Rice straw and Wheat straw

Potential feedstocks for the Biobased Economy

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Executive summary

English name: Rice straw, Wheat straw
Other names for rice straw: rijststro (NL), la paille de riz (F), paja de arroz (S)
Other names for wheat straw: tarwestro (NL), la paille de blé (F), paja de trigo (S)
Latin name:. *Oryza Sativa (*rice), *Triticum Spp.* (wheat) for example *Triticum Aestivum, Triticum Durum*
Plant Family: *Graminae*. Herbaceous, non-woody stems
Origin: China (Rice), Egypt (Wheat)
Occurrence: Rice: tropics, sub-tropics, and Mediterranean climates. Wheat: moderate and Mediterranean climates. In Northern India and Pakistan, rice and wheat are grown in rotation
Current uses: Rural energy, animal bedding, animal feed, building material, mushroom production
Growth habit: Irrigation or rain-fed, depending on climate and location.
Growth cycle: Annual plant; in certain tropical areas several harvests per year (rice)
Agronomic practice: Rice straw and wheat straw are agricultural side products and can be collected after harvest of the main product, paddy rice/rough rice or wheat grain. Unlike rice husk and wheat bran (side streams from rice and wheat that are generated during the processing of rice and wheat grain), straw is generated at the field: straw is a primary biomass residue
Yields: widely variable, depending on variety, soil, and climate conditions
Biobased applications/conversion and quality aspects: rice straw and wheat straw are a lignocellulosic biomass. Relative to other agricultural by-products, it contains a high amount of inorganic components and ash. Straw is seen as a major feedstock for the biobased economy. Currently, combustion of straw is the most common application
Costs: Rice straw is a low cost biomass. However, as most of rice straw is produced by smallholder farmers, collection costs and logistical costs may be high. Wheat straw is already collected and used for different purposes in many countries. Costs for wheat straw depend largely on local circumstances: in some regions a lot of straw is collected for specific purposes such as animal bedding. In other areas wheat straw has no applications and may be available at just over the cost of collection and logistics.
Sustainability/Impacts: Use of rice straw may offset carbon, N_2O, and fine dust emissions from field burning, a common disposal method for rice straw and wheat straw, with retention of minerals in the ash. Legislation to ban field burning leads to disposal problems in many countries. If straw has no or limited alternative uses it may be considered an iLUC free (it does not lead to indirect land use changes) biomass source. Thus avoiding much of the current problems associated with biofuels based on food crops or grown in competition with food crops.
Outlook: Modernization of agriculture in many developing countries will lead to more rice straw being marketed as feedstock for the biobased economy. This is further motivated by increased efforts of governments to ban rice straw burning by farmers. In Europe, wheat straw (as well as other straw, like rapeseed or barley straw) are viewed as one of the primary feedstocks for the Biobased Economy given the volume of straw produced every year.

1 Climate, geographical distribution, and characteristics of straw

In this report, the term rice straw and wheat straw are used to describe the dry stalks of the cereal crops rice and wheat. The stalks remain following the removal of the grain during the grain harvesting process. Often the term " straw" or "cereal straw" is also used in connection with rice and wheat straw, however these terms are more general and indicate residues from a much larger group of agricultural crops including barley, rye, rapeseed, sunflower, and sorghum. The focus of this report is rice straw and wheat straw.

Table 1a: Cultivated agricultural area and rice production in different regions of the world, and estimate of rice straw production. Data based on FAO grain production data of 2009. Data are ranked by size of cropping area.

	Area harvested	Production	Straw production
	1000 ha	kton of Rice/a	kton of straw/a
World	158,511	684,595	727,400
Southern Asia	59,449	202,889	215,600
South-Eastern Asia	48,203	197,777	210,100
Eastern Asia	32,999	216,630	230,200
Western Africa	5,114	10,392	11,000
South America	5,253	25,568	27,200
Eastern Africa	3,147	6,701	7,100
Northern America	1,256	9,972	10,600
Middle Africa	691	663	700
Northern Africa	590	5,593	6,000
European Union	462	3,152	3,350
Caribbean	456	1,246	1,300
Southern Europe	418	2,906	3,100
Central America	326	1,228	1,300
Eastern Europe	225	1,183	1,250
Central Asia	193	696	740
Western Asia	153	927	990
Western Europe	24	138	150
Oceania	14	82	90
Southern Africa	1	3	3

Table 1b: Cultivated agricultural area and wheat production in different regions of the world, and estimate of wheat straw production. Data based on FAO grain production data of 2009. Data are ranked by size of cropping area.

	Area harvested	Production	Straw production
	1000 ha	kton of Wheat/a	kton of straw/a
World	224,389	686,795	583,776
Europe	61,084	228,485	194,212
Southern Asia	47,113	125,458	106,639
Eastern Europe	42,387	114,626	97,432
Northern America	29,830	87,213	74,131
European Union	25,634	138,463	117,694
Eastern Asia	24,828	116,365	98,910
Central Asia	17,372	28,735	24,425
Oceania	13842	22,060	18,751
Western Asia	11853	30,029	25,525
Western Europe	9140	69,001	58,651
Northern Africa	7480	20,248	17,211
South America	7436	18,592	15,803
Southern Europe	5386	17,230	14,646
Northern Europe	4171	27,628	23,484
Eastern Africa	1882	3,220	2,737
Central America	835496	4126	3,507
Southern Africa	666	1978	1,681
South-Eastern Asia	105	183	156
Western Africa	48	77	65
Middle Africa	15	24	20

Rice is primarily grown in tropical and sub-tropical climates, however some rice production occurs in Mediterranean climates. Wheat is primarily grown in moderate and Mediterranean climates. Depending on location, temperatures and availability of water, rice production is combined with wheat production (e.g. Rice-wheat region in S. Asia) or other crops. In tropical climates and with ample water availability (e.g. Mekong Delta in S.E. Asia), more than one crop of rice can be grown per year. This also means that straw is generated more than once a year. In moderate climates, wheat is often grown in rotation with other crops, such as sugar beets.

For rice, the main producers are located in Southern and South-Eastern Asia: China, India, Indonesia, Bangladesh, and Vietnam. For wheat, main producers are located in Southern Asia, Eastern Europe, Northern America and Eastern and Central Asia. For the European Union, wheat is by far the more dominant crop, compared to rice.

The biochemical composition of rice straw and wheat straw is characterized by a typical composition of an agricultural-based lignocellulosic residue: it contains on average 30 – 45% cellulose, 20 – 25% hemicellulose, 15 – 20 % lignin, as well as a number of minor organic compounds. Rice straw and wheat straw are poor in nitrogen, but relatively high in inorganic compounds, often referred to as ash. Table 2 presents an overview of characteristics of wheat straw and rice straw as they occur in the Phyllis database.

Table 2. Fuel characteristics of wheat straw and rice straw (source: www.ecn.nl/phyllis)

		Wheat straw			Rice straw		
Component		**Mean value**	Min value	Max value	**Mean value**	Min value	Max value
Water content	wt% wet	**10.4**	0	18	**23.9**	6.8	88
Volatiles	wt% daf	**81.2**	76.5	87	**83.9**	80.1	98.2
Ash	wt% dry	**7.1**	1.3	22.8	**18**	9.6	24.4
HHV	kJ/kg daf	**19555**	16627	21742	**18824**	17673	19718
LHV calc	kJ/kg daf	**18181**	15202	20487	**17511**	16381	18440
C	wt% daf	**49**	46.5	52.6	**48.7**	43.3	60
H	wt% daf	**5.94**	3.2	6.63	**5.92**	4.94	7.01
O	wt% daf	**43.7**	39.4	50.1	**44.2**	30.8	50.4
N	wt% daf	**0.77**	0.29	2.08	**1.05**	0.57	2.11
S	wt% daf	**0.17**	0	0.46	**0.14**	0.07	0.23
Cl	wt% daf	**0.544**	0.021	2.316	**0.489**	0.013	0.909
Cellulose	wt.% dry	**37.8**	28.8	51.5	**36**	28.1	41
Hemicellulose	wt.% dry	**26.5**	10.5	39.1	**24**	21.5	26.5
Lignine	wt.% dry	**17.5**	5.4	30	**15.6**	9.9	23.3
Lignin acid insoluble (AIL)	wt.% dry	**-**	-	-	**-**	-	-
Lignin acid soluble (ASL)	wt.% dry	**-**	-	-	**-**	-	-
Lipids	wt.% dry	**1.5**	1.5	1.5	**-**	-	-
Protein	wt.% dry	**4.3**	3	6.3	**0**	0	0

There are two particular challenges of wheat straw and rice straw with regard to applications for bioenergy purposes. The high carbon-to-nitrogen content (due to low amounts of nitrogen) of rice straw and wheat straw leads to a very low bio-degradability in comparison to other agricultural residues. This is of particular interest when straw is used for anaerobic digestion to produce biogas. It means that in many cases, straw needs to be blended with other agricultural residues, in order to speed up the degradation of organic constituents contained in straw.

Another challenge, in particular for thermal processes such as combustion and gasification, is the high ash content as well as the high inorganic composition of rice straw and wheat straw. For rice straw for instance, ash concentrations of 18 to 20 weight-% (on dry matter basis) are not uncommon, whereas for wheat, typically 6 – 12 weight -% ash is contained in the biomass. In addition, high occurrences of potassium and chlorine in straw leads to a high tendency for ash slagging and fouling in combustion systems (refer to Chapter 5).

2 Current uses and status as a biomass crop

Since rice is largely produced in developing countries, a lot of current uses of rice straw are traditional, such as fuel for cooking (either directly or by producing briquettes which are produced by compressing the material), animal feed, animal bedding, anaerobic digestion to biogas and building materials such as roof thatching. In many cases, straw is left in piles for composting and returned to the field. In most of these cases, straw is used together with other agricultural residues generated at village level. There are few official statistics on actual rice straw utilization, and therefore quantitative estimates of current uses are difficult to make. Following is an overview of traditional uses for rice straw

Fuel for cooking:	Mainly combustion of straw in stoves. In certain regions, straw is briquetted to produced fuel briquettes. Compared to other agricultural residues such as cotton stalks or rice husks, straw produces more smoke and is therefore less desired as fuel for cooking
Building materials:	Straw is combined with mud to produce simple building blocks. In addition, straw is used for thatching of roofs.
Animal production:	Straw use in animal bedding. Rice straw and wheat straw are used in animal feed. Rice straw is a very low quality roughage feed.
Composting:	In combination with other agricultural residues including animal manure, straw is composted and returned to the field
Incorporation:	Straw is returned to the field, usually by tillage. Incorporation of large amounts of fresh straw is either labor-intensive or requires suitable machinery for land preparation and may result in the build-up of disease problems.

Modernization in rural areas leads to growing access to modern cooking and heating fuels, which means that in most regions, rice straw is no longer used as source of energy for cooking and heating. More modern uses of rice straw include using straw for fibres production, combustion for electricity generation, production of bio-fertilizer, and materials such as erosion-control mats. Still, in many cases rice straw is not used, and disposed of by open field burning. Estimates on how much rice straw is disposed of by field burning vary widely. For example, a study commissioned by NLAgency, assessed rice straw use and disposal in Vietnam, and concluded that whereas some straw is used for mushroom production, and bedding, 25 to 60% of rice straw is burnt depending on the region. In areas where rice harvesting has been mechanized (e.g., Thailand, China, and northern India), all the straw remains in the field and is rapidly burned in situ.

Unlike for rice straw, there are many current uses of wheat straw. The study by IEEP (2012) listed the main conventional uses of straw in Europe, along with their alternatives (Table 3). Current uses of straw include soil improver, animal fodder supplement, frost prevention in horticulture (e.g. straw bedding in flower bulb production in open fields), ingredient for mushroom production substrate, traditional building materials, and energy. In Denmark, Spain and the United Kingdom as well as other countries, dedicated power plants have been installed that use wheat straw as primary fuel. In addition, wheat straw is co-fired in coal-fired power plants. In most of these case, incentive schemes have led to the commercial utilization of wheat straw in the energy market. Wheat straw based pulping mills in Europe have been closed in the past decades (Spain, Denmark) due to heavy competition with wood based pulps and the more complex chemical recovery of the black liquors (containing silica).

Even with the many existing uses for wheat straw, in many regions and countries around the world there is a surplus of wheat straw. Field burning of wheat straw to dispose of this surplus exists as well, although it is practiced less frequently compared to rice straw.

Table 3 Main conventional uses of cereal straw (mainly wheat straw) in the EU (source; IEEP, 2012)

Within Agricultural sector:	Soil improver
	Animal fodder supplement
	Animal bedding
	Mushroom production (growth substrate)
	Frost prevention in horticulture
	Strawberries (preventing damage to the fruit)
	Compost industry
Outside the agricultural sector:	Thatching
	Traditional building materials, fibre boards, insulation material
	Energy (heat, power, fuels)

3 Rice Straw and wheat straw management

3.1 Crop description

Rice and wheat are grown to produce rice grain and wheat grain. Rice grain, often referred to as paddy rice or rough rice is primarily used for human food (~90% or more), with the remainder used for animal feed and other uses. Most wheat (more than two thirds) produced in the world is used for human food, generally in the form of flour to produce bread. About 17% of global production is used for animal feed, although this varies from country to country (in Europe and North America, more wheat is used for feed). In recent years, more wheat and barley grain have been used for the production of bioethanol

As rice straw and wheat straw are side products of the main cereals rice and wheat, we refer to other sources of information for a crop description of wheat and rice. For further information on rice and wheat production, a good reference is the Grain Knowledge bank which can be accessed at www.knowledgebank.irri.org

The primary agricultural residues associated to rice and wheat are rice straw and wheat straw. Straw is a term used for all harvestable residues after wheat and barley grain have been collected by grain harvesting, and includes major parts of the stem, leaves, and spikelets. For off-field utilisation, straw is collected in packs or bales, which are produced by self-propelled baling machines. If straw is not collected but left in the field, it can be ploughed into the field or left as a mulch layer that covers the top soil. In some regions, straw is burned in the field for fast disposal purposes, a process which is referred to as open field burning.

3.2 Rice straw management for biomass

The method of grain harvest that precedes straw collection, affects to a large extent how and how much straw is generated in the field.

There are two main grain harvesting methods that have an effect on straw generation in the field. In the first system, the crop is cut by manual labor and placed in bundles on the surface. The bundles are then placed in a heap in the corner of the field. Threshing (removing the grain from the rest of the crop including the stalks) is done by a stationary thresher/cleaner system that is brought to the field. These threshing machines are often custom-made and locally built. As a result of the threshing operation, straw is located in a heap near the outlet of the thresher. This harvesting system is particularly common in rice-growing areas in developing countries with limited agricultural mechanization. In the manual grain harvesting system, straw may be collected at a central location, where it is packed in bales.

The second system includes cutting and threshing of rice or wheat crop in one operation by a self-propelled combine-harvester (Figure 1). The combine-harvester cuts the crop while it moves through the field, threshes the crop, and places the straw sideways or behind the threshing mechanisms. As a result of the combine harvesting, straw is left in a windrow behind the combine, and windrows are spread throughout the field. After natural drying, the straw can be picked up by a mechanical baler, which compresses the straw in packs or bales. Some combine harvesters are equipped with cutting mechanisms for the straw, in order to speed up degradation of straw in the field. In areas where straw is collected for other uses, these cutters are generally not used.

The main techniques for collecting straw in the field consists of baling straw in small rectangular, large rectangular, or round bales (Figure 2). Besides the difference in dimensions and weight of the straw bales, the packing density of straw differs. For small bales, typical packing densities are 80 – 100 kg /m3, on a dry matter basis. For larger bales, densities may go up to 150 kg/m3, or higher. Further information on the logistics of straw collection is included in Chapter 4.

Figure 1. Combine harvesting of rice in Egypt (source: Wageningen UR-FBR)

Figure 2. Baling rice straw in Egypt (source: Wageningen UR-FBR)

3.3 Rice straw and wheat straw yields

Straw yields vary widely among countries and regions. In many cases, estimates of straw yield are made based on the grain production (ton grain per ha), which are taken from agricultural production statistics, and that can be converted to straw yield by applying a straw: grain ratio. Typical value for straw: grain ratios for rice vary from 0.7 to 1.5, which means that for every ton of rice grain, 700 to 1500 kg of rice straw is produced. For wheat straw: grain ratios are typically lower than for rice. The resulting straw yield should be seen as a theoretical estimate of straw that could be collected, however actual straw yields are generally lower as there are technical and climatological limits (e.g. straw collection machinery, field specific factors, rainfall) that limit the amount of straw that can be extracted from the field in a specific situation. Besides technical limits, there are also economical limits to collection of straw, as many additional operations are necessary to collect straw which may not in all cases be economically feasible.

To some extent, a farmer can influence the amount of straw that can be extracted from the field, by: proper crop management (e.g. reduced lodging of the crop), trafficking patterns during grain harvest (reduce flattening of straw to the field surface), adjusting grain harvest method (selecting cutting height of the crop), and choosing crop varieties with a certain straw to grain ratio. Anecdotal evidence from the Netherlands indicates that when the selling price of wheat straw is higher, farmers will choose wheat varieties that generate more straw per ha of land.

Factors that restrict the amount of straw that can be collected from year to year, include:

- Annual variations in straw production, resulting sometimes in shortages in some years depending on weather conditions. In addition, storage of straw in winter periods may be difficult at times, and leads to straw losse.

- Straw yield varies highly among regions and countries. In Northern Europe, wheat productivity is much higher (typically 7.5 ton grain/ha) resulting in high straw yields, compared to Southern Europe where wheat yields are 3 ton/ha
- Modern grain harvesting systems (combines) cut the crop higher leading to lower collectable straw production, and
- Cereal breeding is directed towards production of short stems varieties (to prevent lodging) , which in turn leads to lower straw production

3.4 Estimates of the potential availability of straw

The availability of a primary by-product such a straw can be defined by a simple formula: **Availability = P - T1 - T2 - T3 - T4**

Where **P** is the amount of straw present. As explained in 3.3 this is variable but can generally be estimated.
T1 are conventional competitive uses (i.e. feed, bedding, fibre uses, etc.).
T2 are new competitive uses that may be relevant in the near future.
T3 is the amount of straw that has to be left behind to conserve soil quality.
T4 is the amount of biomass that is not financially feasible to remove (biomass density ton/ha may be too low to make collection financially feasible)

In particular for the EU, there are quite a number of studies that have estimated the potential of straw for energy conversion. In general, estimates among these studies vary widely, given different assumptions, scenarios, and time frames used in the study. IEEP (1212) quotes unpublished studies by two German institutes that give a technical potential of straw in the range of 50 and 110 million tonnes of straw (dry matter) per year in the 27 Member states. The Biomass Futures project, which is the most recent large European research project to calculate bioenergy potentials, has identified a similar straw potential of 127 million tonnes for the EU-27 in 2020 (note: straw here refers to straw from barley, wheat, rye, oats and other cereals combined). Often, some element of competing uses of straw (i.e. non-energy use of straw) are taken into account in the calculations, which lead to different results. There are also different approaches in relation to the restrictions of straw collection for sustainability considerations (see next paragraph).

3.5 Sustainable straw extraction

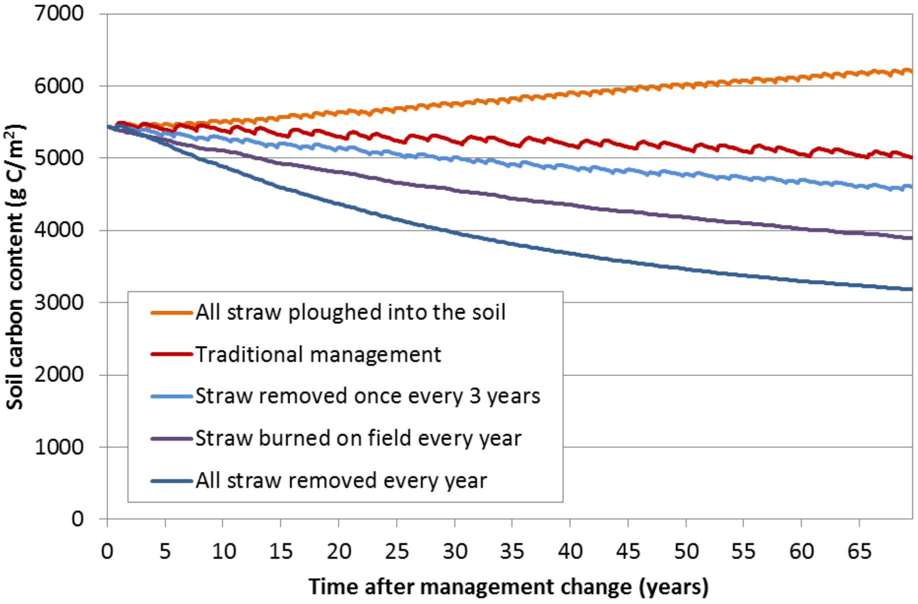
"How much straw can be extracted in a sustainable way?" is a common question that is frequently discussed when estimated the availability of straw. Maintaining soil fertility is a primary factor in assessing sustainability of agricultural residue utilization. Maintenance of soil fertility generally deals with the question how much agricultural residue can be sustainably removed without long-term negative effects on agricultural productivity of the land. As stipulated by Kim and Dale (2004), the fraction of agricultural residues collectable for biofuel, or other purposes, is not easily quantified because it depends on local climate, crop rotation, existing soil fertility, slope of the land, and farming practices which are all very location specific. The impact of the removal rate of other agricultural residue on long-term soil fertility is a topic of many research projects, and general recommendations are difficult to find.

The amount of straw that needs to be incorporated into the soil to maintain soil quality will depend on crop yields, soil type (texture), and on the climate. If crop yields are high more straw can be removed as root turnover and stubble already provide enough organic matter to the soil.

In Figure 3 the results are shown of 5 straw management options on soil organic carbon for a relatively low yield system in Ukraine as modelled with the Century model (Parton, 1996) within the AgNL sponsored "Pellets for Power" project. The results shown in the figure are for wheat straw on a Haplic Chernozem under Ukrainian environmental conditions. First the model was initialised for natural steppe grassland until soil carbon was at equilibrium status. Afterwards a conversion to cropland was simulated for a period of 150 years assuming the average traditional management. This was simulated as a five year rotating period of two years ploughing of straw into the soil, two years burning of straw and one year removal of straw. After this period a change in crop and land management was simulated for several management options (see Figure 3).

As it takes a long period to reach equilibrium in the soil carbon stocks under the relatively dry and cold conditions in Ukraine, the default management still shows a decline in soil carbon stock due to the conversion of natural grassland (high C stock) to cropland (lower C stock). The only management option which actually increases the amount of C in the soil is the simulation in which each year all straw is ploughed into the soil at the end of the growing season. The other options show a decrease in the soil carbon, with the highest losses for the option of 100% straw removal and ploughing.

Figure 3: The change in soil carbon content for wheat straw in Ukraine (for a Haplic Chernozem) modeled for 5 straw management options using the Century model (Ref: Lesschen et al., 2012).



The variability of regional specific extraction rates is also highlighted by other institutes (DBFZ and Oeko-Institut), who reviewed a range of straw availability studies. The sustainable straw extraction rates ranged from 25 and 75 %. They conclude that sustainability issues have not been considered in a consistent way across the different studies.

Evidence gathered from a number of national experts in different parts of the EU suggests a smaller range of 25 to 30 % after competing uses are taken into account. These figures are supported by slightly higher, but consistent figures, from other reports. For example the European Environment Agency (EEA) estimates between 33-37 per cent to be available Europe wide within a range of sustainability scenarios.

As stated by IEEP (2012) in many studies, researchers assume an average rate of 'sustainable straw extraction', whereas in fact this figure is highly variable at the regional and sub-regional level and determines the extent to which residues can be extracted in a sustainable way.

Sustainable availability of straw is difficult to assess because the factors that determine the availability vary or are difficult to determine; The amount of straw present will vary but can be increased by choosing varieties with a high straw to grain ratio. The demand from competing uses will vary. The amount of straw that needs to be left for maintaining soil quality is difficult to determine.

Keeping the above in mind we can state that overall straw availability (for energy) has been found to be between 25 and 75%. Many studies that claim to take all factors into consideration conclude 25 to 35 % of the straw may be available for energy uses.

3.6 Straw disposal: field burning

Compared to other types of straw (e.g. wheat straw, corn stover), rice straw management can be distinguished by its most common disposal technique: open field burning. Field burning of straw is often the most cost-effective technique for rice farmers to quickly dispose of straw. While some nutrients (e.g. potassium) are largely contained in the field, a lot of carbon and nitrogen are released and not returned to the field. Although there are no official statistics, estimates indicate that up to 80% of rice straw is burnt by farmers in certain regions. Furthermore, there are also differences in practices of straw burning (e.g. pile burning, burning of straw that is evenly spread over the field). There are a number of studies evaluating the environmental impact of straw burning. Table 3 provides an example of such a study; it presents the estimated greenhouse gas emissions and other air pollutants (NOx, CO, fine dust) from the burning of rice straw in Egypt, where rice is produced at a very high productivity (more than 8 tons /ha). In total, rice straw burning is shown to release 11 tons of CO2-equivalent per ha of land, in addition to a large amount of NOx (a precursor to photochemical smog) and PM2.5 (fine dust).

The current practice of straw burning is mainly caused by the need of a short turnover time between rice and following crops. With the rice being harvested in or near the end of the rainy season, the next crop (often rice, wheat or other crops) will have the highest yields when this crop can be established as early in the autumn period as possible, thereby benefiting from higher temperatures and longer days. Removal of straw, or processing it in such a way that it does not act as a physical barrier makes it much easier to prepare a seedbed for the following crop. There are various options for incorporating the straw into the field (as alternative for burning) but these options generally require mechanization, water, and additional fertilizer in order for rice straw to quickly decompose in the field. In addition, the degradation of straw in the field may also lead to significant emissions of greenhouse gases, such as methane.

Table 3. Estimated emissions of greenhouse gases and other air pollutants as a result of field burning of rice straw in Egypt (Bakker et al, 2010; unpublished data).

Pollutant	Emission factor	Emissions	Emissions in CO2 Eq.
	g/kg straw, dry weight	kg pollutant/ha	ton CO2eq/ha
CO_2	1460.00	9344.0	9.34
CH_4	0.74	4.7	0.10
N_2O	0.79	5.1	1.57
CO	72.40	463.4	
NO_X	3.52	22.5	
SO_2	0.15	0.9	
$PM_{2.5}$ (fine particulate matter)	12.95	82.9	
Total		9354	11

4 Harvest and logistics

The main techniques for collecting straw in the field consists of baling straw in small rectangular, large rectangular, or round bales (refer to previous chapter). From the time of collection of straw, which is done by custom baling operations, a number of logistical operations are required to deliver straw in packs or bales to the conversion site. For many of these operations, specialized machinery is available for straw collection and transport.

Prior to baling straw, the following field operations may be included in order to collect straw:
- Raking/Windrowing: placing the straw in neat rows in the field, in order to facilitate the baling operation
- Cutting: depending on the length of stalks that are remain standing in the field, an additional cutting operation is done to further increase the amount of straw that can be picked up by baling

After baling straw, the following operation are required:
- roadsiding: in this operation, straw bales are picked up from the field, and placed at the side of the field where they can be stacked and picked up for transport
- stacking: in this operation the individual bales are stacked to facilitate pickup for transport
- transport to storage facility: this operation depends on the distance to the storage facility. Where straw is stored decentrally (in or near the farm), the transport is normally done on simple flat-bed trailers drawn by tractors. For small bales, specific machinery is available that combines roadsiding, stacking and (local) transport.

After storage: baled straw is further transported on special trucks to the conversion facility. Alternately, baled straw is converted into pellets. Straw pellets have a much higher density compared to baled straw, are easier to store and handle both during transport and application. However producing pellets from straw comes at considerable cost.

In cases where the rice or wheat harvest is preceded or followed by considerable rainfall, the composition of straw will change, in particular with regard to the inorganic composition. This field leaching or natural leaching leads to release of potassium and chlorine, which are troublesome elements when straw is used in thermal energy applications (see also next chapter).

The costs for collection and transport of straw are site- and region-specific, and depend on the productivity of the agricultural residue (ton of residue per ha of land) and how much of the residue is removed from any particular field or location. For example, costs for acquiring 300,000 tons of wheat straw in Southern Europe from a 90 km collection radius were estimated at 40 €/ton straw, which includes 6 €/ton as payment to the farmer, 18 €/ton for baling, and 12 €/ton for transport to the conversion facility (JRC, 2008).

5 Straw applications

5.1 Straw for electricity and heat

There are three main reasons for producing energy and heat from straw: (1) there is a market demand for electricity, and often for heat, (2) substantial energy production from agricultural wastes can be accomplished when they are converted to energy, and (3) substantial environmental savings can be provided by avoiding landfilling or open field burning of straw, in particular for rice straw.

The tremendous increase in energy demand of the past 50 year is largely filled by fossil, non-renewable, energy sources such as coal, natural gas, and oil. It is well known that 80% or more of the world's energy demands today comes from non-renewable resources, which clearly indicates the issue of sustainability of our energy supply. Many developing countries have transferred from being a net oil exporter to an oil importer in a short amount of time. Besides increases in energy production and consumption, the production of food crops has also increase over the past decades. According to the International Rice Research Institute (IRRI) , the yearly increase in rice production amounts to 1.5% increase per year, on average. More grain production also means a higher production of by-products, such as rice straw. This provides an important opportunity for using the waste for beneficial purposes.

There are four main technologies available to produce electricity and heat from rice straw. Energy can be produced either directly, by combustion, or indirectly, by producing an intermediate energy carrier like biogas, which later can be converted to electricity or heat. In addition, two important technologies that are developed are in development are gasification and pyrolysis. The main conversion energy technologies are summarised in the paragraphs below. Not included in this overview are biofuels used for transportation: these will be dealt with in separate paragraph.

5.1.1 Combustion

Combustion is the most well-known conversion method, and the technology generally consists of a boiler coupled to heat exchanger, and a steam turbine with electricity generator. Options for rice straw combustion are dedicated systems, and co-combustion, where the straw is combustion together with coal or other fuels (co-firing).

As noted earlier, there are specific and important challenges related to rice straw combustion, these are mainly related to the high ash content (up to 20%), and the ash composition. Due to its chemical composition, at higher temperatures inorganic components in rice straw react with each other, leading to problems in boiler systems. Quality of rice straw is therefore a major issue. Many boiler operators have found that they could not accept rice straw as fuel, whereas they are successfully use other biomass fuels, such as woods. Finally, a separate bottleneck is the need to densify or compress the straw prior to combustion, for both economic (logistics) and technical reasons.

Biomass-fuelled power plants at smaller scale (5 – 15MW_e) are well established, while for larger systems the transportation distances to bring the straw to one combustion facility may become a problem. In addition, an outlet for straw ash needs to be identified

There are a number of solutions for ash-related problems of rice straw and wheat straw combustion:

- Rice straw and wheat straw can be combined with other fuels that are lower in ash, alkali and chlorine
- boiler systems can be designed with lower operating temperatures, thereby reducing ash agglomeration problems
- troublesome components, such as K and Cl, can be removed prior to combustion in a process known as leaching, which can be accomplished either by natural means (rainfall) or by washing the straw prior to combustion

Some of these solution have been successfully tried with rice straw. In general, these solutions also lead to higher costs for straw utilization, which often makes the use uncompetitive (refer to Chapter 6).

5.1.2 *Anaerobic Digestion*

Anaerobic digestion is a well-proven technology for various agricultural wastes, including straw. The technology can be characterized by low maintenance costs, and the technology is not complicated. Also, it can be implemented at relatively small scale, which translates in short transportation distance from the field to the facility.

There are two main applications for the end-product Biogas. Direct use of biogas can be done when gas is used for cooking and heating. Indirect use of Biogas involves feeding the gas into an engine that is equipped with an electricity generator. In some cases, biogas is used for lighting as well.

Often, rice straw and wheat straw are digested together with other biomass types, including Animal manure, or other organic wastes. Biogas technologies that only use straw, are still in development. Therefore, the major drawback of this technology that besides straw, there is a need to have other raw materials available to effectively turn rice straw into biogas. There are also pretreatment technologies available that lead to an increase biodegradability of the straw. These pretreatment techniques are often too costly to be used in combination with biogas production, but are an important step in the production of biofuels from straw (refer to 5.2).

5.1.3 *Pyrolysis and Gasification*

Pyrolysis is done at lower temperatures and yields two fractions: bio-oil and bio-char. Gasification yields only a gas, but the composition is quite different compared to biogas. The produced gas can be used, however it needs cleaning of impurities. These technologies have shown great promise, and have a potentially higher energy conversion efficiency, but they have so far not been implemented at large scale. In Denmark, a system was developed whereby straw is first gasified, and the gas is then converted to electricity in a different boiler.

Related to rice straw is the combustion of rice husk or rice hulls, which is often more successful compare to combustion of rice straw. There are three reasons for this: (1) rice husk is already collected in one site (at the rice mill); (2) its composition is somewhat more benign than rice straw, especially in regard to alkali and chlorine, and (3) rice husk ash is a marketable product, depending on operating conditions. There are many commercially operated, small scale rice husk furnaces, gasifiers, and pyrolysis units. In addition, industrial scale rice husk utilization can be found throughout the rice growing areas of the world, including the USA, Thailand, China, etc.

Following is a short summary of examples of experiences with rice straw conversion to energy.

Example 1: Rice straw power production in China (source: Gadde et al, 2008)
There are various biomass power projects in Jiangsu Province. The typical size of the straw-fired power plants is 12 – 25 MW electricity, per power plant. In all cases, the fuel consists of 50 – 60% of rice straw, and the remainder is made up of other types of agricultural waste. Most facilities source their raw material from an area with a radius of 25 to 50 km radius around the power plants. The main concern of the power plant operators is the cost of the raw material, as this quote suggested "It is assumed that collection and transportation charges will increase every year because of increasing labor and transport costs." (Gadde, 2008)

Example 2: Biomass power production in California (source: Jenkins et al, 2000)
In California, rice is produced as a mono-crop, and straw becomes available after the grain harvest in August-September. Since the 1990's, legislation passed by the State of California has led to a mandatory phase-out of field burning of rice straw. Currently, the primary disposal method is in-field recycling/incorporation by farmers. In California, there are at least 10 medium-sized facilities to produce electricity from biomass. However up to now, these facilities have largely used other types of agricultural waste, and not rice straw, due to the anticipated problems with firing straw fuels with high ash and chlorine content (see also 5.1.1). There are however some other uses of rice straw in California, including the use of rice straw for erosion control. For instance, the State of California uses rice straw to avoid erosion of embankments of public roads.

5.1.4 Conclusions

Many technologies are available for producing electricity and heat from rice straw and wheat straw. However, up to now the potential of rice straw has not been realized. This is in contrast with energy production from rice husk, which in general is quite successful. Major challenges that are encountered with straw include

- Technological challenges, mainly related to the chemical compositions of rice straw,
- Organizational challenges: mainly related to the logistics of straw collection
- Economic challenges: mainly related to the cost of straw conversion, versus revenues.

Even with these important challenges, substantial environmental savings can be achieved, if rice straw conversion to energy leads to avoidance of field burning.

5.2 Straw for production of biofuels for transportation

Biofuels are commonly defined as transportation fuels that are derived from biomass. The most prominent examples are bioethanol, which is used as replacement for gasoline (petrol), and biodiesel, which can replace normal diesel fuels. In many countries throughout the world, legislation for mandatory use of biofuels in the transportation sector has been implemented that leads to higher demand for biofuels. Currently, there is large scale production of biofuels in Brazil, the U.S.A., China, and a number of European countries. Current raw materials used for biofuels include: Sugarcane, Maize, Wheat, Barley, Sugar beet for bioethanol production, and Rapeseed, Sunflower, and Palm oil for biodiesel production. The use of these raw materials also leads to discussion on whether it is desirable to use agricultural feedstocks that are also used for food production, into fuel (i.e. Food vs Fuel debate). Furthermore, questions are raised in regard to the environmental sustainability of current biofuel production.

Currently, the transportation sector in many countries is for more than 80% dependent on oil imports. One of the main drivers for biofuels therefore is to reduce the dependency on imported oil. Another very important driver for biofuels, is the reduction of greenhouse gas emissions in the transportation sector. Also, biofuel production may lead to new economic impulses for agriculture and agri-industry, and it may add value to by-products, in case by-products or wastes are used to produce biofuels. The main biofuels currently used in the world are bioethanol (or alcohol), and biodiesel. In the world, bioethanol production by far exceeds the biodiesel production. The main producers are Brazil, and the United States.

5.2.1 Using rice straw and wheat straw to produce Biofuels

Converting straw to biofuels is often characterized as "2nd Generation" or "Advanced" biofuel. Most advanced biofuel production technologies today are focused towards converting lignocellulosic biomass into transportation fuels. One of the main drivers for transportation biofuels is to reduce the dependency on imported oil. Another very important driver for biofuels, is the reduction of greenhouse gas emissions in the transportation sector. Also, biofuel production may lead to new economic impulses for agriculture and agri-industry, and it may add value to by-products, in case by-products or wastes are used to produce biofuels.

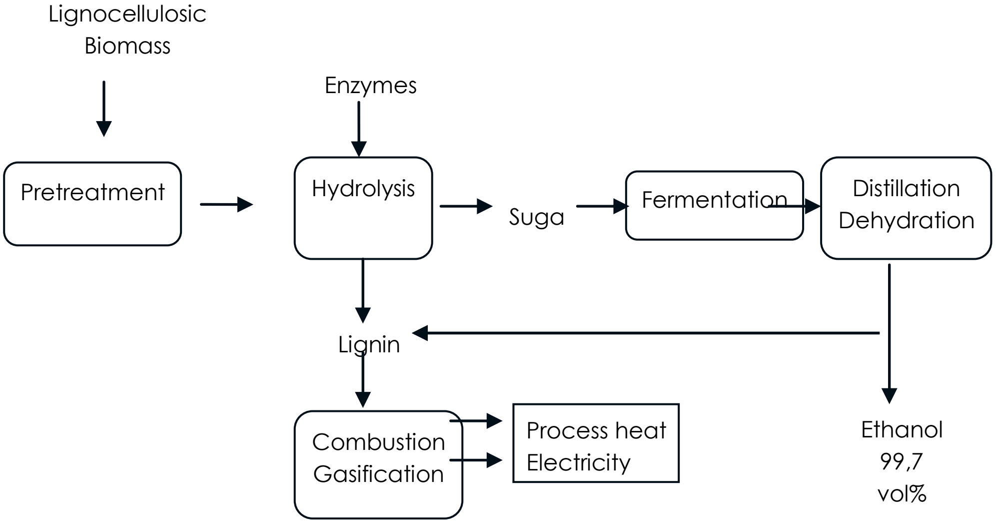
The main biofuels currently used in the world are bio-ethanol (or alcohol), and biodiesel. In the world, bioethanol production by far exceeds the biodiesel production. The main producers are Brazil, and the United States. Lignocellulosic biomass refers to plant biomass that is composed of cellulose and hemicellulose, which are natural polymers of carbohydrates, and lignin. Cellulose and hemicellulose are tightly bound to the lignin, by hydrogen and covalent bonds. Lignocellulose comes in many different types, such as wood residues, crop residues from agriculture, industrial residues from agro-food processing operations, and dedicated energy crops (e.g. switchgrass). Rice straw and wheat straw are major examples of lignocellulosic biomass that is available throughout the world. However, the technologies for producing biofuels from raw materials such as rice straw are still in development, as current production costs are not yet competitive with current biofuel production.

There are two main methods of producing biofuel from lignocellulose: the thermochemical method, and the biochemical method. For both these pathways, technologies are in various stages of development.

The thermochemical pathway, often referred to as Biomass to Liquids or BTL is in development. Essentially, from the raw material a synthetic gas is produced, which is further processed into a synthetic liquid, Fischer Tropsch liquid, that can be used in petrol or diesel engines. the transportation sector in many countries is for more than 80% dependent on oil imports.

A simple schematic of the biochemical pathway is shown in Figure 6. The process consists of a pre-treatment step, a hydrolysis step, and a fermentation step, followed by distillation and dehydration. In this process, lignin is discharged as a by-product and can be used to generate electricity to supply the process with energy, or to export to the electricity grid.

Figure 6. Simple block scheme of production of lignocellulosic biomass conversion to ethanol.



Pre-treatment is necessary to break open the lignocellulosic structures and to facilitate the separation of the main carbohydrate fractions hemicellulose and cellulose from lignin, in order to make these better accessible for hydrolysis, the next step in the process. Pre-treatment is considered by many as the most costly step in lignocellulosic biomass conversion to ethanol. A variety of pre-treatment methods have been studied and some have been developed at pilot scale or demonstration scale. Current pre-treatment methods include: steam explosion, liquid hot water or dilute acid -, lime-, and ammonia pre-treatments. Hydrolysis is the process to convert the carbohydrate polymers cellulose and hemicellulose into fermentable sugars. Hydrolysis can be performed either chemically in a process involving the use of concentrated acids, or enzymatically by using enzymes. Most pathways developed today are based on enzymatic hydrolysis, by using cellulose-degrading enzymes that are specifically developed for this purpose. Fermentation is the main process used to convert fermentable sugars, produced from the previous hydrolysis step, into ethanol. While in principal, the fermentation process is largely similar to that in the current ethanol production facilities, a major fraction of sugars produced from lignocellulosic are pentoses (5-carbon sugars such as xylose), which are difficult to ferment with standard industrial microorganisms. Therefore, a second important challenge in the conversion of lignocellulosic biomass to ethanol is the optimization of ethanol-fermenting microorganisms that can convert all biomass-derived sugars, including xylose and arabinose. Furthermore, the efficient integration of various unit operations into one efficient facility is challenging. In some processes, the hydrolysis and fermentation steps are combined into one process which is often referred to as simultaneous saccharification and fermentation or SSF.

5.2.2 *Ethanol from straw: developments*

There are several companies around the world that are developing biofuel production technologies based on lignocellulosic feedstocks, including straw. Examples are Abengoa (Spain and USA), Iogen (Canada), Dong Energy/Inbicon (Denmark) and M&G/Chemtex (Italy) that are developing bioethanol production methods based on straw. In general, there are large capital investments associated with these types of industrial developments. In 2013, two larger demonstration plants are expected to operate on lignocellulosic biomass, to produce ethanol. After successful conclusion of the demonstration phase, it is expected that full industrial scale facilities for the production of ethanol from straw will be built. In the Netherlands, several parties are involved in Research and Development related to biofuel production as well. Most of the research is done in public-private partnerships, with active support by the Dutch and European government. An example of such a project was the bioethanol/lactic acid research program which was funded by the Dutch Ministry of Economic affairs through the EET (economy, ecology, technology) grant program. Production costs of bioethanol produced from straw were estimated at around half a euro per litre, although in a commercial business model (which includes a commercial rate of return) that price would increase to about 0.75 €/L (Reith et al, 2007). Important improvements have been realized in recent years in particular by innovations in Industrial Biotechnology (development and improvement of enzymes and microorganisms) and Process technology. The outlook for coming years is that further transfer of technology to the industry will be accomplished.

In summary, the technology for conversion of lignocellulose, including rice straw and wheat straw, is applicable to a broad range of raw materials, and a broad range of fuels and products.

6 Economics of using straw

The cost of using straw for energy purposes have been subject to a number of studies. Many studies include the cost of collection and transport of straw to the factory gate, but do not incorporate additional costs or benefits to the farmer, or additional conversion costs related to the use of straw in energy installation (e.g. higher ash disposal costs-rice and wheat straw contain more ash than most other biomass fuels). One of the few studies that does estimate costs factors along the entire straw production-to-conversion chain, is a study by Jenkins et al. (2000) who estimated the commercial use of rice straw in combustion power plant in California. The economic impacts of straw are classified as follows:

- Costs or benefits to the farmer: these are related to avoided costs for straw incorporation, costs for (additional) nutrient replacement, and timeliness cost (i.e. cost associated to potential delays in other farming operations due to straw collection)

- *Straw acquisitions and logistics costs:* these are direct costs of straw collection and handling, and payments to the farmer

- Power plant costs: includes a range of additional costs to the power plant operator related to straw conversion, including fuel handling, changes to plant performance (in comparison with at standard biomass fuel, like wood), changes in availability and emissions, but also credits due to incentives geared at increasing the use of agricultural residues that are otherwise disposed of by open field burning.

In the analysis for rice straw, total costs for rice straw combustion (where straw is fired in a 20:80 blend with wood) amount to $ 52.8 ton fuel (equivalent to 69.4 $/MWh electricity), which includes $ 26.9 ton for straw harvesting and handling, $7.8 for transportation (up to 32 km transport distance), $3.8 ton for straw storage, and $10ton for power plant handling and processing. These costs are significantly higher compared to the costs of running the power plant on wood fuel alone. However, if an incentive scheme is adopted for using straw or other agricultural residues, costs can potentially be reduced, generating cost to levels at or below current costs for wood alone.

7 Sustainability

Given the recent implementation of sustainability criteria as defined in the Renewable Energy Directive (RED, 2009), it is important to assess whether straw-to-energy chains could comply with greenhouse gas reduction schemes in the EU. This is both relevant for straw generated inside the EU, as well as agricultural biomass from non-EU sources. As an example of such an assessment, a case study for rice straw production in Egypt is presented here. In recent years, Egyptian agriculture has undergone a tremendous growth, leading to a growing export of agricultural produce. However, much of the agricultural residues in Egypt are not used economically, and their disposal often leads to environmental pollution. Probably the most prominent example of this is rice straw, of which nearly 3 Million tons is burned annually in the field every year, creating economic waste as well as air pollution and smog formation. The resulting, well-known "Black Cloud" is a yearly health problem covering a.o. Cairo and other urbanised areas in the Egyptian Delta.

Based on a business case with five pellet plants operating in three major rice producing regions in the Nile Delta, the greenhouse gas emissions occurring in all operations of the biomass-to-energy chain were quantified (Poppens and Bakker, 2010). By using straw residues for the production of pellets and transporting these for use in electricity plants, significant overall emission reductions could be achieved compared to the current practice of field burning. Furthermore, expected emission reductions were calculated in comparison with the use of fossil fuels. The calculations performed were based on the methodology used by the European Commission, as documented in the Renewable Energy Directive (2009) and the Dutch NTA 8080 standard for bio-energy chains. Results were analysed for compliance with these standards' minimum requirements for greenhouse gas emission reductions.

The rice straw production chain consists of the following chain operations: Traders buy straw from contractors and farmers; baled straw is stored decentrally; baled straw is transported to pellet plants where pelletization occurs; Pellets are then transported by truck to the Egyptian port of Alexandria; straw pellets are then shipped in medium-sized carriers to Rotterdam; and finally, pellets are co-fired in coal-fired power plants. Table 4 presents the calculated CO2 emissions along the chain. The results suggests that Egyptian rice straw use for co-firing in Dutch electricity plants may indeed meet the requirements for net emission savings set by the RED and NTA 8080 standards. With 79,94 percent of savings, the biomass chain operations stay clear of the minimum emission savings of 70%. This result may hold promise for future biomass based business development in Egypt, and the possibility of certifying biomass operations against international sustainability standards for improved market access.

Table 4: Greenhouse gas emissions and emission reductions as a result of using rice straw pellets for co-firing

CO_2 –equivalent emissions and savings			
Operation ***Factor***		***T CO_2-e/year***	***gCo_2-e/MJ_{pellet}*** ***electricity***
Rice straw baling	E_{EC}	18572	2.14
Rice straw supply	E_{TD}-1	29913	3.44
Rice straw pelletizing (including milling and conveyer belt transport to silo)	E_P	104659	12.05
Pellet transport to Alexandria	E_{TD}-2	125109	14.40
Pellet shipment to Rotterdam	E_{TD}-3	71048	8.18
Total CO_2 equivalent bio-chain emissions	**E_B**	**349301**	**40.22**
Fossil fuel comparator	E_F		200
Net GHG emission savings	$(E_F-E_B)/E_F$		**79,89 %**

However, any results should be treated with some caution. Any slight change of one or more important calculation variables may have a big impact on the final result. This is the case, for example, for the emission factor of coal-fired electricity plants.

7.1 Indirect effects

The indirect effect of using biomass for non-food uses has in recent years become a concern, mainly when speaking about first generation biofuels which are produced from crops that can also be used for food. This may lead to increased food prices and decreased food security. It may also lead to indirect land use change (iLUC) as more land is needed for agriculture, which may lead to conversion of forests and grasslands which generally leads to significant greenhouse gas (GHG) emissions (Searchinger 2008). This can actually completely undo the GHG benefits of using biomass instead of fossil fuels.
As stated by Fritsche et al (2010) the iLUC risks are low or close to zero for bioenergy and biofuel feedstocks which do not require land for their production.
Thus, iLUC can be avoided by preferred use of such feedstocks. Crop residues, like straw, are generally not in competition with other uses due to their low-to-zero economic value. Still, there are exceptions, when straw has competing uses. As is generally the case in The Netherlands (Koppejan et al., 2010). As discussed in chapter 3, uses include improvement of soil organic carbon, existing fiber applications and animal bedding. In those cases, indirect effects could occur from displacing those uses, with potential impacts on GHG emissions. A methodology to assess this is under development (Ecofys et al. 2012).

Another emission factor worthy of further exploration in the context of Egypt is the *emission savings from carbon capture and replacement* (E_{ccr}). Here too, lack of a reliable methodology is the reason this factor was not included in the study. Current practices in Egypt, of large-scale rice straw burning and rotting on the fields, produce enormous amounts of GHG. Use of rice straw for energy purposes would help avoid these emissions, even more so through substitution of fossil fuels in electricity plants. It is highly recommended that more research funding goes into development of methodologies, for more accurate and reliable estimations of biomass related GHG emissions and other effects on sustainability. This is crucial for assessing the real importance of biomass-to-energy operations, as an instrument to reduce global GHG emissions, protect the environment and help alleviate poverty.

Finally, the quality of (straw) pellets was not included in the Egypt study. Anticipated ash-related problems with straw (high in ash; high in chlorine and potassium) may have a significant impact on the economic value of rice straw as fuel for combustion, as was also described in Chapter 5. It is likely that conversion costs for straw are much higher compared costs for using current solid biofuels (wood chips, etc). Also, it should be understood that only a limited amount of straw can be used in co-firing in coal-fired powerplants, without pretreatment of straw that removes some of the minerals that lead to ash-related slagging and fouling.

8 Conclusions

The following is a SWOT assessment of various aspects of rice straw and wheat straw, when used as a feedstock for the biobased economy, as discussed in this report.

Strengths

- Rice straw and Wheat straw are available in many countries around the world
- Rice straw and wheat straw are the most abundant agricultural residues in the world (next to residues from maize production, and sugar cane)
- Straw is a "Non-food" feedstock: it does not play a large role in current food or animal feed markets
- Straw exhibits a high cellulose content
- In general terms, there is a positive environmental impact of using straw, especially when straw collection and use replaces open field burning

Weaknesses

- There are high Costs associated to collection, handling, and transport of straw
- Straw has a high carbon to nitrogen ratio, and low degradability
- The high ash concentration makes straw less attractive compared to clean wood and biomass grasses, as fuel
- The ash composition of straw, make straw less favorable compared to wood or biomass grasses (in particular for thermal conversion)
- Nutrients are extracted from the field when straw is collected on annual basis, these need to be replenished
- In many countries the supply chain of straw is very fragmented (especially in developing countries with small farm sizes)

Opportunities

- Increased grain production in the world leads to more straw being produced
- Increased legislative efforts to ban open field burning of straw will make straw available for the biobased economy
- Development and implementation of technologies for 2nd generation biofuels may lead to a higher demand for straw
- Limiting 1st generation biofuels in favor of 2nd generation biofuels may increase demand for straw as a feedstock
- Straw is an underutilized by-product which means that it offers an opportunity to produce biofuels without concerns for competition for food and indirect land use changes

Threats

- Other non-energy uses of straw compete with straw use for biobased economy
- Implementation of Sustainability criteria might lead to lower extraction rates

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