occurred.

11.1.6 Determine selection criteria for indicators

Selection criteria are developed and implemented to determine the particular suite of indicators to use. This step is a critical and challenging aspect of bioenergy sustainability assessment and is central to the indicator selection framework. The importance of indicator selection cannot be overemphasized since any long-term monitoring program will only be as effective as the indicators chosen (Cairns et al. 1993). This step of the framework involves modifying general selection criteria for indicators in a context-specific way, specifying criteria that are appropriate to objectives for particular sustainability analyses, and considering the set of potential indicators in relation to goals and objectives holistically.

The general criterion of legitimacy to stakeholders as discussed above is also important. These general selection criteria are universally applicable to all indicators; however, their meaning varies with context and according to specific assessment goals. For example, what may be cost-effective in one situation may be cost-prohibitive in another.

Many of the concerns that impede the use of ecological indicators (Olander et al. 2006) are useful in guiding selection of sustainability indicators for bioenergy. These include (Landres et al. 1988):

- oversimplification resulting from the selection of only one or few indicators,
- unclear or ambivalent goals that can result in the measurement of incorrect variables for the place and time under study, and
- difficulty in validating information provided by indicators .

The clear articulation of goals and objectives for analyses provides means for considering the selection of criteria for indicators. This filter ensures that irrelevant criteria (and therefore irrelevant indicators) are disregarded. Information and indicators are only useful if they guide people in meeting desired standards or outcomes (McNie 2007).

Analyses of bioenergy sustainability may involve widely differing goals and objectives, and indicators and criteria for their selection should reflect these objectives. For instance, objectives involving trend analysis require indicators that are measurable on a regular basis, but they do not require land managers or program managers to attain specified targets. Other approaches such as GBEP aim to support specific development goals and best practices and therefore recommend that indicators be linked with locally determined targets. If the objective of an analysis is to identify bioenergy supply chains that meet pre-defined performance thresholds, then indicators should be selected that provide useful information about these targets for environmental, economic, or social sustainability. If the objective of an analysis is to determine whether progress has been made toward a sustainability goal, then priority should be given to indicators that are sensitive enough to provide data on changes relative to the goal. If the objective is to compare alternative crops at any scale, the indicators must measure relevant properties for each crop studied. Comparisons of alternative planting locations or management routines must include indicators that are measureable at local scale and are sensitive to differences at the plot scale. Indicators that are meant to compare life-cycle effects of alternative energy or fuel policies must apply to a broadly defined scale rather than to only farm production or bioenergy utilities or to properties of only one fuel type. Historical information is often needed to understand trends in indicator values, and the availability of that information affects the selection of indicators. Defining baselines requires that potential indicators are measurable for appropriate historical periods. Yet most work on developing indicators, even very comprehensive schemes, do not address the need to document reference scenarios, baseline conditions, and trends for sustainability analyses.

If the objective of an analysis is to assess the sustainability of future bioenergy production, the indicators must be able to be modelled or statistically projected. If the goal is to conduct life-cycle assessments for bioenergy, the indicators should be measurable with respect to the stages of the life cycle where effects are significant. The uncertainty associated with indicator values intended to contribute to regulatory policy for bioenergy should be known or measurable.

Selection criteria that are applicable to a *set* of indicators may be different from those applicable to *individual* indicators (Niemeijer and de Groot 2008). The interpretations of individual indicators may depend on the entire set of which they form a part, and therefore, interpretation varies as the set is modified to meet particular goals. Together, the set of indicators should be able to integrate sustainability information to meet various objectives.

11.1.7 Identify and rank indicators meeting the selection criteria

In selecting indicators for assessing bioenergy sustainability, the land managers, regulators, or others conducting analyses determine the set of indicators that *as a group* best meets the selection criteria. Each individual indicator should be evaluated according to its intended purpose within a particular set. For example, GBEP proposes that technical experts rate each potential indicator on scientific merit (i.e., established relationship between the indicator and goal); that decision makers rate each indicator for practicality and utility (usefulness for decision making);

and that all stakeholders rate the indicators for relevance to their values (GBEP 2011). Moreover, stakeholders should be involved in developing clear and concise indicator definitions.

Ranking indicators may require several iterations. The first pass may result in several set of indicators that meet the selection criteria. Subsequent passes may involve determining which of the set fits within budgets and is best suited to the goals and objectives for analysis. The process may be enhanced by devising a scheme that facilitates ranking according to a variety of perspectives or through query and response check lists. Past experiences underscore the need to budget for the costs of developing and applying monitoring and evaluation systems up front and to assure that data collection and analysis balance what is feasible with available funds and what is wanted in terms of outcomes.

11.1.8 Identify gaps in ability to address goals and objectives

After the assessment is complete, the users of the assessment framework should evaluate whether the specific objectives for analysis are achievable with the selected indicators, existing data, and resource constraints. If measuring a set of indicators requires resources that are not attainable, it may be necessary to revise goals or objectives and revisit the criteria and indicator selection process (Figure 28). Similarly, an examination of data may show that large spatial or temporal gaps in data negate the value of the indicator. Testing the validity and ability of indicators to perform as planned is a critical step that should be completed before too much time and effort is used on data collection. While policy makers may desire data representations and conclusions that are easy to communicate to a larger audience (Dale et al. 2013b), Scientists may require a higher level of granularity. The general public may need visual displays that are readily understandable, and producers may need to be assured about economic impacts.

11.1.9 Determine whether objectives are achieved

It is important to get feedback on the effectiveness of indicators as information is provided to stakeholders. Evaluating the achievement of stated objectives using pre-established criteria is fairly straightforward while trying to gauge whether broader goals were achieved may be challenging. If stakeholder feedback reveals perceptions of ineffectiveness, the user of the indicator selection framework should attempt to determine the reason for that perception. Are the indicators themselves disputable, or was the manner in which data were collected, interpreted and presented inappropriate (e.g. too little detail or too much)? Or perhaps the spatial or temporal scale was believed to be inappropriate for the goal of the assessment. At this point, decision makers may find it necessary to revisit the goal definition step and modify the objectives or the indicators.

As data are collected and evaluated, it is not unusual to discover that some indicators are unnecessary or even detrimental to the assessment goals. Care must be taken to assure that indicator sets provide information in support of objectives and constructive decisions. The development literature is filled with case studies demonstrating that emphasis on reaching specific indicator targets (e.g. trees planted or schools built) undermined achievement of the overall goals (e.g. forest ecosystem services and education).

11.1.10 Assess lessons learned and identify good practices

Periodic assessment is highly important. Too often participants scatter, when the stakeholder engagement stage is completed, or a specific project is finished, and valuable lessons are lost. Even when goals are met successfully, stakeholders are able to identify aspects that they would approach differently if they were to repeat the process. Also crucial at this stage is the documentation of significant success factors and good practices for applying the indicator set. While the term 'best management practices' is common, it actually means 'good practices that can be continually improved' (Rossi 2012). Sustainability is not a fixed state but an aspirational goal, and mechanisms for continual improvement are an essential part of the framework supporting assessment of sustainability of bioenergy systems (Lattimore et al. 2009).

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