Food & Bio Cluster
Denmark

Straw to Energy

Technologies, policy and innovation in Denmark

SECOND EDITION

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 818369

AgroBioHeat

Food & Bio Cluster Denmark is the national cluster for food and bioresources in Denmark.

About Food & Bio Cluster Denmark

We are the collective platform for innovation and growth in the cluster – for both Danish and international companies and knowledge-based institutions. We promote increased cooperation between research and business and offer our members one-stop-shop access to networks, funding, business development, projects and facilities. We offer various consultancy services, i.e. innovation processes, writing applications for soft funding, organising thematic tours and business missions, writing reports on different topics within our areas of expertise, and much more.

Please visit **www.foodbiocluster.dk** for more information.

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The AgroBioHeat project aims to produce a mass deployment of improved and market ready agro-biomass heating solutions in Europe. Agro-biomass is a large, underexploited resource, which can support the achievement of the European Energy and Climate targets, while promoting rural development and circular economy.

For more information about the project, please visit
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PHOTO *Torben Skøtt, BioPress.*

Straw as a source of energy

Straw can be a significant source of renewable energy, as outlined by Denmark's example.

The use of straw for energy production in Denmark has increased significantly since the 1980's, but there are still more than two million tonnes of surplus straw available, and if the right varieties are grown, the surplus can be even larger. In recent years, some environmental organizations – among others – have been questioning the increasing use of biomass for energy production. However, when it comes to straw (as well as other residues and by-products) of which there is a considerable surplus, energetic utilization makes sense.

The biggest advantage of using straw in the energy sector is that it is a CO2 neutral fuel, which does not contribute to an increase of the atmosphere's content of greenhouse gases. Only a few decades ago, straw was considered a problematic residue, which farmers wanted to dispose of as quickly as possible. The part of the straw which was not used for feed or bedding was typically burnt in the fields after harvest. However, in 1991, field burning became illegal, and since then there has been a greater focus on using straw for energy purposes.

Thanks to targeted policies and technological developments, Denmark has become a global leader in straw utilization for energy. Straw amounts to more than 2% of the Danish gross energy consumption production and around 10% of renewable energy production. At the moment, straw is primarily used as fuel at individual farm plants, at district heating plants, and in large power and CHP plants. In the future, as new technologies mature and become more cost-effective, straw may also be used for production of liquid biofuels and renewable gases as well as a feedstock for various bio-based materials and products.

The present guide focuses on the straw-to-energy sector in Denmark, the prominence of which is a unique feature of the country. However, it should be noted that there are several examples of straw utilization for energy beyond Denmark, often but not always developed with Danish technologies. More information on specific cases can be found on the Agrobiomass Observatory (www.agrobiomass-observatory.eu) of the AgroBioHeat project.

Energy policy – An important tool

Straw would not have had its current place in the Danish energy mix had there not been political will to exploit this abundant renewable resource in the energy system.

Today, almost all parties in the parliament agree that Denmark should be independent of fossil fuels by 2050.

For decades, Danish governments have incentivized the use of renewables. In 1976, Denmark launched its first energy plan "Danish Energy Policy 1976" and has since then become known for an active energy policy that emphasizes efficient energy use, energy savings and sustainable energy. Today, almost all parties in the parliament agree that Denmark should be independent of fossil fuels by 2050.

From 1993 central power plants were required to take 1.4 million tonnes of biomass per year, of which at least 1 million should be straw. **PHOTO** *Torben Skøtt, BioPress.*

Since the 1980's there has been a decentralisation of Danish energy production, and today many smaller plants generate electricity and district heating. **PHOTO** *Kirsten Krogh.*

Readjustment of the energy system

The Danish energy system, which in the 1970's was almost entirely based on imported oil and coal, is today characterized by a large diversification of different energy sources. There has been an ongoing expansion of renewables, including wind power, waste, biogas and straw. The steps that have paved the way for this development include energy price surcharges, political agreements supporting the establishment of certain kinds of sustainable energy, as well as tax exemption on biomass. Particularly the latter has meant that a large number of households, farms and district heating plants up through the 1980's chose to exchange oil for biomass.

In 1993, a large parliamentary majority entered into a biomass action plan, which required the central power plants to take 1.4 million tonnes of biomass per year, of which 1 million tonnes was straw. The targets were supposed to be reached in 2000, but the agreement was revised several times and it was not until 2009 that the final elements were in place, with the opening of a new power plant for 170,000 tonnes of straw per year on the Danish island of Funen (Fyn).

Since the 1980's, there has been a decentralization of Danish energy production. Electricity production happens all over the country, rather than at just a few central plants. District heating based on the excess heat has contributed to Denmark being one of the most energy efficient countries in the world. It has been possible to keep energy consumption largely constant, while there has been an economic growth of around 80% since 1980.

In 1990, the Danish parliament agreed on the so-called Heating Supply Law, which provided the Minister for Energy with the far-reaching authority to regulate fuel choice in district heating plants and decentralized combined heat and power plants. As a result, a large number of coal and natural gas heated district heating plants were converted to combined heat and power plants, while a number of smaller district heating plants switched to biofuels.

International agreements on climate change mitigation

Some decades ago, energy policy was primarily considered a national affair, but today it is - to a great extent - international events, which set the tone for Danish policy in this area. The development on the global energy markets, the liberalization of the energy sector, and obligations relating to the Kyoto protocol and the Paris Agreement, have had, and continue to have, a considerable impact on the Danish energy sector.

Denmark is one of the few nations to have ratified article 3.4 of the Kyoto protocol, and this means that changes in the soil's carbon content must be included in the climate accounts. This can become important for the use of biomass for energy purposes, particularly straw, because the utilization of straw reduces the soil's carbon pool, while perennial energy crops such as willow increase

Denmark has a national target of reducing greenhouse gas emissions by 70% in 2030 compared to 1990 levels to combat climate change.

PHOTO *Food & Bio Cluster Denmark.*

the amount of carbon in the soil. The lack of carbon storage from removing straw from farmland, however, can be compensated by growing autumn crops, and the CO_2 savings from using straw for energy purposes is significantly larger than the effect that the lack of carbon storage causes.

In 2016 Denmark ratified the Paris Agreement and took on the commitment to work to limit global warming to well below 2°C and pursuing efforts to limit it to 1.5°C compared to pre-industrial levels. Denmark's contribution to the agreement is negotiated via the EU.

National targets

On the national level, the Danish Parliament approved a new climate law in 2019 setting the target of a 70% reduction in greenhouse gas emissions by 2030, which is among the most ambitious in the world. There is no specific mention of the use of straw – or biomass – to reach this goal.

On one hand, there is a specific mention of the need for the agricultural sector to reduce its emissions of climate gasses; intelligent use of straw and other residual plant material could be one of the tools in order to improve agriculture's overall carbon footprint. On the other hand, researchers and environmental organizations are increasingly stressing that in the longer term, biomass should be used for production of high-value products instead of energy.

Independence of fossil fuels

In September 2010, the Danish Climate Commission published a report, which shows that Denmark can become independent of fossil fuels by 2050 and that this is possible without affecting the economy negatively.

According to the Danish Climate Commission, the central elements in a green energy system will be:

- Energy savings
- Offshore wind turbines, which can deliver a much of the electricity that will become the foundation of the future energy system
- Biomass, which will play an important role; partly as fuel in the transport sector, partly for production of electricity and heat, when there is a shortfall from wind turbines
- District heating and heat pumps for heating of homes
- Electricity and biofuels for the transport sector
- Intelligent use of electricity, where the consumption to a higher extent than today, is capable of following the production

The analyses of the Danish Climate Commission show that it will cost about 0.5% of the GDP to make a complete change to a green energy system, or about the same as it will cost, if we continue to use coal, oil and gas. This is because our current energy system will become more expensive due to higher costs on fossil fuels and CO_2 quotas, and this will largely compensate for the investments in new energy technology, which will make it possible to become self-sufficient with renewable energy.

Straw as a fuel

Straw normally contains 14-20% water, which vaporizes during combustion. The dry matter consists of about 50% carbon, 6% hydrogen, 42% oxygen as well as small amounts of nitrogen, sulphur, silicon, alkali, chloride and more.

When straw is used as fuel, the water content must not exceed 20%. If the water content is higher, there is a risk that the bales of straw become too hard and compact. Similarly, a high water content increases the risk of condensation and corrosion.

The presence of chlorine and alkali in the flue gas can be a problem at combustion, leading to the development of sodium chloride and potassium chloride, which are highly aggressive and cause corrosion in boilers and pipes – particularly at high temperatures. The aim is to use straw with a low content of harmful matter, and here the weather plays a significant role. Straw, which has been exposed to a lot of rain after maturing - especially after harvest, and has turned grey ("weathered"), is far less aggressive than yellow straw, which only has been exposed to a limited amount of rain.

The ash content can vary between 2-10%, the average being 4-5%. Straw from crops that have been cultivated on sandy soil normally has the lowest content of ash, while straw from lowland soils usually has the highest ash content. The heating value is highest with the lowest ash content, so it can be an advantage to use straw from sandy soil for heating purposes.

PHOTO *Adam Weller*

Grey straw is far less corrosive in the boiler than yellow straw.

The ash from straw burning can already become viscid at 600 degrees, and this is important for the power plants, where a high steam temperature is envisaged in order to obtain high electricity efficiency. New boiler types and better steel alloys have reduced the problem over time, but power plants still consider straw a more troublesome fuel than wood.

Straw resources

There is some doubt about current and future availability of straw for energy production. Agriculture not only delivers raw material to the energy sector, but also has to produce food and feed and show consideration for nature protection, biodiversity, nutrient leaching, and the soil's carbon pool. If the farmer chooses to plough the straw into the soil, then this will increase the soil's carbon content, which has an impact on the climate records as mentioned on the previous page.

Over the years, a number of analyses have been completed concerning the available straw resources in Denmark as well as abroad. Even though there can be great differences in the individual studies, there is general agreement that resources are far greater than current consumption.

However, handling and transport of straw can be very expensive, so even though resources are plentiful, there may not be an economic

	Yellow straw	Grey straw	Wood chips	Hard coal
Water content	10-20%	10-20%	40-50%	12%
Ash	4%	3%	1%	12%
Carbon	42%	43%	50%	59%
Hydrogen	5%	5%	6%	4%
Oxygen	37%	38%	38%	7%
Chloride	0.75%	0.20%	0.02%	0.08%
Nitrogen	0.35%	0.41%	0.30%	1.00%
Sulphur	0.16%	0.13%	0.05%	0.80%
Heating value	14.4 MJ/kg	15.0 MJ/kg	10.4 MJ/kg	25.0 MJ/kg

TABLE 1
Parameters of importance for the fuel value of straw, wood chips and hard coal. Yellow straw is collected immediately after it has been harvested, while grey straw has been subjected to rain before collection.

incentive to utilize the straw. While energy wood today has become an international commodity, straw is mainly still traded locally. In principle, nothing prevents straw pellets from being sold across borders, but this does not really occur.

In Denmark, there was a total straw production of approx. 5.5 million tonnes per year between 2013-2019 on average, of which 3.4 million ton was used in agriculture and for energy purposes. As a result, there is an annual straw surplus of about 2.1 million tonnes. However, 2018 stands out with a production of only approx. 4 million tonnes due to a severe drought that year, showing that climate change, not surprisingly, can influence supply security.

The question, however, is how accurately the straw surplus is estimated, and how much the surplus can vary from one year to another. The more straw that is needed for energy production, the more important it becomes that the predictions prove correct to secure the supply.

The consumption of straw for feed and bedding can vary a great deal from year to year, but over a longer period of time there are no large variations. An increased tendency for straw to remain in the fields can reduce the supply of straw for energy purposes – especially if initiatives for further ploughing down of straw happen at the political level.

The area given to cereals has proven to be relatively constant, although there can be significant variations in the yield from year to year. Annual variations are one of the largest sources of insecurity in supply of straw apart from unforeseen weather occurrences.

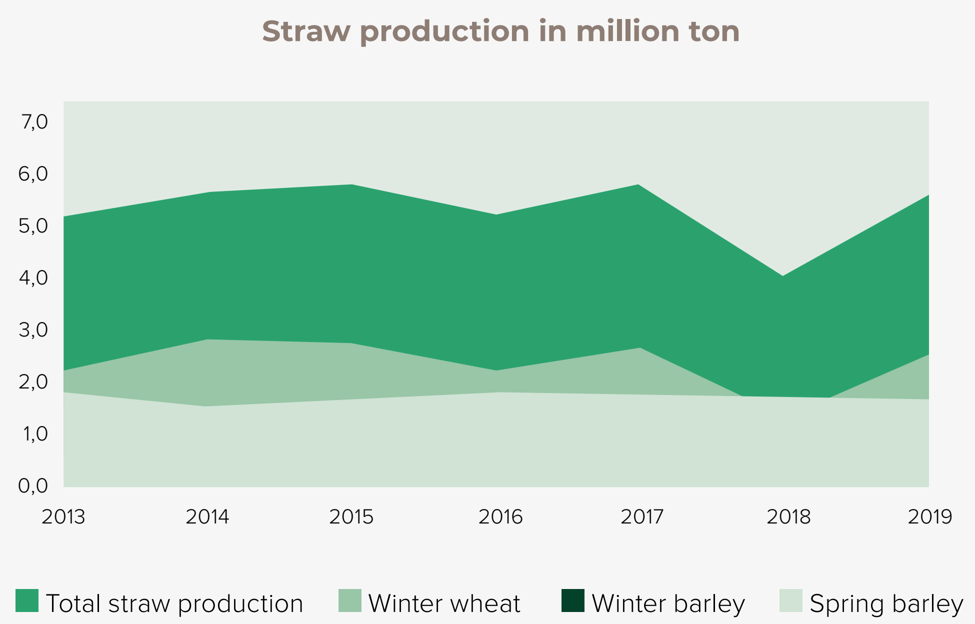


FIGURE 1
The total Danish straw production in total and for selected crops. Even a small change in the proportions between grains results in a significant variation in straw production. Each time the amount of wheat straw is changed by 1 kg per 100 kg grain, total wheat straw production in Denmark changes by 47,000 tonnes. Source: Statistics Denmark.

PHOTO *Jørgen Hinge/Danish Technological Institute.*

Europe

On the European level, Helin et. al. have estimated the annual quantity of removable straw at 33,4 million tonnes (DM), with France and Germany having by far the largest quantities. In table 2, Ukraine and the Balkan countries are also included. However, this seems to be a rather conservative estimation, exemplified by the fact that the annual Danish surplus in a "normal year" is 2,1 mill. tonnes as compared to 1,4 mill tonnes estimated by Helin et al.

Country	Potential of removable straw (1000 tonnes)
France	5474
Ukraine	5774
Germany	5320
Italy	1142
Hungary	1356
Romania	1032
Poland	2252
Spain	1770
UK	2477
Serbia & Montenegro	413
Czech Republic	1480
Denmark	1409
Bulgaria	641
Austria	331
Greece	303
Slovakia	496
Sweden	478
Croatia	101
Lithuania	452
Finland	402
Belgium	83
Bosnia & Herzegovina	0
Latvia	157
Portugal	0
Estonia	75
Slovenia	0
Netherlands	0
Albania	0
Luxenburg	5
Cyprus	0
Ireland	0
Malta	0
Total	33423

TABLE 2
Annual quantity of removable straw for EU27, Ukraine and the Balkan Countries (Helin et al.).

The relation between straw and grain depends on the variety. If the most straw-rich winter wheat is selected it is possible to increase the total straw amount by 800,000 tonnes per year. **PHOTO** *Jørgen Hinge/Danish Technological Institute.*

Yield depends on type

Field trials with winter wheat in the harvest year 2008 have shown that the relationship between straw and grain mainly depends on the variety. From ten different varieties of winter wheat, there was a range of 35-53 kg straw per 100 kg grain, so the choice of wheat variety can be one of the deciding factors in obtaining a larger surplus of straw. Furthermore, fertilizer trials have shown that the share of straw in winter wheat is reduced as more fertilizer is used, but as the amount of fertilizer is set by official norms, this is not expected to have any great importance in practice.

As the straw yield from winter wheat, as mentioned earlier, can vary between 35 and 53 kg straw per 100 kg grain, it will theoretically be possible to change the total amount of straw by 800.000 tonnes per year. In practice, many varieties of cereal are grown and the figures illustrate the potential for increasing the total amount of grain by choosing types with a high straw yield.

Straw handling

In order to secure large scale straw supply of satisfactory quality at reasonable prices, straw handling must be carried out as efficiently as possible. Straw producers and purchasers are still working on optimizing the different elements of the supply chains, and to organize transport and storage in an efficient way. While most supplies are still in the form of big bales, optimization efforts have for instance resulted in an increased use of so-called midi-big bales, because these allow for more efficient road transport.

The handling of straw has developed into an independent discipline within agriculture, with heavy duty machinery primarily used by large farms and agricultural contractors. Since the 1980's, when the big balers hit the market, agriculture has invested considerable amounts of money in balers, rakes, front loaders, transport equipment, and storage facilities in order to be able to supply straw to the energy sector.

Raking and pressing of straw in the field.
PHOTO *Jørgen Hinge/Danish Technological Institute.*

After harvesting, straw lies in swaths in the field and the following handling elements are applied depending on the weather conditions and other factors:

- Raking
- Baling
- Pellets, briquettes and chaffed straw
- Loading and unloading from trucks and lorries
- Field transport
- Decentral storage
- Loading for road transport
- Road transport
- Unloading at the plant
- Registration of weight and moisture content
- Buffer storage (at the plant)

Raking

If weather conditions are good during harvest, the straw can be baled immediately after the combined harvester has left the swaths in the field. If the straw is too wet (typically average moisture content above 15%), it must be allowed time to dry in the swath before baling. If, in the meantime, there is a rain shower, it may be necessary to apply raking again. Modern rakes are designed to either spread the swath over the entire width of the rake (in order to expose more of the straw to air-drying), or gather/turn around the straw in swaths.

Baling

Today, power plants and district heating plants almost exclusively use big bales or midi-big bales. Small bales are rarely used for energy production anymore (perhaps for very small and old farm heating plants) and round bales are only used for farm plants especially designed for this.

Bale type	Dimensions L x W x H(cm)	Weight kg.	Density (kg/m³)
Small bales	70-90 x 46 x 36	12-15	90-100
Round bales	120 x 170*	220-270	100-120
Mini-big bales	200-240 x 80 x 80	200-250	110-150
Midi-big bales	230-250 x 120 x 90	450-650	160-230
Big bales	230-250 x 120 x 130	450-650	140-170

TABLE 3
*Properties of straw bales. *width x diameter.*

Over the years, there have been many attempts to increase the weight of big bales, and efforts are still ongoing. Equipment along the supply chain must be modified accordingly, and with cranes now able to handle a bale weight of about a ton, the road is paved for heavier bales.

Another way of improving efficiency in straw supply chains is that more and more plants are now able to receive midi-big bales in addition to the "traditional" big bales. The main advantage is reduced costs for road transport, because road trucks can carry three layers of midi-big bales instead of two layers of big bales. Because the midi-big bales can be produced at almost the same weight as big bales, it is possible to transport almost 50% more straw on a truck thereby reducing the costs considerably.

Pellets, briquettes and chaffed straw

Baling of the straw is the most expensive handling element of the straw supply chain. So would it be interesting to produce straw pellets or briquettes instead? Or even to just cut the straw and handle it as such, without baling or pelletizing?

By pelletizing or briquetting the straw, it is possible to make subsequent handling of the straw more efficient and in most cases cheaper. This is because straw pellets/briquettes have a higher density, and therefore road transport will be cheaper. Furthermore, unloading and in-plant transport of pellets can be more effective, because pellets can be blown through pipes, so cranes to unload and handle the bales in and out of the buffer storage at the plant are not needed. However, in order to produce pellets, you would still have to bale the straw and transport it to a pelletizing facility, so the total costs will be higher than for the big bale and midi-big bale supply chains, unless:

- The transport distance is very far, making sea transport of pellets feasible, or
- Equipment for direct pelletizing in the field is further developed, so that initial baling is not necessary (it exists, but is not cost-effective)

In the beginning of the millennium, straw pellets were used in large scale at Amager Power Station in Copenhagen. The pellets were produced just 50 km south of Copenhagen at Køge Bio Pellet Factory and the pellets were shipped to Amager by water, in order to avoid heavy lorry transports with straw bales through Copenhagen, and yet the Amager plant now uses wood pellets instead of straw pellets.

Straw briquette. **PHOTO** *Food & Bio Cluster Denmark.*

Briquetting of straw under high pressure has been shown to have the positive side effect that it increases the digestibility of the straw in biogas plants. This may indeed make it feasible to choose this handling method, if straw is intended for biogas production.

In the early 1990's, experiments were done with cut straw, which was stored in haystacks in the fields in order to reduce the costs of straw handling. The first tests suggested that the price could be reduced by 50%, but there were too many practical problems and the concept was skipped in the mid-1990's.

Unloading two bales of straw at once with a telescope loader reducing the workload. **PHOTO** *Torben Skøtt, BioPress.*

Loading and unloading from trucks and lorries

When loading straw, a front loader, excavator, tractor shovel, telescope loader or a mini loader is used. In principle, there is a not a big difference between the first three types, which are all based on a front installed loading system.

Telescope loaders, on the other hand, have a greater lifting capacity and can reach further so that the bales of straw can be stacked high, which reduces storage costs. Telescope loaders are therefore becoming more and more widespread. The mini-loader is not quite as common, but is very flexible and can be used in tight locations.

As evident in figure 2, the work load is biggest when loading with a front loader and smallest when using a tractor shovel and telescope loader, as they are always able to load two bales at a time. Converted into tonnes, it appears that there is a difference of 2.5 minutes per ton between loading with a tractor shovel and loading with a front loader. While this may not sound much, when loading one million tonnes, which is the annual delivery made to power plants, it results in an extra work effort of about 41,000 hours. Larger plants usually unload with a portable crane; more on this in a later section.

Field transport

Field transport is carried out with tractor and wagon. This is used for transport to field storage or other decentral storage (for instance at the farm), and also sometimes for road transport to the plant if the distance is rather short, typically less than 10 km. If the plant has the capacity to receive a given amount for its buffer storage, some bales can be loaded directly on a lorry/trailer for road transport directly to the plant.

Decentral storage

In general, the plants only have buffer storage capacity for a few days, so the vast majority of the annual consumption of straw has to be stored in decentral storage facilities. There are different methods; some rather cheap and others quite expensive. However, the price per tonne stored reflects quite closely the quality of the straw taken out from a given storage – or there may be a large number of throwaway bales from cheap storages.

Storage under roof in barns with walls and concrete floor provides straw of high quality, but is also the most expensive type of storage, at least, if new facilities must be established for the purpose. However, if old buildings can be used, this may be the optimum solution for supply of high quality straw bales. Barns without walls are also widely used because exposure of the side of the bales to normal weather conditions will usually not affect the quality significantly.

Wrapping of the straw in long wrapped stacks is becoming more and more common. It is cheaper than establishing permanent facilities (a new barn) and also more flexible. You can have a wrapped stack in the field where the straw was produced (less field transport) and close to a main road, making loading for road transport easier; and if the bales are delivered during the months after harvest, the field can be ready for the next crop in due time. One of the main reasons for the increased use of wrap-storage, however, is the development of more efficient equipment over the last decade(s). Where the first wrapping machines stacked two big bales on top of each other, equipment for stacks with up to 12 bales in transection is now standard. According to experienced users, there are few things to be aware of regarding wrap-storages. If you establish the storage in the lower part of the field, there is the considerable risk that moisture will penetrate the wrapping from below, so it should be established in the more elevated part of the field. Furthermore, sometimes the moisture content of the straw may cause condensing on the plastic, resulting in the upper bales becoming more moist.

Open storage is still used by some straw suppliers. Some cover the stacks with plastic and keep the cover in place by having a layer of bales on top of the plastic, others just leave the stack completely open and exposed to the weather conditions. This is obviously the cheapest way of storing large quantities of straw. However, if choosing this option it must be taken into consideration that a number of bales cannot be traded to heating or CHP plants because the quality is too poor after storage. The top layer is most likely ruined, and often also the bottom layer because it has absorbed moisture from the soil. If those bales could be used for biogas production instead, it might still be a feasible solution. If not, it may prove quite costly to get rid of the wasted bales in terms of the effort it takes to split up the bales, spread the straw and incorporate it into the soil.

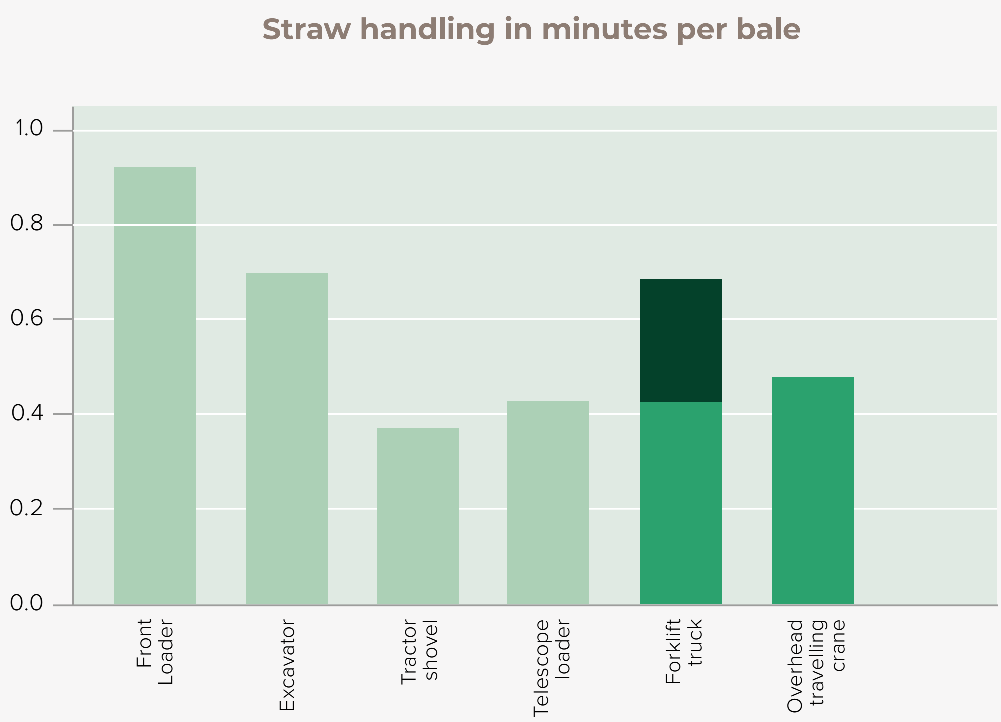


FIGURE 2

Time consumption for loading and unloading straw. When unloading with a forklift, extra time is spent on weighing and analyzing the water content of the straw. Additionally, time must be spent on moving the bales if the stockroom is to be completely filled (Source: Centre for Biomass Technology).

The plants only have buffer storage capacity for a few days, so the vast majority of the annual consumption of straw has to be stored in decentral storage facilities.

PHOTO *Food & Bio Cluster Denmark.*

Road transport

Road transport is usually carried out with lorry/trailer. If the distance to the plant is short, typically less than 10 km, road transport can be done with tractor and wagon. Often, the receiving facilities at the plant requires the bales to be loaded in a specific way for transport – typically in layers of 6 (2 x 3) on the lorry and/or trailer. Some plants also require that the bales are covered with a net during transport in order to prevent straw from being blown off the bales by the wind.

Unloading at the plant

While many smaller district heating plants still use front loaders for unloading of the straw bales, the larger plants have established automatic unloading by crane, which lifts an entire layer of bales from the lorry and trailer and place it in the buffer storage at the plant. The same crane is used to lift the bales from the buffer storage onto the conveyor belt(s) transporting the straw to the shredders and feeding it in to the boiler facilities.

Many of these cranes are equipped with technology for automatic registration of weight and moisture of the bales, effectively reducing the time needed to unload and register a lorry-full of straw. The moisture content is measured by means of microwaves. If a front loader is used for unloading, weighing of the load typically happens on a weighbridge, while moisture content of the bales is registered manually with a moisture meter, where a probe is inserted in the straw bales.

Health and safety aspects

Working in the agricultural sector in general involves some risks, and straw handling is no exception. Apart from dealing with heavy machinery, the straw bales themselves are heavy and must be handled with caution. For instance, when establishing stacks of straw bales – whether in barns or in the open – it is important to arrange them in layers to minimize the risk of stacks collapsing.

Furthermore, careful measures must be taken to avoid fires – especially in storages with large quantities. In Denmark there are quite strict regulations regarding a) the amounts of straw stored in one storage, b) dimensions of the stack, c) distances from the storage to buildings and d) public roads. The main reason is that if a stack of straw catches fire, it has proven virtually impossible to put out the fire, so all you can do is control the fire until it burns out. The legal measures are meant to:

- **a)** Limit the amount of assets, which can go up in smoke in one fire
- **b)** Making sure that the fire can be contained and controlled
- **c)** Making sure that it does not spread to buildings or other storages
- **d)** Prevent dangerous situations on roads caused by smoke from a fire

Straw handling may also result in a lot of dust – and even fungal spores - if the straw has been wet, so there may be health issues if one is working continuously in closed environments. A dust mask should be applied when working regularly with straw.

The moisture content in the straw is controlled before the unloading takes place. If the water content is above 25% it is normally rejected. **PHOTO** *Torben Skøtt, BioPress.*

Wrapping allows for decentralised outdoor storage without damaging the quality of the straw.

PHOTO *Food & Bio Cluster Denmark.*

Sustainability aspects of straw firing

Removal of the straw for energy production can be sustainable provided proper measures are implemented.

As mentioned in a previous section, continuous removal of straw from the field for combustion year after year may result in depletion of the soil carbon content, compared to fields where the straw is continually incorporated into the soil, either directly or after being used in animal production for bedding material. Many years of research have shown that this is not necessarily a big problem and by applying ash from combustion, many nutrients and minerals can be recirculated.

Effects of straw removal

At Danish research stations Askov, St. Jyndevad and Rønhave, trials have been done where, for decades, straw has been removed from plots in order to compare the carbon content of those plots with plots where the straw was incorporated in the soil in the same period. The results show that soil carbon content in the upper 20 centimeters is significantly higher when straw has been incorporated for 36 years (Rønhave) and 29 years (Askov and St. Jyndevad), respectively.

It is clear that there is a significant effect of continuous straw removal on soil quality, but it is debated among Danish farmers and agronomists, which effects it may have on yield potential for the areas in question. In the short term, yield is not affected as long as nutrients are applied through animal manure/slurry and/or mineral fertilizer. Many tend to believe that the biggest challenge is a greater risk of erosion and other structural damages caused by a lower humus content in the soil.

In any case, it has been shown that the carbon effect of straw removal can be compensated by using cover crops after harvest, which are then incorporated into the soil.

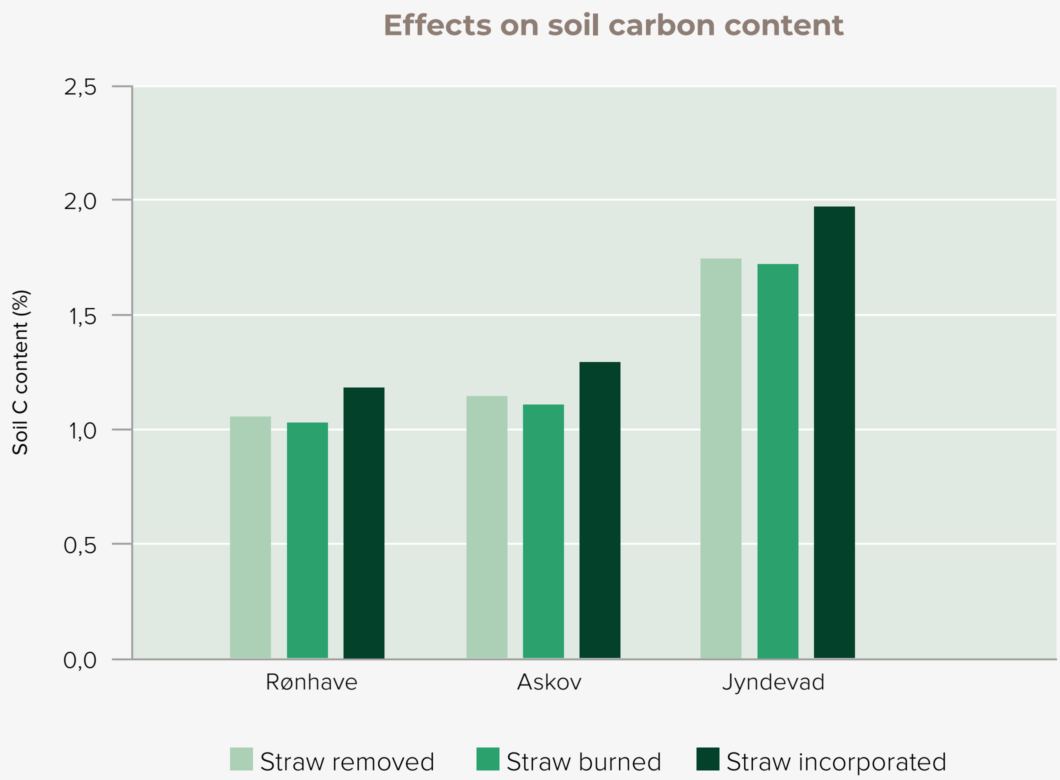


FIGURE 3
Effects on carbon content in the upper 20 centimeters when either removing, burning or incorporating the straw back in the soil.

Heavy metal	Threshold (mg per kg dry matter)
Mercury	0.8
Lead	120
Nickel	60
Chrome	100
Cadmium	5

TABLE 4
Heavy metal thresholds.

Application of ash from straw combustion

Ash from combustion of straw contains several valuable nutrients –phosphorous and potassium in particular – and it is therefore recommendable to recirculate the ash to agricultural soil. However, there are also some challenging substances – mainly heavy metals – in the ash, so it is important to regulate the amount of ashes recirculated to a given area.

In Denmark, the application of ash from combustion of biomass – including straw – is regulated through "Bioaskebekendtgørelsen" (Executive Order on the Use of Bio-ash for Agricultural Purposes), the main focus of which is to control the amounts of heavy metals applied to the field. In table 4 the threshold values for heavy metals in the ash are listed.

Apart from the heavy metal threshold values, the order also states that a maximum of 0.8 g cadmium per hectare may be applied annually (as an average over five years) and that a total of maximum five tonnes of ash (DM) may be applied per hectare over a five year period.

Ash from combustion of straw contains several valuable nutrients.

PHOTO *Adam Weller.*

Biochar. **PHOTO** *Food & Bio Cluster Denmark.*

Application of biochar and biofertilizer

Compared to ash from combustion, biochar from gasification/pyrolysis of straw or other types of biomass still contains a certain amount of carbon as well as nutrients. Therefore, from an agricultural point of view, biochar from gasification plants represents a superior fertilizer compared to ashes; however, as described in later, gasification of straw is a challenging process, and large-scale gasification plants for straw are rare or non-existing.

Superior to biochar is biofertilizer from anaerobic digestion in biogas plants, which still contains quite a lot of carbon. When straw is digested in a biogas plant, typically between 40-60 % of the organic material is converted to methane and carbon dioxide, so about the same amount of carbon is recirculated back to the soil with the biofertilizer. This of course reflects the fact that the energy yield from combustion of straw is substantially higher than from anaerobic digestion.

Another feature of biofertilizer from biogas plants is, that basically all nutrients from the substrates fed into the biogas plant are still in the biofertilizer after digestion. During combustion, some nutrients are lost with the flue gas, especially nitrogen, and others, such as phosphorous, may be immobilized in the ashes from combustion at high temperatures. So even though straw does not contain a lot of nitrogen, biofertilizer from anaerobic digestion can still be considered a much better fertilizer than ash from combustion.

Small-scale straw boilers

Individual straw-fired boilers have gone through a rapid development since the first ones appeared on the market in the late 1970's. Efficiency has doubled, while the emission of harmful substances has been reduced significantly. Many Danish farmers have chosen to invest in slightly larger boilers, so that their neighbors can get cheap and environmentally friendly heating through the district heating network.

Following the first energy crisis in 1973, many people started to look for a cheaper and more reliable heat source than oil, and for farmers it was natural to turn their attention to the large quantity of straw, which at the time was just burnt off in the fields. Throughout the 1970's, a number of machinery manufacturers started to produce simple straw-fired boilers, which were designed for small bales.

Later on, straw-fired boilers for round bales and big bales were also produced, and automatic heating plants demanding only minimal attention were developed.

In general, there are two types of straw boilers: manually heated plants, also known as portion plants, and automatically heated plants. The portion plant is the simplest type of plant, where whole bales of straw are fed in the boiler manually (see figure 4). In the case of a plant for small bales, this is usually done by hand, while a front loader is typically used if it is a plant for round bales or big bales.

A portion plant boiler is relatively cheap and operating costs are minimal. However, a great deal of time must be spent on removing ash and supplying new fuel.

A portion plant straw-fired boiler with a storage tank

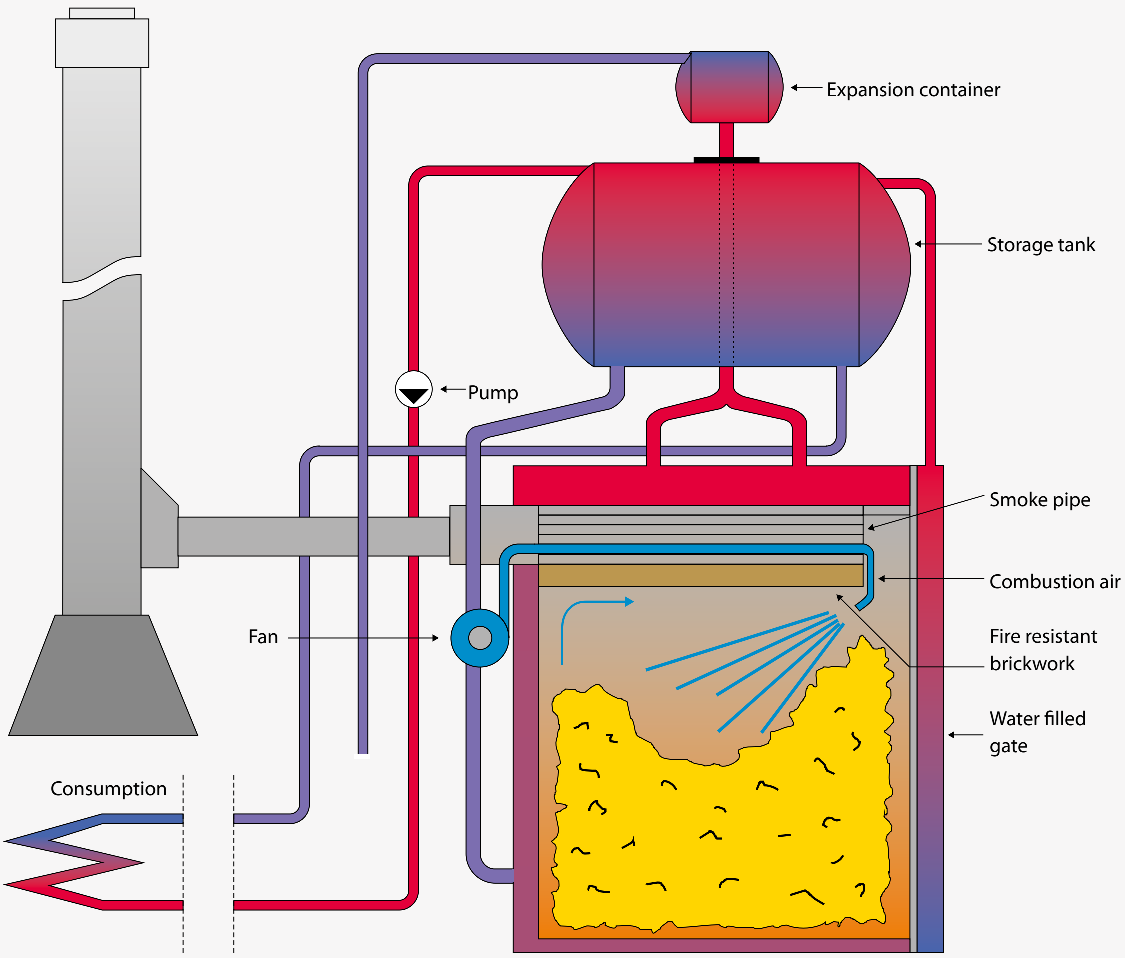


FIGURE 4
A portion plant straw fired boiler with a storage tank.

Portion plant for big bales. **PHOTO** *Torben Skøtt, BioPress.*

Manual or automatic?

Automatic heating plants consist of a straw boiler and a supply system, which includes a conveyor – a so-called straw lane and a collector, which grinds the straw before it is led into the boiler by means of a screw conveyor or blower.

These plants are generally more expensive than the manually heated plants, and the operating costs are higher, but in return, the need for attention is minimal.

800 kW automatic plant from Linka Energy. **PHOTO** *Linka Energy.*

Portion plants are often installed in a separate building in order to reduce fire risks. **PHOTO** *Torben Skøtt, BioPress.*

Efficiency and the environment

The efficiency of the first straw boilers was often as low as 30- 40%, resulting in poor combustion and pollution from the smokestack. However, in 1976, the Danish Agricultural Research Institute began testing straw boilers and helping the manufacturers with product development. Furthermore, in order to speed up development, the Danish Energy Agency implemented a subsidy scheme in 1995, where the size of the subsidy depended on how effective the boiler was. This led to significant improvements of the straw boilers, and the efficiency increased from the original 30-40% to over 80% (see figure 5).

Meanwhile, as boilers became more efficient carbon monoxide emissions dropped significantly. Carbon monoxide is not harmful for the surroundings in small doses per se, but indicate how much the boilers pollute in general. If there is a lot of carbon monoxide in the smoke, there will also be a number of other harmful substances emitted. Examples include soot and tar, the latter consisting of various organic acids and the so-called PAH's, which are carcinogenic.

The presence of these substances is evidence of an incomplete combustion, and the most sensible way to remove these is to improve the combustion, so that the substances are burned off while at the same time the fuel is better utilized. This is possible by ensuring a high temperature in the combustion chamber. Straw and other types of biomass create gasses, which do not ignite until the temperature has reached around 800-900 degrees. If the temperature falls too low, the gasses will not be combusted before they are emitted through the smokestack, which leads to a bad heating economy and unnecessary emissions.

Older straw boilers typically consist of a water-cooled chamber, with the smokestack at one end, while the combustion air is injected into the opposite end. Based on this simple design, there will be a tendency for the smoke to be emitted through the smokestack without being combusted. Fortunately, this can be remedied and many the new boilers are designed, so the gasses are forced to pass in front of the air nozzles, which ensures a far greater probability of ignition and conversion into heat, instead of pollution of the surroundings.

If the temperature in the combustion chamber is too low, the results are a bad heating economy and unnecessary emissions.

Energy efficiency of straw boilers in per cent

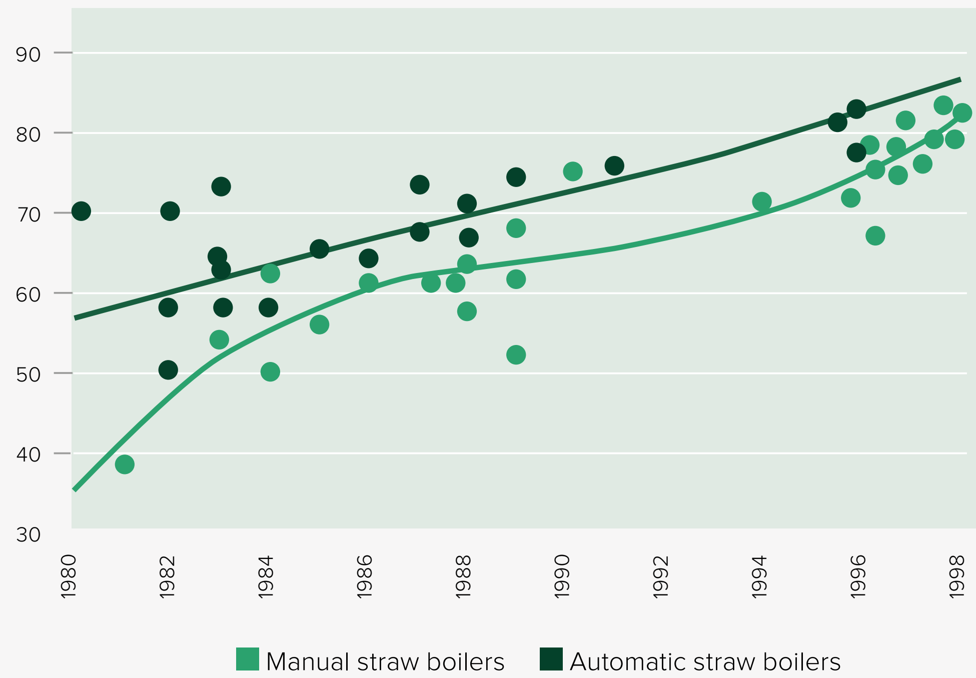


FIGURE 5

Efficiency for manual and automatic fired straw boilers in the period 1980-1998, where regular tests were conducted by Danish Agricultural Research Centre, Bygholm. Source: Danish Agricultural Research Centre.

Boiler size

Many people are tempted to buy a straw boiler that is larger than needed. This is not a good idea, however, and often leads to a poor heating economy and bad environmental impact. The right choice is a boiler, which is slightly too small to cover the heating needs on the very coldest days. A straw boiler is most efficient with a full load, and therefore, the larger the boiler is, the greater the risk that it will operate with partial loads for most of the year.

The optimal boiler size will typically be about 75% of the need on the coldest day. In the few periods of the year, where the straw boiler cannot cover the consumption, an oil-fired boiler or electric heating can supplement it.

Storage tank

Manually fired plants should always be equipped with a storage tank, so that the heat does not necessarily have to be used at the same speed as it is produced. Especially in summer, where heat consumption is low, a storage tank can help to secure good combustion. The storage tank is often a separate tank placed on top of the boiler, but it can also be a complete unit with a boiler and storage tank. The tank normally ought to contain 60-80 liters of water for each kilo straw the boiler room can contain.

Many of the automatic plants will be able to achieve a better combustion if they are connected to a storage tank. A full day's heating demand can be produced in around 6-8 hours, and can reduce many the start/stops of the boiler, which otherwise would result in poor combustion.

PHOTO *Food & Bio Cluster Denmark.*

PHOTO *Food & Bio Cluster Denmark.*

Neighborhood heating

Today, over 60% of all Danish households are connected to the district heating network, but the market for traditional district heating plants (i.e. larger villages or towns) is more or less fully covered.

It can be difficult for small towns to make a profit with a district heating plant, and a new term has evolved called neighborhood heating. In principle, it can be any household supplying their neighbors with heat, but in practice, it is often farmers, who chose to invest in a larger straw boiler than necessary for their own consumption in order to deliver heat to their neighbors.

Just like farm plants, the straw boiler should be sized to deliver 70-80% of the heating needs on the coldest day. This gives the best heating economy over the course of a full year - both in the winter and during summer when consumption is minimal. During the winter period, an oil-fired boiler can be used as a supplement, and is usually designed, so it can handle the entire consumption in case of a boiler breakdown.

The existing neighborhood heating plants in Denmark vary from a few houses and up to 70-80 homes. The vast majority are established by farmers, who have considerable amounts of straw at their disposal, and are able to deliver cheap heating to their neighbors as a result.

The experiences with neighborhood heating are generally very positive. For the farmers, there will typically be an economic gain, consumers are happy to receive cheap heating, and the fact that you can purchase cheap heating might make the smell from the nearby farm easier to accept.

In order for neighborhood heating to be a success, consider the following:

- The buildings should be as close as in normal urban areas, in order to avoid too much loss from transmission pipes
- Large-scale consumers such as schools, nursing homes or companies make a big difference for the economy of the project
- Consumers should be able to achieve a financial savings by replacing oil-fired boilers with neighborhood heating
- Consumers should be guaranteed cheap and stable heating prices for at least 10 years

District heating

Straw-fired district heating plants can be a cheap and environmentally friendly alternative to other kinds of heating – especially if the plant is placed in an area with a large straw surplus.

Some years ago, there was a tendency of the district heating plants favoring wood chips as fuel, but from an economic perspective there is not much of a difference between the two fuels today.

Straw-fired district heating plants have been built in Denmark since 1980, and today, there are about 55 plants in operation. Several of the plants have been built in close co-operation with local farmers, and in some cases, farmers have been responsible for the construction, as well as the operation of the plant. The effect of the plants varies from around 500 kW up to 12 MW, and the technical designs cover a wide range, although of course there are elements, which are generally used at all plants.

At one point, there were 61 straw heating plants in Denmark, but around the year 2000, several plants chose to replace the straw boilers with wood chip boilers. The main reason was a decrease in wood chip prices, due to a considerable import of wood from the Baltics. Furthermore, several plants had poor experiences with the original contracts with straw suppliers. Many of the first straw plants had chosen to enter into long-term, indexed contracts with farmers, resulting in rather high prices as time went on. Today, straw is mainly traded in an open market via bidding, which has made it more competitive and resulted in the expansion of straw-fired heating plants once again.

The question about whether a straw or a wood chip plant is the most feasible depends to large degree on local circumstances. Straw trade is mainly regional, while wood chips have become an international commodity. If the plant is located in an area with a large straw surplus, it can provide low heating prices and increased revenues to the local farmers. Generally, straw is a cheaper fuel than wood chips in Denmark, although the plant investments are slightly more expensive and the operating costs slightly higher.

PHOTO *Torben Skøtt, BioPress.*

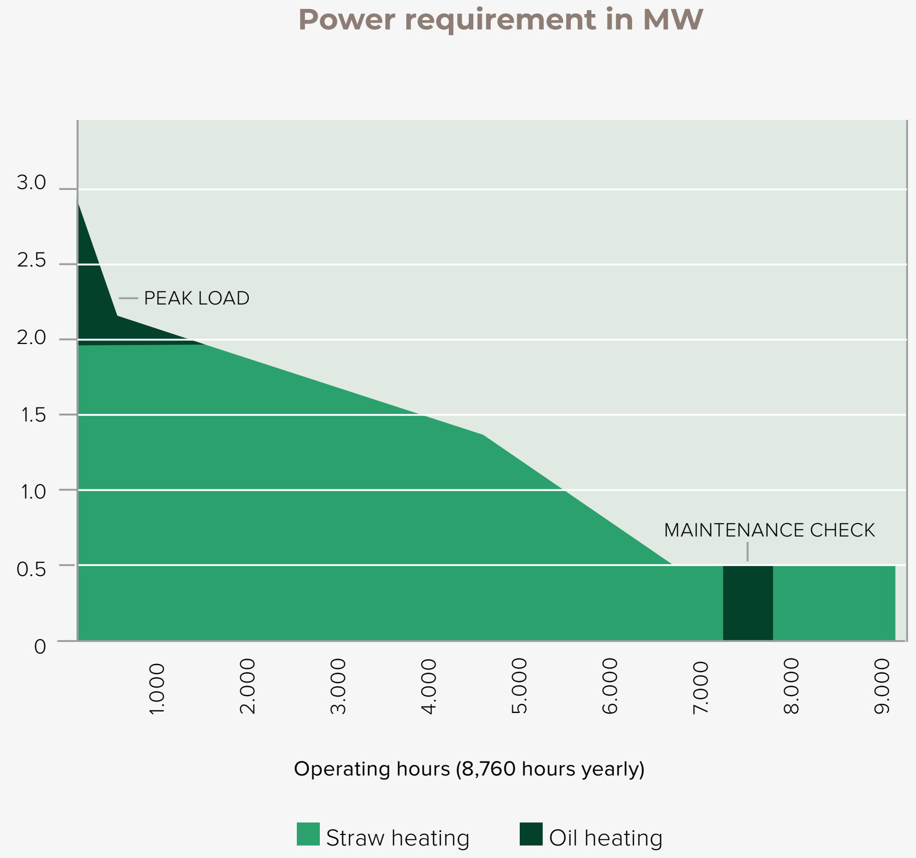


FIGURE 6
The straw boiler should be dimensioned, so it can cover about 70% of the maximum load. When there is a peak load or maintenance check, the heating demand is covered by an oil-fired boiler. The graph shows the distribution of straw and oil for a 3 MW district heating plant with a 2 MW straw boile- Source: Centre for Biomass Technology.

The plant should be dimensioned to cover around 70% of the maximum demand.

As with farm plants, it is appropriate to dimension the plant so that the straw boiler covers around 70% of the maximum consumption demand (see figure 6). Based on this, the boiler will perform at about 25% of the maximum effect in summer, which improves efficiency.

If the straw boiler is too big, the plant will run with partial load for much of the year, which means lower efficiency and negative environmental impact. A heat accumulation tank can be used to even out the variations over the year and in the instances in winter where the straw boiler cannot cover the heating requirements, it can be supplemented by an oil-fired boiler.

Straw handling at the district heating plant

Today, all straw-fired district heating plants use either big bales or midi-bales, which are 30 cm lower than big bales. It is normally the farmer or an agricultural contractor who manages the straw supply to the heating plant, although in some cases, the heating plant manages the transport and storage of the many tonnes of straw themselves. Transport is usually by tractor, if the supplier is located close (<5-10km) to the heating plant and by truck for longer distances.

Unloading at the plant typically takes place with a telescope loader or with a forklift, which normally unloads two bales at a time. Several new forklifts are now equipped with special “grab arms” which grab the bales furthest away. This way a lorry load can be emptied from one side of the lorry.

Payment for the straw happens according to weight and water content. The weighing of the straw load takes place either on a weighbridge or a so-called platform scale. The weighbridge is the fastest one to work with, as it is only done twice, while the platform scale requires that the forklift drives up on the scale with each load. However, a weighbridge is 2-3 times more expensive than a platform scale, so it is a balance between time consumption and investment that determines which solution is the most suitable for each plant.

Before unloading, the water content is measured with a device mounted with a pointed spike, which can be inserted into the individual straw bale. A water content of 14-15% is optimal. If the water content is 18-20%, some plants will reduce the price, and most plants will reject the straw completely if the water content is 25% or higher. Green and wet straw will usually also be rejected.

A straw storage room requires a lot of space, and as a result, most plants only have room for about a week's consumption at full load. There are typically four bales piled on top of each other in marked areas, so the crane can automatically place the bales on a conveyor belt – a so-called straw lane, from where the bales are transported to a shredder or directly into the boiler. A few smaller plants do not have a crane, and bales must be placed manually on the straw lane.

Design of the boiler

A straw boiler is, obviously, designed for straw, but the majority of the plants will also be able to handle other kinds of biomass, as long as it is a dry fuel. Several plants have positive experiences with supplementing with grain husks, cherry stones, and dry and clean wood waste.

Straw boilers can have different designs, but generally, plants are equipped with a vibration grate at the bottom, where the combustion takes place. The grate is divided into several combustion zones and can be moved backwards and forwards, so the burning straw is transported towards the ash removal point. The combustion can be directed towards each zone by providing it with more or less air.

Most of straw's energy content consists of volatile gasses, which are burnt in the boiler chamber above the grate. Design of the boiler chamber and control of ventilation are crucial to ensure correct combustion of the different gasses, some of which will not ignite until there is a temperature of around 800-900 degrees Celsius. Unburned gasses exit via the smokestack, which gives poor energy efficiency and unnecessary pollution.

After the boiler chamber, the flue gasses are led through the convector, where the heat is transferred to the water, typically via a row of vertical water filled pipes. Most plants are equipped with a so-called economizer – a kind of heat exchanger capable of drawing the last heat out of the smoke before it is led through the smokestack.

Whole bales or shredded straw?

The great majority of straw-heated district heating plants use shredded straw, but there are also some that use "sliced straw bales" and a few plants where the bales are thrown directly into the boiler – also called cigar firing. The latter system had its golden age up through the 1980's, but is rapidly on the decrease as it struggles to meet current environmental standards.

The system with sliced straw consists of a feeding box, which tips the bale of straw vertically. When there is a need for new fuel, a hydraulic knife cuts a slice of the bale of straw, which is subsequently pushed into the boiler. It is a relative simple principle and can be considered as a cross between cigar heating and heating with shredded straw.

For shredded straw, a shredder is simply placed between the straw lane and the boiler. Shredders can have different designs, but in principle it is all about returning the straw to the same condition as it was before it was pressed. Over the years, many tests have been carried out to see whether it is possible to cut out the baling and shredding process and transport the straw directly from the field to the heating plant instead. It seems like an obvious solution, but the practical problems with storing and handling loose straw have been so large, that this system has been given up.

Boilers with shredded straw generally have high efficiency and low emissions.

Boilers with shredded straw generally have high efficiency and low emissions. When the straw is shredded, it is easier to control the inflow of fuel and air than when it is thrown in as whole bales. Investments and operational costs are a bit higher than for whole bale boilers, but this is normally compensated for by higher efficiency. Plants with shredded straw should always be equipped with a safety lock between the shredder and boiler in order to prevent a fire from spreading to the straw outside the boiler.

Environmental considerations

The environmental impact from straw-fired district heating plants attracts the attention of local authorities, as well as the local population who has considerable interest in a problem-free plant. All straw-fired district heating plants in Denmark are equipped with a filter bag or ESP filter, which

Straw bales are placed in the buffer storage with a forklift truck. The bales must be unloaded and placed within the area marked yellow, so that the crane automatically can collect the bales from the storage.
PHOTO *Torben Skøtt, BioPress.*

Straw stockroom at Terndrup district heating plant. The transport from the stockroom to the boiler takes place with an automatically controlled crane. The stockroom can contain straw for about one week's operation during winter. **PHOTO** *Torben Skøtt, BioPress.*

reduces the amount of fly ash so particles do not spread to the surrounding community.

The content of CO (carbon monoxide) in the smoke is a measure of how effective the combustion is. A high content of CO shows a low efficiency. The smoke smells and it will presumably contain PAHs (Polycyclic Aromatic Hydro Carbons) which are carcinogenic. It is relatively simple to measure the content of carbon monoxide and public authorities have high standards for how much carbon monoxide is permitted in the smoke.

Nitrogen Oxides (NOx) in the smoke can travel over long distances and be converted into for example nitric acid, which can lead to damage to forests, lakes, and buildings. In addition, nitrogen compounds from the air can cause over-fertilization of sensitive nature areas, such as moorlands and heaths. Furthermore, nitrogen oxides can reduce the lung function for people with asthma and bronchitis, but here it is especially NO_2 and not so much NO that is the problem. NOx can be removed from the smoke, but the filtering systems are costly, and as a result, rarely installed at district heating plants.

It is also possible to clean the smoke for sulphur dioxide (SO_2), but as is the case with NOx, filtering systems are too expensive for the straw-fired district heating plants to invest in the technology. By cleansing the smoke of sulphur dioxide, it is possible to avoid paying a sulphur tax to the state, but it requires investments in both desulphurization plants and measuring equipment, which can prove that emissions remain under the maximum permissible values.

Several plants have conducted experiments with installing technology for flue gas condensation in order to achieve better efficiency, but in most places these have been given up after a few years of operation. In Høng, north of Slagelse, a completely new plant for flue gas condensation was installed, which can improve the efficiency by about 10% while also removing the sulphur content. If this proves successful, it could become standard in both old and new plants – especially if it is possible to exempt the plants from sulphur tax without having to install expensive and complex measuring equipment.

Straw bale conveyor for automatic loading.
PHOTO *Cormall A/S.*

Denmark is world-leading in combined heat and power production from straw.

PHOTO *Food & Bio Cluster Denmark.*

Straw for centralized combined heat and power plants

Centralized combined heat and power plants (CHP) based on straw is a Danish specialty. Since the 1980's, considerable research funding has been applied for developing technology which makes it possible to use straw in coal-fired plants and establish combined heat and power plants fired by straw or together with other biomass types.

A power plant consists roughly of a boiler, a steam circuit, a turbine and an electric generator. In the boiler, the fuel is transformed into heat, and the energy from this is transferred to a steam circuit and then to the turbine, which is connected to an electric generator. When the steam has passed the turbine, it is condensed into water by means of cooling water from the sea, after which it returns to the boiler.

In a traditional power plant, only 40-45% of the fuel is transformed into electricity. The rest of the energy disappears up through the smokestack and along with the cooling water into the sea. A combined heat and power plant produces electricity in the same way as a standard power plant, but instead of cooling the steam from the turbine with seawater, return water from a district heating network is used and thereby being reheated. By producing both electricity and heat, 85-90% of the fuel can be harnessed for energy purposes, and as no seawater is required, the plants can be placed in any city with a sufficiently high heat demand.

In Denmark, combined electricity and heat production has high priority. Previously, it was normal to have very large plants placed close to the big cities such as Copenhagen, Aarhus, and Odense. However, in 1986 the parliament entered into a political energy agreement, which included the construction of new decentralized combined heat and power plants for biomass, municipal waste, and natural gas. This led to the construction of the world's first straw-fired combined heat and power plant in Haslev in 1989.

Since then another ten straw-fired plants have been constructed. In Aarhus, a new straw-fired plant was built in Lisbjerg in 2017, which helped the municipality to phase out coal completely. The 110 MW plant is designed for 100% straw, but can co-incinerate up to approx. 50% of the heat input as wood chips.

In 1993, the parliament agreed on the so-called Biomass Action Plan, which required that central power plants utilized 1.4 million tonnes of biomass per year, of which at least 1 million tonnes should be straw. The experiences from other countries were very limited at this time and encompassed only the use of wood as fuel. Basically, straw for energy production was an unknown concept within the heating sector, and it was necessary to instigate an ambitious development and demonstration program. The program did solve many of the teething problems, which affected the first plants up through the 1990's, and today, Denmark is one of the leading countries when it comes to effective use of straw for electricity production.

Research and development efforts within combined heat and power plants for straw have been particularly focused on grate firing, dust firing, circulating fluid bed systems, and flux firing where straw and coal are burnt in the same boiler.

Straw handling at the plant

Combined heat and power plants handle far greater amounts of straw than district heating plants. A plant like the Funen plant, for example, takes 150-170,000 tonnes of straw per year, equivalent to more than 300,000 big bales.

In order to handle the large quantities of straw, most plants are equipped with automatic cranes that can lift twelve bales at a time. That way it only takes two lifts to empty a lorry and trailer. Because the crane registers both weight and water content at the same time, there are rarely bottlenecks at the straw storage entrance. Registration of the water content takes place by means of microwaves, and a load cell on the crane registers the weight of each lift.

Schematic diagram of a grate firing power plant block at the Funen plant

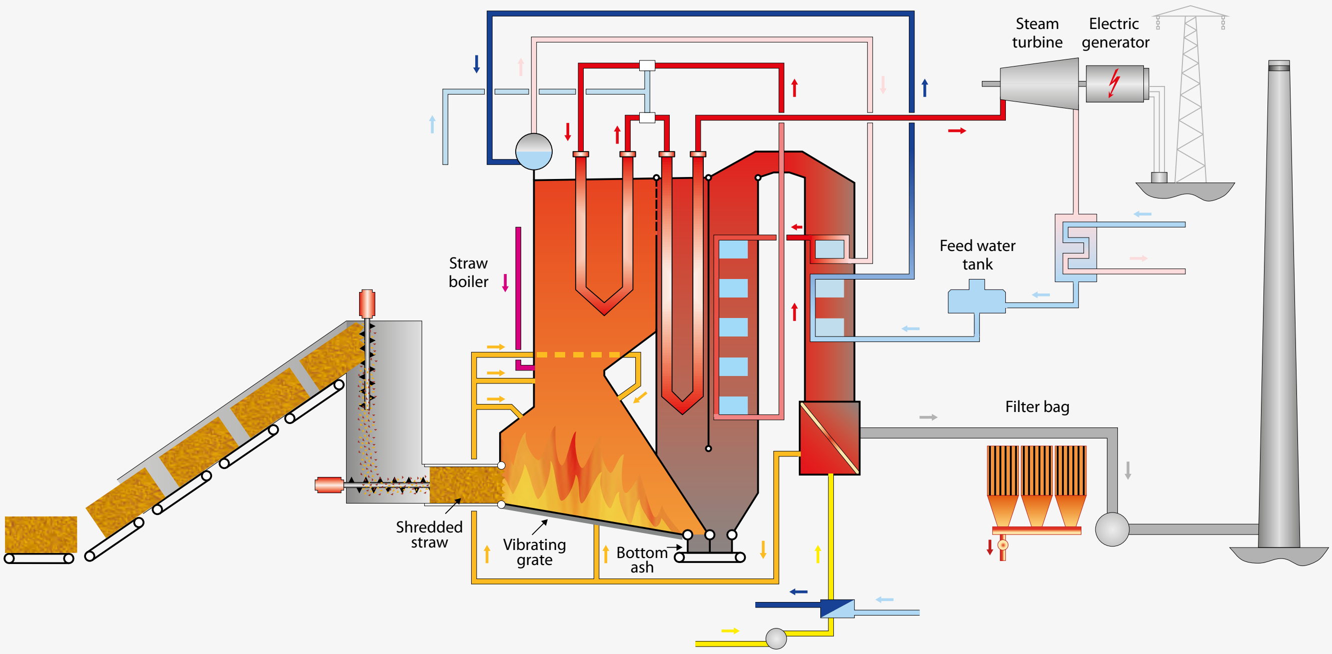


FIGURE 7
Schematic diagram of a grate firing power plant block at the Funen plant.

The bales are loaded from the straw storage on to a conveyor belt by a crane, which then transports them to the shredders. The number of conveyor belts varies between plants, but most plants have four parallel belts in order to be able to handle the large quantities of straw.

Grate firing

Grate firing is the most widespread technology for utilization of straw in Danish combined heat and power plants (see figure 7). As the name suggests, combustion takes place on a grate at the bottom of the boiler chamber. In most cases, it refers to a slanting, water-cooled grate, which vibrates at regular intervals, moving the straw slowly towards the ash removal exit. A smaller proportion of the ash - the fly ash - is led through the boiler plant and is collected in a filter bag, before the smoke is led up through the smokestack.

At the majority of grate-fired plants, the straw bales are fed from the storage room through a shredder, after which the straw is fed on to the grate by means of an auger. In some of the older plants, however, the bales are fed directly into the boiler after the so-called "cigar firing principle". There is no splitting of the straw bales, as the bales simply burn from one end to the other. Some of the straw burns in the chamber above the grate while the rests falls down on the grate where it burns out.

Dust firing

Coal dust fired power plants can be rebuilt to fire with straw pellets instead of coal. This requires other storage facilities and the grinder must be able to crush straw pellets instead of coal, but in principle, the injection of the fuel in the boiler takes place in the same way. The combustion of straw can lead to the same problems with blockage and corrosion of the boiler's super heater pipes, so it may be necessary to lower the steam temperature in order to prolong the boiler's service life.

Circulating fluid bed

In a so-called fluid bed boiler, it is possible to burn straw together with coal. Here the combustion takes place in a bed of floating sandy particles, which allows a lower combustion temperature than when using flux firing and grate firing. As a result, the formation of NOx is reduced, and it is possible to remove sulphur from the flue gas by adding limestone in the boiler.

Fluid bed boilers are flexible in relation to the choice of fuel, but are sensitive towards ash with a low melting point, including for example straw ash. The reason is that melted ash makes the sandy particles stick together so they are no longer floating. As a result, straw can maximum comprise 50% of the total fuel.

Coal ash has a very favorable influence on the corrosive elements in the straw.

As seen with grate-firing combustion plants, there have been many similar challenges with regards to coating and corrosion. Furthermore, there have been problems with mechanical wear on the boiler pipes, but various replacements and reconstructions have solved the biggest problems.

The fluid bed combustion method of using coal and straw together results in a residual product which cannot be reused, and which is the main reason that the technology is used in only one plant in Denmark.

Co-firing

When using the co-firing method, straw is combusted together with coal in a coal dust firing power plant boiler. There is no need to establish a new boiler and turbine plant, and plant investments is therefore very limited in comparison to a grate-fired plant. At the same time, the emission of harmful substances in the atmosphere is limited, as the coal fired power plants are already equipped with effective systems for cleansing the smoke.

Co-firing was developed in the beginning of the 1990's, and was first demonstrated in full scale at the Studstrup Power Station, just outside Aarhus. Here it was proven that co-firing results in a very effective combustion, and the content of fixed carbon in the ash is generally lower than with combustion of coal alone. In the first years, it was problematic to dispose of the fly ash, but that problem is solved. The ash can be used in the production of cement and concrete. However, straw is restricted to 20% of the volume fired, corresponding to around 13% of the fired energy.

During the development of co-firing technology, a lot of attention was directed at the risk of increased corrosion in the boiler, as was the case with grate-fired plants. However, it turns out that coal ash has a very favorable influence on the corrosive elements in the straw. As long as the proportion of straw is not too high, there is no chlorine coating in the boiler and the risk of corrosion is therefore limited.

The Studstrup power station close to Aarhus – the first to co-fire wood pellets with straw in Denmark.
PHOTO *Torben Skøtt, BioPress.*

The combination of straw and coal also has a beneficial effect on the catalytic converters, which reduce the amount of NOx in the flue gas. In grate-fired plants, the catalytic converters are often destroyed by potassium combinations, but when using co-firing, potassium is sealed in coal ash and becomes less harmful.

In recent years, the Studstrup plant has been rebuilt. In 2016, the municipality of Aarhus decided to phase out coal completely and the plant was retrofitted to burn wood pellets. Since then tests done by Ørsted, the plant operator, have shown that it is possible to co-fire with straw and replace 8-10% of the wood pellets, which they started doing in 2019.

Challenges

One of the biggest challenges regarding straw-fired CHP plants has been the design of the so-called super heater pipes in the boiler. In order to ensure high electricity efficiency, the steam must have a sufficiently high temperature and pressure, but as straw ash has a low melting point, there is a great risk that corrosion and coatings appear in the pipes.

In the first plants, it was often necessary to stop the boiler regularly in order to clean the pipes, but in newer straw-fired plants, the distance between the super heater pipes is so large, that there is room for the buildup of a thick coating of straw ash. Combined with the use of soot blowers, this has made it possible to improve the operating time for straw-fired power plants.

Coatings in connection with straw firing can be excessive and the problem increases with higher temperatures, so there are limits for how high the temperature should be to secure a reasonable service life for the plants. In the earliest plants, the steam temperature was about 450 degrees Celsius, but today it has reached 540 degrees Celsius. This has resulted in a noticeable increase in the efficiency, though it is not on the same level as the newest coal fired plants, which operate at steam temperatures of 580-600 degrees Celsius.

Much research has been done in relation to the formation of surface coatings and corrosion when grate firing straw. This includes the amount of potassium chloride, which vaporizes from straw during combustion and is deposited on the super heater pipes. Furthermore, the corrosion mechanisms have been carefully studied. Super heater pipes contain iron, chrome and nickel and it has become evident that at high temperatures the chlorides selectively remove chrome from the steel, thereby weakening the mechanical strength of the pipes. A chrome content of 12-18% has proven to provide the best protection of the pipes. Finally, adding different additives to the combustion in order to reduce the corrosion has been attempted.

This technology has worked well when firing with wood, but in straw firing the quantity of ash is so large that the consumption of additives is too high to be cost-effective.

Recently, the Studstrup plant has been rebuilt to fire with wood pellets and straw.

Other applications for straw

Combustion of straw – small, medium, or large scale – is by far still the most applied use of straw for energy purposes in Denmark.

Several other applications and conversion methods have been developed and tested, such as gasification and bioethanol production. Pilot scale plants have been running for long periods of time, and technologies have even been exported for establishing large-scale commercial plants in other countries, but a mass deployment of the technologies on a commercial scale has still not happened. These, and various other applications and technologies, will be described in the following section.

Gasification

In a circulating fluid bed gasification (CFB), biomass is converted into gas, after which the gas can be combusted in a power plant boiler. In that way, the ash can be kept out of the boiler chamber, which provides the possibility for utilizing a number of different biofuels, without heavy and corrosive coating in the boiler. The system can be used for example for co-firing of straw and waste in existing coal boilers, as the different types of ash are separated and can be reused separately.

Traditional CFB gasifiers require typically temperatures of 850-900 degrees and when biomass from agriculture is used, there is a great risk that the ash melts. Similarly, high concentrations of vaporized ash components can cause problems when the gas is cooled down and is being cleansed. Consequently, in Denmark, the company Danish Fluid Bed Technology has developed a special version of the plant with the less idiomatic name, Low Temperature Circulating Fluid Bed (LT-CFB). Here biomass is converted into gas at a temperature that is just below the melting point of the ash, and this makes the plant suitable for degassing straw.

As in a traditional CFB gasifier the biomass is led into a reaction chamber, where it is quickly heated by means of sand and ash particles that circulate around the system (see figure 8). In the LT-CFB gasifier, the primary reaction chamber is smaller and the temperature is lowered as the intention is to achieve a quick pyrolysis and not the more time-consuming gasification of coke.

As there is no oxygen present, the biomass does not set alight, but is converted to about 80% pyrolysis gas and 20% coke. The coke particles are gasified via inflow of air and potentially water vapor in a separate coke reactor.

How the LT-CFB gasifier converts straw to gas

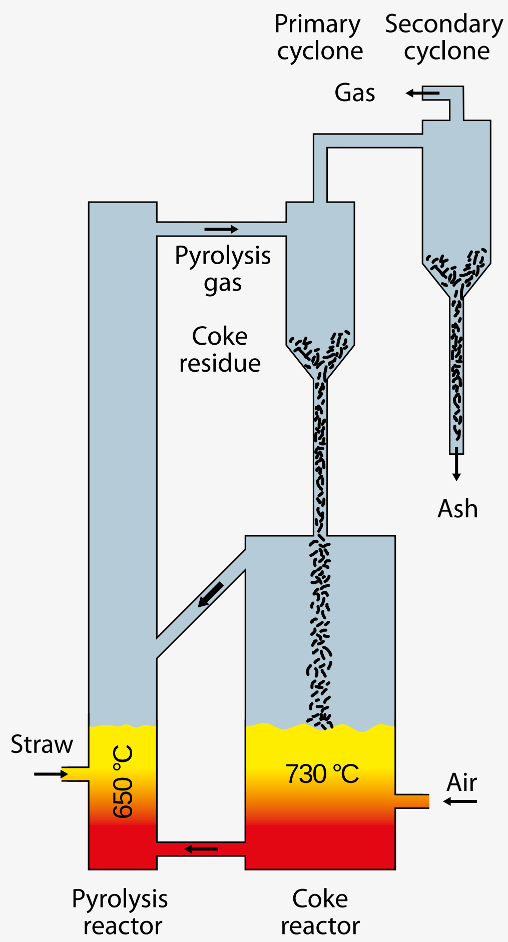


FIGURE 8
This is how the LT-CFB gasifier is able to convert straw to gas. In the LT-CFB gasifier, the straw is added at the bottom of the pyrolysis chamber, where it is heated to about 650 degrees. As there is no oxygen present, the straw does not set alight, but is converted into 80% pyrolysis gas and 20% char. A stream of circulating sand particles tears the char particles along with it, after which they are extracted by a primary cyclone and re-circulated to the bottom of the pyrolysis chamber via a reactor, which converts the coke into gas. By gasifying the coke part in a separate chamber, it is possible to keep the process temperature low, so that the ash does not melt. As a result, the ash, including alkali salts and phosphorus, can be separated, so a gas is obtained that does not cause coatings and corrosion. Subsequently, the nutritious ash can be reused as fertilizer.

Straw gasification is not common practice yet, but some companies offer the technology and are working to achieve a commercial breakthrough.

The Pyroneer gasification plant in Kalundborg.
PHOTO *Torben Skøtt, BioPress.*

The concept was first tested in a small scale experimental plant at the Technical University of Denmark in 2000 and three years later, a 500 kW plant was established, which can gasify up to four tonnes of fuel per day. In 2011, Dong Energy (today called Ørsted) started a 6 MW demonstration plant in Kalundborg under the name Pyroneer, where the gas was being utilized at a nearby power plant. However, in 2014, the plant was shut down, because there was no market for the technology. They could not find a partner to explore the market possibilities, nationally or internationally.

Versalis' €165 million industrial-scale second-generation ethanol plant in the Crescentino, province of Vercelli, Italy.
PHOTO *Food & Bio Cluster Denmark.*

Straw to bioethanol

Production of bioethanol based on grain, maize or sugar cane is a well-known technology. A number of 1st generation bioethanol plants have been established in countries such the U.S. and Brazil, where they deliver large quantities of bioethanol as a petrol substitute.

However, the use of agricultural food and feed products for production of bioethanol has been criticized over the past years. Many people fear that a massive use of bioethanol will lead to drastic increases in food prices and worsen the hunger problems in poor countries, as well as cause indirect land use change, which ultimately results in deforestation and offsets the intended climate benefits. This has led to a considerable development effort towards the so-called 2nd generation technologies, where the production of bioethanol is based on residual non-food products. In Denmark, two concepts were developed and tested in pilot scale from 2006 and 2009, respectively, but both were ultimately shut down indefinitely.

The Inbicon bioethanol concept

In November 2009, DONG Energy's subsidiary INBICON established a plant close to Kalundborg, with the capacity of converting 30,000 tonnes of straw annually into bioethanol, fodder and fuel pellets. It was at the time one of the world's largest plants for production of 2nd generation biofuels.

A major challenge was to develop a technology, which makes it possible to feed the straw into a reactor, which operates at a pressure of 15 bar and a temperature at about 185 degrees C. In the reactor, the straw is pretreated, after which it is broken down into sugar substances by means of enzymes. The remaining process steps is similar to a conventional 1st generation plant, where the central process is yeast cells converting sugar into bioethanol (see figure 9).

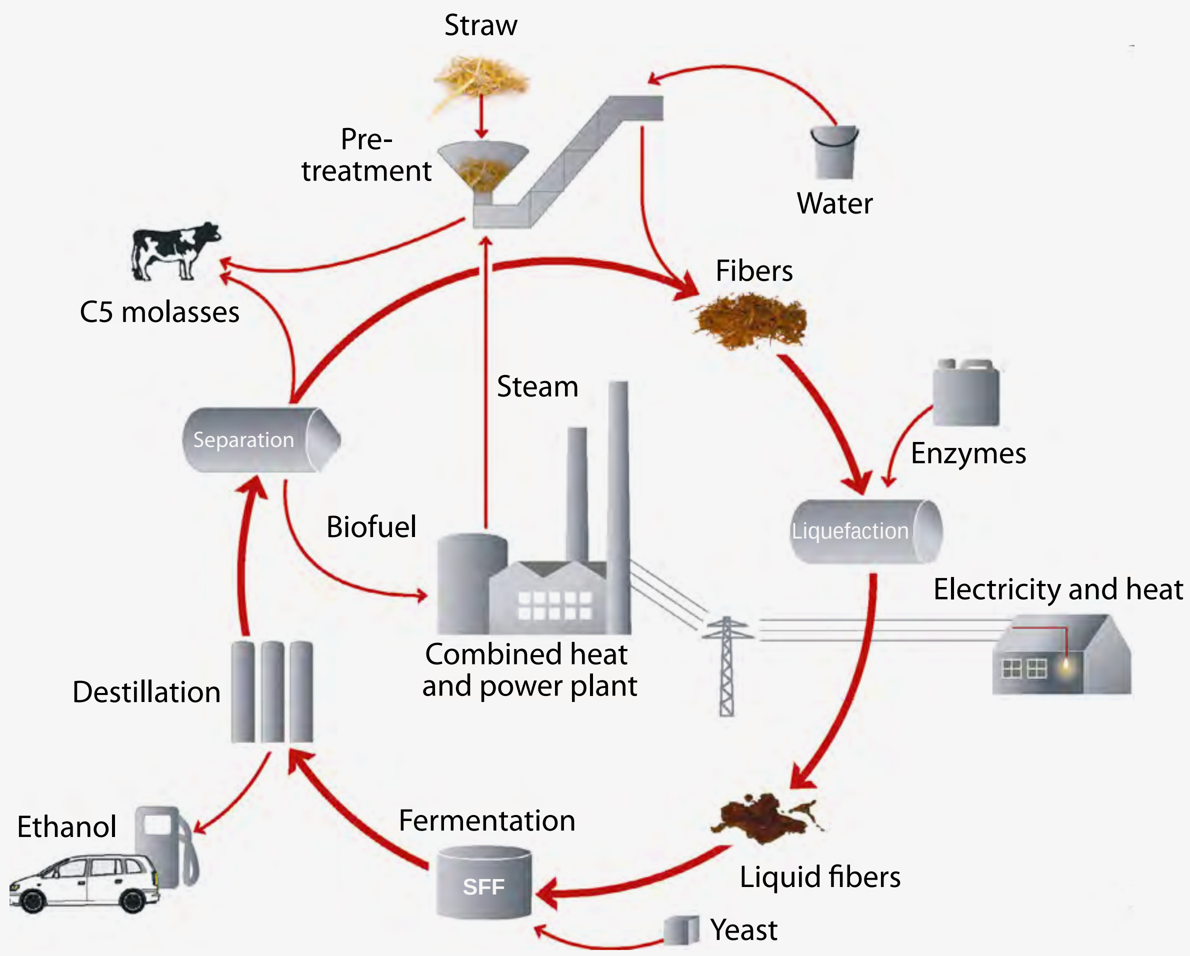


FIGURE 9
Schematic diagram of Inbicon's plant for production of bioethanol from straw. One of the central elements is pretreatment of the straw, which takes place with a pressure of 15 bar and a temperature of about 185 degrees. The plant is built in connection with a power plant, so that the surplus heat can be used for production of ethanol, and the power plant can utilize a part of the biomass from the ethanol plant as fuel.

In 2013, a full-scale production plant based on the technology was established near Crescentino in the Piemonte Region in Italy by the consortium Beta Renewables 2G. The production capacity of the plant was 40.000 tonnes of bioethanol per year. However, the plant was shut down in late 2017. Among other things, difficulties in maintaining a satisfactory straw quality has been cited as one of the challenges. In 2018 Versalis S.p.A. (a subsidiary of compatriot oil, gas, and energy major Eni S.p.A) acquired it after a bankruptcy of the initial owner, and they have invested another €15 million in improving the plant and plan to re-start bioethanol production in 2020.

The INBICON plant in Kalundborg was shut down in 2014. In the spring of 2020 the plant was sold to the company RE Energy, who plans to produce bioethanol there again, although this time not from straw.

The BioGasol bioethanol concept

The Danish development company BioGasol has developed another concept for production of bioethanol, where the by-products - besides solid biofuel - also include gaseous fuels in the form of methane and hydrogen. The principle in this process is illustrated in figure 10.

The first step is a thermal pretreatment of the straw with inflow of oxygen, after which the biomass is broken down by means of enzymes. The fermentation that follows is carried out in two steps, where the first step converts cellulose and the second step converts hemi-cellulose into bioethanol. In the final step of the process, water and remains of biomass are led into a reactor, where methane and hydrogen are produced.

Schematic diagram of BioGasol's ethanol production

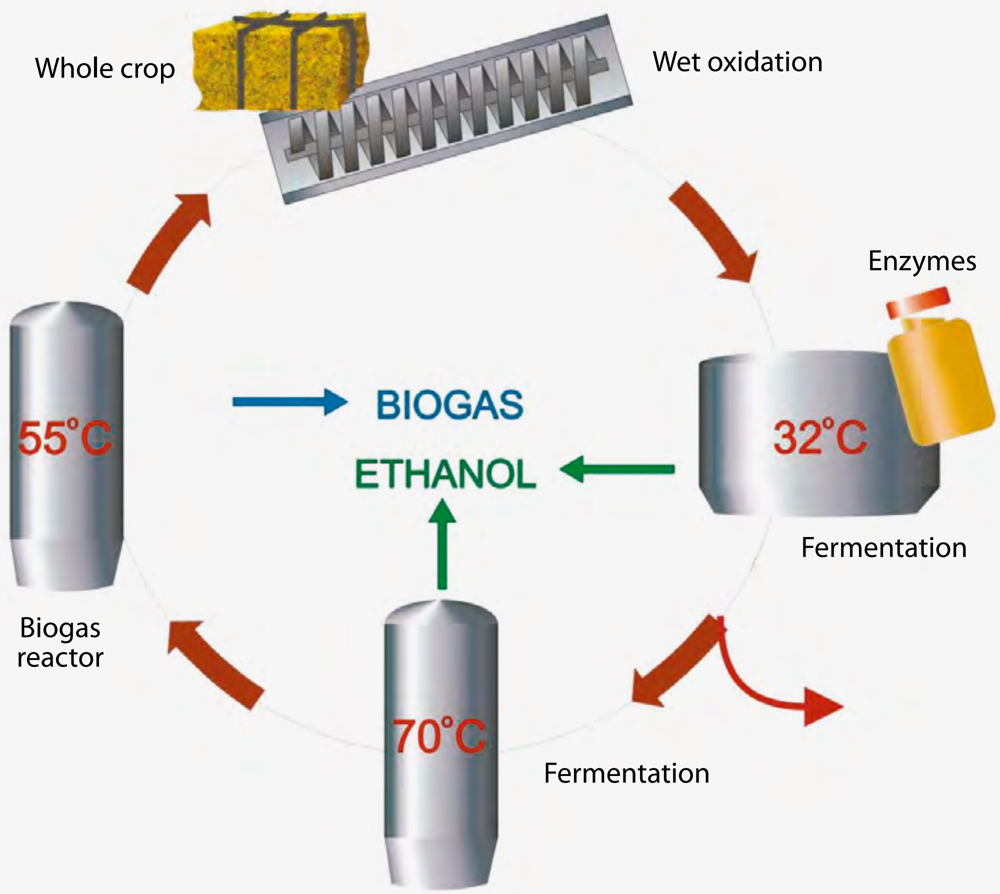


FIGURE 10
Schematic diagram of Biogasol's ethanol production. At Biogasol's pretreatment the biomass is "opened" by the method of pressure cooking in a mild acid or base dissolution. As a result, the sugar chains become accessible for the further treatment with enzymes and/or fermentation. In addition, Biogasol has developed a genetically modified thermophilic micro-organism, which is capable of converting C5 sugar to ethanol, which increases the ethanol yield from straw with 30-40%.

In September 2006, a pilot plant named Maxi-fuel opened at the Technical University of Denmark. The plan was to establish a larger pilot plant on the Danish island of Bornholm, but this plan has not been realized.

In conclusion, the production of 2nd generation bioethanol from straw has not yet proven to be a commercial success in Denmark, even though the technology seems to be well documented. Elsewhere in Europe, developments are underway; Clariant is building the first, flagship plant for its Sunliquid® technology for cellulosic ethanol from straw in Romania (expected to start operation in 2020).

Straw in biogas plants

These days, focus on non-combustion conversion of straw in Denmark is mostly on anaerobic digestion in biogas plants. There is a lot of work being done on optimizing the use of straw in biogas plants as a means of increasing the average dry matter content in the input material and thereby increasing the biogas yield.

The main substrate in Danish biogas plants is manure, and since the late 1980's, organic waste from the agricultural and food industries have been used to boost the gas production and feasibility of the plants. However, with the increase in number (and size) of plants in recent years, sources of supplementary organic waste have dried out, and the plants are looking for other substrates such as energy crops and crop residues. Dedicated energy crops, however, compete with food and feed crops for land, and therefore energy crops such as corn are not considered a long-term sustainable solution in Denmark. Straw, on the other hand, is a by-product from grain production, and there is – as explained earlier - a substantial annual surplus.

When used in a biogas plant, the energy yield from the straw is only about 60% of what is achievable by combustion. However, gas has far more possibilities for application, and nutrients are recirculated

to the farmland, along with part of the carbon, with the bio-fertilizer from the biogas plant.

The digestion of untreated straw in biogas plants under standard conditions is rather slow, and it is not easy to mix untreated straw with liquid manure. This means that either retention time in the digesters must be increased (doubled, compared to normal retention time), or the straw must be pretreated to increase digestibility. While in Germany, the trend has been to build plants with longer retention time, in Denmark focus has mainly been on pretreatment of the straw to increase digestibility.

Mechanical pre-treatment

Quite a few technologies have been developed to “open up” the straw, in order for the bacteria to have easier access to the sugars. In a report prepared for the “Biogas Taskforce” under the Danish Energy Agency, it is mentioned that methane yield from straw can be increased between 10-20% with pretreatment technologies such as hammer mill, briquetting, extruder and X-chopper. When deep litter is added to an X-chopper, the biomass is macerated by rotating chains inside it.

Deep litter, composting and ensiling

Using deep litter from animal productions seems to be an easy and feasible way to utilize straw in biogas plants; the straw is already mixed with manure, and degradation - or ”opening” of the straw - has already commenced before the deep litter is fed into the plant.

In the above-mentioned report, composting the straw before feed-in is also mentioned as having a positive effect on the methane yield. Furthermore, the results indicate that straw of poor quality, i.e. too wet to be combusted or used for feed, may be used with good results in biogas plants.

Finally, ensiling of the straw or co-ensiling with other plant material, for instance grass or beet tops, has been shown to also increase the digestibility of the straw.

Other pre-treatment methods

One of the more well-known technologies to “open up” straw is pressure cooking, which is also used for production of 2nd generation bioethanol. However, this is rather energy intensive – and thus costly - and is not considered feasible as pre-treatment of straw for biogas production. The same goes for enzymatic treatment.

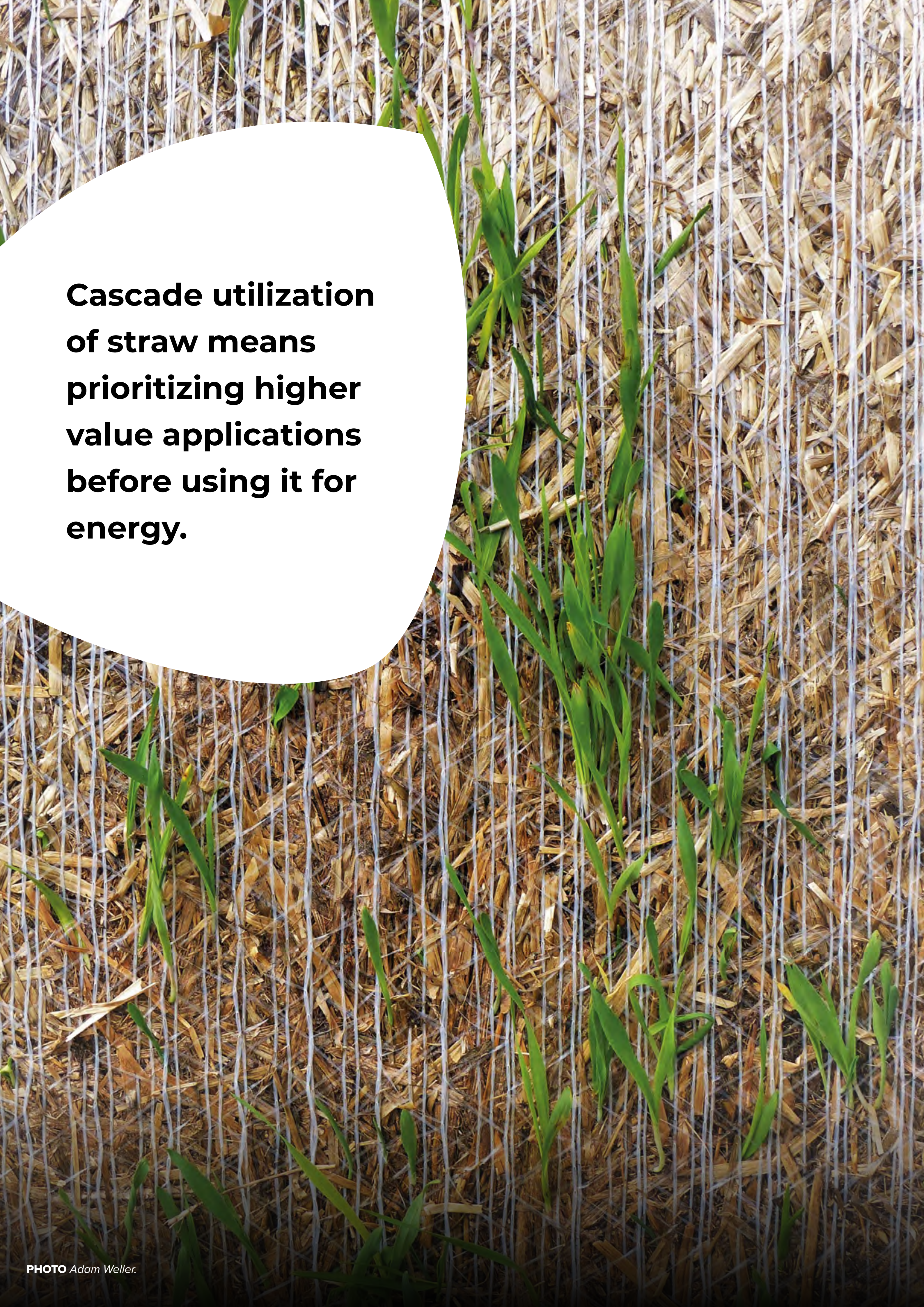
Fuel oil from straw

Another way of attempting to utilize straw for energy purposes is through hydrothermal liquefaction - essentially pressure cooking as well. This is a technology that is being used and developed by a few universities and private companies to create a biomass-based oil product. A spin-out from the Technical University of Denmark (DTU), Kvasir Technologies, has a proprietary liquefaction technology to convert straw (and other cellulosic biomass) to fuel oil. Pilot studies are ongoing and the goal of the company is to start construction of a commercial plant in 2023 if all goes well. A type of fuel of this kind would be highly suitable for replacing bunker oil in the shipping industry, which is still highly reliant on fossil fuel, if it can compete in the market. Another DTU spin-out, MASH Energy, is also working on producing fuel oil products from agricultural residues via pyrolysis.

Building materials from straw

As described in the previous chapters, utilization of straw for energy production has proven to be a viable solution at many levels, and progress is still being made regarding development, optimization and implementation. However, there is an increasing awareness regarding the need for intelligent use of the biological resources; renewable energy can be produced from sun and wind energy, whereas biomass can be used for numerous other purposes. With the increased focus on use of sustainable materials, there is a considerable interest in the development of straw-based products for the building industry.

One of the applications, is simply to use straw bales as “bricks” to erect walls in a house, and then cover the surface, for instance with clay, to prevent the straw bales from taking up moisture. Straw bale houses are well-known in many countries, and you can find companies offering turnkey solutions for standard dwellings. For wider and more complex applications, a number of companies in the EU and beyond currently produce straw panels commercially. Research and development in the use of straw fibers for more environmentally friendly composite materials are ongoing.



Cascade utilization of straw means prioritizing higher value applications before using it for energy.

PHOTO *Adam Weller.*

Staramaki is a social cooperative enterprise from Kilkis in Northern Greece that produces drinking straws from cereal straw, using its own patented process. A natural alternative to plastic straws, Staramaki illustrates another, innovative way in which cereal straw can contribute to the bioeconomy. **PHOTO** *Staramaki.*

Creating green growth from straw in the future

Several Danish research institutes and private actors have intensified research and development of technologies for cascade utilization of straw (and other types of biomass). This includes for instance fractioning (dry- or wet-) of the biomass in order to first extract high-value products such as fibers, polymers, wax, etc. Other parts can then be used for feed products, and finally, residues and waste streams can be used in biogas plants or for combustion. This kind of bio-refining of the straw is considered by many to be most sustainable way of utilizing this valuable resource in the long run. However, many bio-refining technologies are still not (fully) developed and ready for production on a commercial scale and will not be for years to come.

Meanwhile, there is a lot of straw in excess all over Europe, and we desperately need to reduce our fossil fuel consumption to lessen the harmful impacts of climate change and fulfil our commitments in the Paris agreement. The Danish example shows that straw combustion is a viable solution for carbon neutral heating and electricity production today. The technology is proven and mature. Hopefully, this publication serves as inspiration for others and this can be replicated anywhere in Europe (or beyond) with a large production of grains and a desire for a greener, and in many cases cheaper, heating supply. Straw to energy means independence from fossil fuels, and potentially local jobs and green growth in rural areas.

Directory of companies with straw expertise and technologies
(not a complete list – for more check the AgroBioheat Observatory).

LOGO	CONTACT	DESCRIPTION	AREAS OF EXPERTISE W	MANUFACTURER / EQUIPMENT PROVIDER	PRODUCER, OPERATOR & END-USER	OTHER (CONSULTANCY, RESEARCH, ASSOCIATIONS, ETC.)
ALCON ALHEAT WWW.ALCON.NU +45 86662044	Alcon ALHEAT ApS Ole Rømersvej 15 DK-8670 Låsby **www.alcon.nu**	More than 40 years of experience with sales and service of indoor and outdoor straw boilers ranging from 75kW to 1 MW all over Europe.	PRODUCTION, HARVESTING AND LOGISTICS	●		
			PRE-TREATMENT	●	●	●
			CONVERSION	●	●	●
BYGGERI & TEKNIK I/S Rådgivere | Arkitekter | Ingeniører	Byggeri & Teknik I/S Birk Centerpark 24 DK-7400 Herning **www.byggeri-teknik.dk**	Consultancy to agriculture regarding energy matters, buildings, dimensioning of heating systems, subsidiaries etc.	PRODUCTION, HARVESTING AND LOGISTICS			●
			PRE-TREATMENT			
			CONVERSION			●
C.F. Nielsen A·S	C.F. Nielsen A/S Solbjergvej 19 DK-9574 Bælum **www.cfnielsen.com**	Mechanical and extrusion briquetting installations for the production of briquettes. Raw materials besides wood are agri residues such as straw, rice husks, miscanthus etc. Complete production lines can be delivered with capacities of 200 kg/h and upwards.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT	●		
			CONVERSION			
CM BIOMASS COPENHAGEN MERCHANTS GROUP	CM Biomass Partners A/S Pakhus 48, Klubiensvej 22 DK-2150 Nordhavn **www.cmbiomass.com**	CM Biomass Partners A/S work with a variety of Biomass products, from very large producers and utilities to smaller regional producers and distributors. Today, we are one of the largest independent Biomass trading and logistic companies in the world. We implement multimodal logistic solutions including vessels, barges, railways, containers and trucks in bulk, bigbags or small bags.	PRODUCTION, HARVESTING AND LOGISTICS		●	●
			PRE-TREATMENT		●	●
			CONVERSION		●	●
cormall	Cormall A/S Tornholm 3 DK-6400 Sønderborg **www.cormall.dk**	Cormall is a Danish company founded 1961, the main area of activity is within diet feed mixers for automatic dairy cattle feeding, straw processing machinery and biomass technology.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT	●	●	●
			CONVERSION			
DANSK ENERGIRÅDGIVNING	Danish Energy Consulting Glarmestervej 18 B DK-8600 Silkeborg **www.danishenergyconsulting.com**	Offers targeted consulting about energy optimisation of straw boilers and heat exchangers, including the choice of technical solutions and applications for potential grants. Moreover, the biogas department and laboratory consult about the use of straw in biogas production and conduct biological analyses to stabilise and optimise gas output.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION			●
DANSK FJERNVARME	Dansk Fjernvarme Merkurvej 7 DK-6000 Kolding **www.danskfjernvarme.dk**	Trade association to protect the interests of the Danish district heating plants. 64% (equivalent to 1.7 million) of Danish households are heated with heat from the Danish District Heating Associations' member plants. Members include both small, local district heating plants, and the big companies.	PRODUCTION, HARVESTING AND LOGISTICS			●
			PRE-TREATMENT			●
			CONVERSION			●

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DANSK HALM	Danish Straw Producers Axeltorv 3 DK-1609 København V **www.danskhalm.dk**	Private supplier association which aims to serve members' interests. The association follows closely the political and regulatory framework for the use of straw, follows the development of new technologies for the use of straw to e.g. materials, chemicals and other uses in circular bio economy.	PRODUCTION, HARVESTING AND LOGISTICS			●
			PRE-TREATMENT			
			CONVERSION			
DSE TEST SOLUTIONS	DSE Test Solutions A/S Sverigesvej 19 DK-8700 Horsens **www.dse.dk**	Develops and produces microwave based moisture meters that monitor actual and average moisture values in baled biomass of all types, incl. straw. These are useful for accounting when the straw is delivered to the power plant, but also for managing the balance of wet bales going in the boiler.	PRODUCTION, HARVESTING AND LOGISTICS	●		
			PRE-TREATMENT	●		
			CONVERSION	●		
FARMERTRONIC INDUSTRIES A/S	Farmer Tronic Industries A/S Nyskovvej 13 DK-6580 Vamdrup **www.farmertronic.com**	Develops and manufactures moisture meters / temperature sensors / scales and app's for agriculture and the CHP industry. Professional users are offered a calibration procedure which ensures the instruments meet the strictest requirements that are reflected in the quality management systems of combined heat and power plants.	PRODUCTION, HARVESTING AND LOGISTICS	●		
			PRE-TREATMENT			
			CONVERSION			
FASTERHOLT	Fasterholt Maskinfabrik A/S Ejstrupvej 22 DK-7330 Brande **www.fasterholt.dk**	Bale wagons for round balers and square balers.	PRODUCTION, HARVESTING AND LOGISTICS	●		
			PRE-TREATMENT			
			CONVERSION			
Faust	Faust ApS Vester Fjordvej 2 DK-9280 Storvorde **www.faust.dk**	Faust designs and produces manual and automatic straw boilers and woodchip boilers from 140 kW to 2.5 MW.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION	●		
JUSTSEN	Justsen Energiteknik A/S Grimhøjvej 11 DK-8220 Brabrand **www.justsen.dk**	Founded in 1959, Justsen Energiteknik A/S is an original equipment manufacturer (OEM) specializing in biomass-fuelled boiler systems. Water-cooled moving grates is the key element of Justsen boiler systems. The scope of supply typically covers all pressurized parts, hardware, and all integral parts/components of the system.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION	●		
K.F. HALMFYR	KF Halmfyr Hjulmagervej 12-16 DK-9490 Pandrup **www.kfhalmfyr.dk**	KF Halmfyr produces portion fired straw boilers tested by the Danish Technological Institute. The boilers are adjusted to the needs of the individual customer and are built outside as separate building.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION	●		

LOGO	CONTACT	DESCRIPTION	AREAS OF EXPERTISE W	MANUFACTURER / EQUIPMENT PROVIDER	PRODUCER, OPERATOR & END-USER	OTHER (CONSULTANCY, RESEARCH, ASSOCIATIONS, ETC.)
	Kinetic Biofuel Solbjergvej 19 DK-9574 Bælum **www.cfnielsen.com**	Pre-treatment technology for agricultural lignocellulosic crop residues, such as cereal straw, which allow co-digestion with animal manures in a biogas plant and achieving the full theoretical biofuel potential of both biomass resources.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT	●		
			CONVERSION	●		
	Kvasir Technologies Maskinvej 5 DK-2860 Søborg **www.kvasirtechnologies.com**	Kvasir Technologies has a proprietary technology to convert straw (and other cellulosic biomass) to fuel oil. The process is simple, cheap and yields a marine quality fuel in a single step. Pilot studies are ongoing and the goal is to start construction on a commercial plant in 2023.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION			●
	Danish Agriculture & Food Council Axeltorv, Axeltorv 3 DK-1609 Copenhagen V **www.lf.dk**	Interest organisation whose purpose is to handle common tasks and business interests of farmers and food companies, including production. An use of biomass for bioenergy and circular bio economy.	PRODUCTION, HARVESTING AND LOGISTICS			●
			PRE-TREATMENT			●
			CONVERSION			●
	Lekea – Dan Trim Højvejen 18 DK-8860 Ulstrup **www.lekea.dk**	Developer and manufacturer of manual fired straw combustion boiler. Straw boilers from 48 kw to 130 kw for heating in agriculture and industry.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION		●	
	Linka Energy A/S Nylandsvej 38, DK-6940 Lem St. **www.linka.dk**	Development, production, installation and service of fully automated biomass plants for production of heat or steam. Our straw fired systems are customized and designed to achieve the highest possible efficiency, while maximizing the utilization of the fuel. We offer boilers from 100 - 15,000 kW, with various fuel feeding systems.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT	●		
			CONVERSION			
	MASH Energy ApS Fruebjergvej 3 DK-2100 København Ø **www.mash-energy.com**	MASH's gasifier solution enables highly efficient, modular and cost-effective energy production from straw pellets. Furthermore, depending on the customer requirements, the process can be configured produce an increased yield of highly valuable biochar for soil amendment or activated carbon for use in water and gas cleaning.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION	●		●
	ParkLand Maskinfabrik A/S Vejlemosevej 14 DK-4160 Herlufmagle **www.parkland.dk**	Production of straw wagons to be fixed to big balers in order to have a quick and efficient collection of big bales in the field. The wagons can also be equipped with weights for weighing bales.	PRODUCTION, HARVESTING AND LOGISTICS	●		
			PRE-TREATMENT			
			CONVERSION			

LOGO	CONTACT	DESCRIPTION	AREAS OF EXPERTISE W	MANUFACTURER / EQUIPMENT PROVIDER	PRODUCER, OPERATOR & END-USER	OTHER (CONSULTANCY, RESEARCH, ASSOCIATIONS, ETC.)
	PlanEnergi Jyllandsgade 1 DK-9520 Skørping www.planenergi.dk	PlanEnergi is an independent consultancy company organised as a non profit foundation. We have knowledge about harvesting, pre treatment and conversion of straw for combined heat and power, heating plants and anaerobic digestion.	PRODUCTION, HARVESTING AND LOGISTICS			●
			PRE-TREATMENT			●
			CONVERSION			●
	POMI Industri ApS Abildvadvej 5 DK-9610 Nørager www.pomi.dk	Produces: Bale accumulator to be fixed to large square balers in order to have a quick an efficient collection in the field. Bale stacker which allows you to collect and stack with the same wagon. Wrappers for big bales 5, 7 and 12 in each pile.	PRODUCTION, HARVESTING AND LOGISTICS	●		
			PRE-TREATMENT			
			CONVERSION			
	Processbio A/S Fiskerhusvej 20 DK-4700 Naestved www.processbio.com	Processbio supplies industrial bale handling systems for large square straw bales incl. bridge cranes, moisture meters, computerized barn management software, fully automated truck unloading systems, infeed systems with bale- splitting, tilting and distribution as well as de-stringing and de-baling. Capacities ranging from 1 t/h up to 75 t/h.	PRODUCTION, HARVESTING AND LOGISTICS	●		
			PRE-TREATMENT			
			CONVERSION			
	REKA A/S Vestvej 7 DK-9600 Aars www.reka.com	Produces fully automatic combustion plants from 10-6500 kW for most types of solid fuels (biofuel) such as straw, wood chips, pellets, wood shavings, sawdust, coal, grain and husks. Has developed chain hopper for loose straw and electro filter for the cleaning of smoke from straw combustion.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT	●		
			CONVERSION	●		
	Scanboiler Varmeteknik Vangvedvænget 1 DK-8600 Silkeborg www.scanboiler.dk	Specialises in sales and design of biofuel plants for wood pellets, wood chips, log wood, with boilers from 10.5-1000 kW. Scanboiler also sells solar and geothermal energy systems.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION	●	●	●
	SEGES Agro Food Park 15 DK-8200 Aarhus N www.seges.dk/en	SEGES has extensive knowledge on straw production and how to optimize biomass yield and quality targeted specific applications. SEGES can through the farmer-owned advisory companies efficiently implement new production methods. SEGES biomass screening tool can quantify the amounts of straw available in a specific geographic area of interest.	PRODUCTION, HARVESTING AND LOGISTICS			●
			PRE-TREATMENT			●
			CONVERSION			●
	Stratek ApS Bragesvej 11 DK-8660 Skanderborg www.stratek.com	Stratek is specialized in straw preparation and processing for any industrial application like pelleting, briquetting, baling and TMR feedstuff making, etc. Custom made systems for any capacity and to any product fineness. The list of products contains bale conveyors, shredders, de-balers, de-stringers, metering systems, de-dusting, belt driers, baling- and bagging machines.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT	●		
			CONVERSION			

LOGO	CONTACT	DESCRIPTION	AREAS OF EXPERTISE W	MANUFACTURER / EQUIPMENT PROVIDER	PRODUCER, OPERATOR & END-USER	OTHER (CONSULTANCY, RESEARCH, ASSOCIATIONS, ETC.)
Supertech Agroline	Supertech Agroline ApS Maltgørervej 7 DK-5471 Søndersø www.supertechagroline.com	Develop and produce portable equipment for measuring water content and temperature in hay, straw and silage in the measuring range 8.5% to 80% water content.	PRODUCTION, HARVESTING AND LOGISTICS	●	●	
			PRE-TREATMENT			
			CONVERSION			
DANISH TECHNOLOGICAL INSTITUTE	Danish Technological Institute (DTI) Agro Food Park 15 DK-8200 Aarhus N www.teknologisk.dk	DTI has more than 20 years of experience in all aspects of straw production and utilization. We provide services to Danish and international companies regarding optimization of straw yield and quality, machinery and technology, logistics, pre-treatment, conversion including combustion, anaerobic digestion, biorefining into new products as well as economy optimization.	PRODUCTION, HARVESTING AND LOGISTICS			●
			PRE-TREATMENT			●
			CONVERSION			●
VERDO	Verdo Agerskellet 7 DK-8920 Randers NV www.verdo.com	Verdo have more than 100 years of experience within energy production, counselling, development and service of turnkey energy solutions. Today, we are one of the leading suppliers of high-efficiency biomass-fired plants (straw, wood chips, pellets or waste) with capacities between 1 and 20MW for production of heat and steam.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION	●	●	●
UNIVERSITY OF COPENHAGEN	University of Copenhagen - Dept. of Geosciences and Natural Resource Management (IGN) Rolighedsvej 23 DK-1958 Frederiksbjerg C www.ign.ku.dk	IGN is working on bioenergy, which includes characterization of fuels, analysing energy content and ash, re-use of nutrients from ash, conversion to liquid fuel, and sustainability issues.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION			●
AARHUS UNIVERSITET	Aarhus University Dept. of Engineering Research Centre Foulum Blichers Alle 20 DK-8830 Tjele Denmark www.eng.au.dk/en	Application of straw is a research area at Aarhus University. The University has conducted projects focusing on developing new straw and biomass boiler technology. Key issues have been increased energy efficiency, low emissions and reduced environmental impact. Logistics and optimization of supply chains are also focus areas.	PRODUCTION, HARVESTING AND LOGISTICS			●
			PRE-TREATMENT			●
			CONVERSION			●
TRUTNOV Step	CZECH REPUBLIC Step TRUTNOV a.s. Na příkopě 1047/17 110 00 Praha 1 www.steptrutnov.cz	Step TRUTNOV a.s. offers the latest advances in biomass boilers with an emphasis on economic return and fundamental environmental care. Generating electricity from biomass presents an attractive technology in terms of economy for combined heat and power generation.	PRODUCTION, HARVESTING AND LOGISTICS	●	●	
			PRE-TREATMENT	●	●	
			CONVERSION	●	●	
tts boilers	CZECH REPUBLIC TTS eko s.r.o. Průmyslová 163 674 01 Třebíč https://www.ttsboilers.cz	The development and construction of straw combustion boiler of VESKO-S type. It is produced in a power range of 2 to 5 MW and allows the burning of square straw bales (grain crops, rapeseed, hay, flax, sorrel, etc.). The first boiler VESKO-S was put into operation in autumn of 2006 in Třebíč.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION	●		

LOGO	CONTACT	DESCRIPTION	AREAS OF EXPERTISE W	MANUFACTURER / EQUIPMENT PROVIDER	PRODUCER, OPERATOR & END-USER	OTHER (CONSULTANCY, RESEARCH, ASSOCIATIONS, ETC.)
	LITHUANIA Atenergy Verslininku str. 11A, Juodeliai Sirvintos regiona, Lithuania, LT-19131 **www.strawcomfort.com**	Atenergy is one of the biggest straw pellets producer in Baltics. Our brand Strawcomfort offers regular (8 or 10 mm) straw pellets and crushed straw pellets used for animal bedding. All raw material is gathered by ourselves and pellets are 100 % natural, without any additives and extremely high quality.	PRODUCTION, HARVESTING AND LOGISTICS		●	
			PRE-TREATMENT		●	
			CONVERSION			
	ROMANIA Erpek IND Ltd. 527035 Bodoc 14/A Jud. Covasna **www.biosistem.ro**	The company has a long experience in the technical field, relying on the design and manufacturing in its own conception: I. Bakery ovens and other accessories in the field II. Automatized biomass thermal plants based on biomass waste and pellets.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT	●		
			CONVERSION	●		
	UKRAINE Briquetting technologies 13306, Ukraine, Zhytomyr region, Berdychiv, st. Semenovskaya, 116 **www.briq-tech.com**	Briquetting Technology Company develops and manufactures products for briquetting and granulation of straw: Shock-mechanical presses, granulators, Aerodynamic dryers, and straw bale shredders. We assemble briquetting and pelletizing lines with productivity from 350 kg/h to 1200 kg/h.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT	●		
			CONVERSION			
	UKRAINE Institute of Engineering Thermophysics of NAS of Ukraine 2a, Zhelyabova Str. Kyiv, 03057 Ukraine **www.ittf.kiev.ua**	The Institute of Engineering Thermophysics of NAS of Ukraine works in the field of heating, and performs work for the industry and agro-industrial sector. The important directions of scientific activities are investigation of combustion technologies of different biomass types, including straw, in small and medium capacity boilers; investigation of biomass fast ablative pyrolysis and biogas production technologies.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			●
			CONVERSION			●
	UKRAINE SEC Biomass 03067, Ukraine, Kyiv-67, p/o 66 **www.biomass.kiev.ua**	Scientific Engineering Centre "Biomass" Ltd. (SECB) provides consultations, performs research, analytic and engineering work in the followingareas: bioenergy technologies, bioenergy policy, biomass potential, DH based on biomass, energy efficiency.	PRODUCTION, HARVESTING AND LOGISTICS			●
			PRE-TREATMENT			●
			CONVERSION			●
	UKRAINE ZAVOD KOBZARENKO, LTD Ukraine, 42500, Sumy region, Lypova Dolyna, Rusanivska street, 17 **www.kobzarenko.com.ua**	Production and sale of equipment for baling, transporting, storing and heating straw: Trailer for square bales PT-16 KVADRO, self-loading trailers for round bales, platform trailers, balers, bale grabber, round bale wrapper, agrofibre for covering and qualitative storage of straw, and straw heat generators.	PRODUCTION, HARVESTING AND LOGISTICS	●	●	
			PRE-TREATMENT			
			CONVERSION		●	
	FRANCE COMPTE.R 4 Industry Street Arlanc, 63220 **www.compte-r.com**	COMPTE.R, manufacturer of biomass boilers, has developed for many years real skills in the field of agrofuel combustion. Straw, corn cob, flax ana, wine growing waste, COMPTE.R offers high performance and low NOx solutions for the energy recovery of agricultural by-products.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION	●		

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BIOFACT	ITALY Biofact www.biofact.eu	BIOFACT is an engineering firm focusing on quantitively predicting ash related issues (slagging, fouling, corrosion) in combustion plants. BIOFACT can support boiler manufacturers and operators of straw fired units, to predict the extent of slagging, fouling and corrosion for the specific fuel, in each energy plant. No fuel is ever the same: ash depends on species, climate and soil composition, fuel fertilization and harvesting.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION			●
GILLES BIOMASS HEATING	AUSTRIA GILLES Energie- und Umwelttechnik GmbH & Co KG Koaserbauerstrasse 16, 4810 Gmunden www.gilles.at	GILLES is one of the pioneers in the field of renewable energy. The technologies from 12.5 – 2500kW have been continuously developed over the last 28 years. The fully automatic biomass heating systems are amongst the safest and most reliable in Europe.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION	●		
POLYTECHNIK Biomass Energy	AUSTRIA Polytechnik Luft- und Feuerungstechnik Hainfelderstr. 69 2564 Weissenbach (NÖ) biomass.polytechnik.com	World's leading supplier of advanced biomass to energy, combustion solutions, heat/cogeneration and carbonization plants. We are able to provide customers with state-of-the-art technology for the use of biomass for energy. With 150+ biomass fuels and more than 55 years of experience Polytechnik is an expert in generating energy from renewable biomass.	PRODUCTION, HARVESTING AND LOGISTICS			
			PRE-TREATMENT			
			CONVERSION			●

AgroBioHeat Consortium

CERTH CENTRE FOR RESEARCH & TECHNOLOGY HELLAS	CERTH is one of the leading research centres in Greece. Among its areas of expertise, activities in renewable energy sources, solid biofuels production and utilization, energy saving and environmental protection are included. www.certh.gr
aveBiom Asociación Española de la Biomasa	AVEBIOM is the Spanish Bioenergy Association which represents all the companies of the whole supply chain of the bioenergy in Spain. www.avebiom.org
BIOS BIOENERGIESYSTEME GmbH	BIOS is an Austrian R&D and engineering company with more than 20 years of experience in the field of energetic biomass utilisation. www.bios-bioenergy.at
Bioenergy EUROPE	Bioenergy Europe (formerly known as AEBIOM) is the voice of European bioenergy. It aims to develop a sustainable bioenergy market based on fair business conditions. www.bioenergyeurope.org

AgroBioHeat Consortium

Food & Bio Cluster Denmark	Food & Bio Cluster Denmark is the national Danish cluster for food and bioresources. We promote increased cooperation between research and business and offer our members one-stop-shop access to networks, funding, business development, projects, facilities and offer various consultancy services. www.foodbiocluster.dk
circe RESEARCH CENTRE FOR ENERGY RESOURCES AND CONSUMPTION	Technology Centre funded in Spain in 1993, seeking to provide innovative solutions in the field of energy for a sustainable development. www.fcirce.es
INASO-PASEGES INSTITOUTO AGROTIKIS & SYNETAIRISTIKIS OIKONOMIAS	PASEGES is a civil non profit organisation, established in 2005 in Athens by the Panhellenic Confederation of Unions of Agricultural Cooperatives (PASEGES). www.neapaseges.gr
ZEZ Zelena Energetska Zadruga	The Green Energy Cooperative (ZEZ) was established in 2013 as part of the project "Development of Energy Cooperatives in Croatia" implemented by the United Nations Development Program (UNDP) in Croatia. www.zez.coop
GREEN ENERGY Romanian Innovative Biomass CLUSTER	The Cluster's main purpose is to develop the bioenergy sector in Romania and raising the interest towards the production and utilization of the biomass. www.greencluster.ro
UABIO Bioenergy Association of Ukraine	UABIO was established in 2013 as a public organisation. The purpose of the Association's activity is to create a common platform for cooperation on the bioenergy market of Ukraine. www.uabio.org
Aile initiatives énergie environnement	AILE is working on renewable energies and energy savings in agricultural and rural areas of Western France. www.aile.asso.fr
WhiteResearch	White Research is a social research and consulting enterprise specialising in consumer behaviour, market analysis and innovation management based in Brussels. www.white-research.eu
Agronergy	Agronergy is a French ESP (Energy Service Provider) dedicated to Renewable Heating. www.agronergy.fr

The Danish example shows that straw combustion is a viable solution for carbon neutral heating and electricity production today.

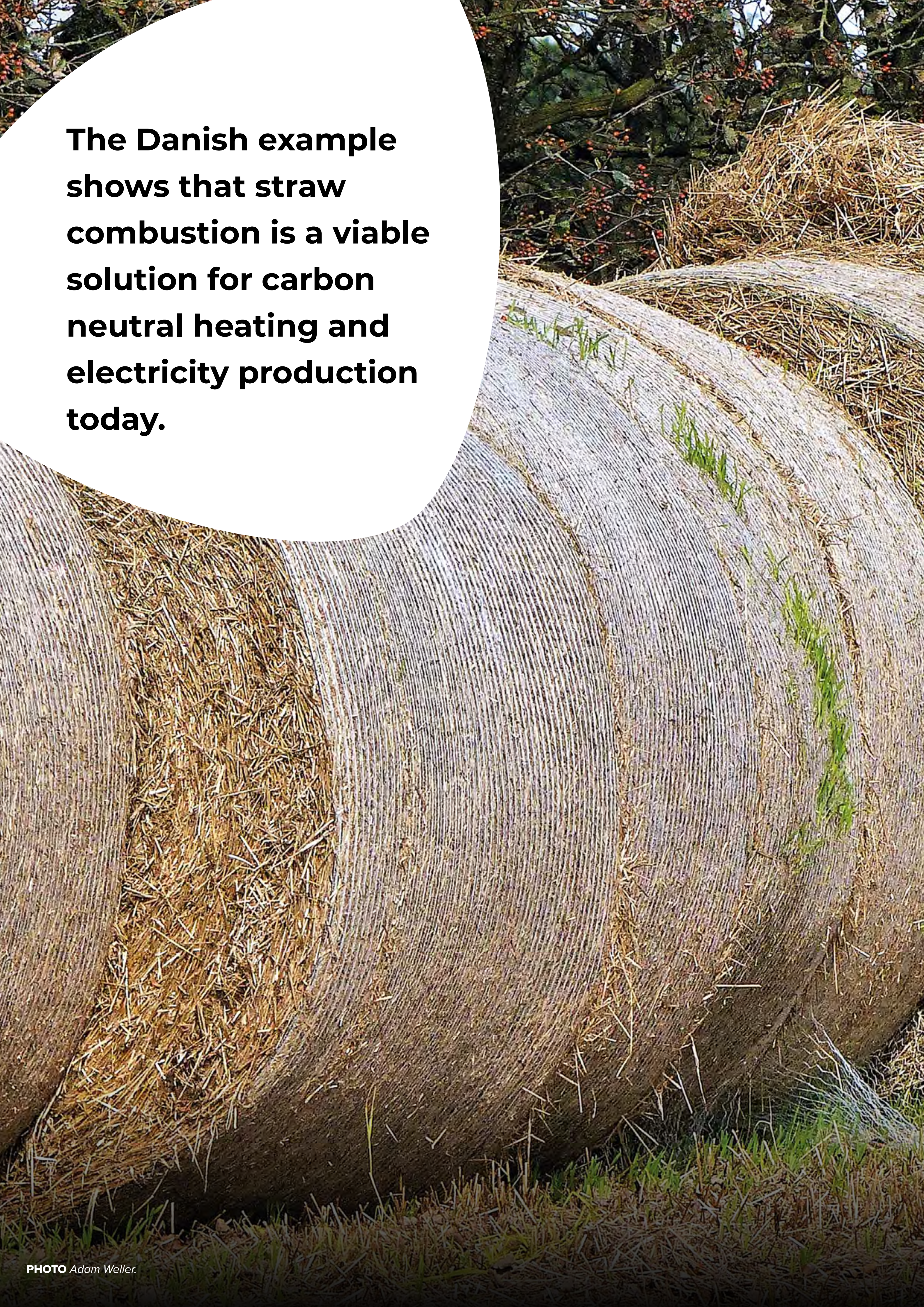

PHOTO *Adam Weller.*

Publication

This publication from Food & Bio Cluster Denmark takes stock of the use of straw for energy purposes in Denmark and provides a review of technologies, policies and innovative solutions useful in other countries with an unutilized surplus of straw.

It also includes a list of companies and organizations with specific skills and technologies in the supply chain for straw to energy.

It has been created in the project AgroBioHeat, which is co-funded by the Horizon 2020 programme of the European Union. AgroBioHeat works to promote economically and environmentally sustainable agro-biomass heating solutions in Europe.

About Food & Bio Cluster Denmark

Food & Bio Cluster Denmark is the national cluster for food and bioresources in Denmark. We are the collective platform for innovation and growth in the cluster – for both Danish and international companies and knowledge-based institutions. We promote increased cooperation between research and business and offer our members one-stop-shop access to networks, funding, business development, projects, facilities and offer various consultancy services.

Please visit **www.foodbiocluster.dk** for more information.

Food & Bio Cluster
Denmark

AgroBioHeat

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