

Initial study – compilation and synthesis of knowledge about energy crops from field to energy production

Magnus Berg, Monika Bubholz, Maya Forsberg, Åse Myringer, Ola Palm, Marie Rönnbäck, Claes Tullin

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**Förstudie - sammanställning och syntes av kunskap
och erfarenheter om grödor från åker till energiproduktion**

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Abstract

Literature on existing knowledge on agrifuel, straw, energy grain, willow, reed canary grass and hemp has been reviewed with the aim of identifying knowledge gaps and areas for future research. This work covers the entire chain from cultivation, harvesting, storage and transport to quality assurance, preparation, refining, dosing, combustion, emission, flue gas cleaning and ash disposal.

Summary

Energy crops constitute an as yet not fully utilised potential as fuel for heating and power production. As competition for biomass increases interest in agricultural fuels such as straw, energy grain, willow, reed canary grass and hemp is increasing. Exploiting the potential for energy crops as fuels will demand that cultivation and harvest be coordinated with transportation, storage and combustion of the crops.

Together, Värmeforsk and the Swedish Farmers' Foundation for Agricultural Research (SLF), have taken the initiative to a common research programme. The long-term aim of the programme is to increase production and utilisation of bioenergy from agriculture to combustion for heat and power production in Sweden. The vision is that during the course of the 2006 – 2009 programme, decisive steps will be taken towards a functioning market for biofuels for bioenergy from agriculture.

This survey has compiled and synthesised available knowledge and experiences about energy crops from field to energy production. The aim has been to provide a snapshot of knowledge today, to identify knowledge gaps and to synthesise knowledge we have today into future research needs. A research plan proposal has been developed for the research programme.

Key words: energy crop, agrifuel, straw, energy grain, willow, reed canary grass, hemp, literature survey, synthesis

Foreword

This initial study is indebted to a reference group that has very actively and enthusiastically shared their views during a workshop. The reference group was made up of the following members:

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1 Introduction

1.1 Background

To exploit the potential to cultivate energy crops on arable land, Värmeforsk and The Swedish Farmers' Foundation (SLF) have initiated a joint research programme. Värmeforsk and SLF represent two sectors that, between them, embrace the whole chain from cultivation, harvesting, storage and transport to quality assurance, preparation, refining where applicable, feeding, combustion, emission flue gas cleaning and ash disposal of fuel crops. The programme addresses every part of this chain. The long-term goals of the programme are to increase the production and use of bioenergy from agriculture for combustion for heating and power production in Sweden. The vision is that during the course of the programme, 2006-2009, decisive steps will be taken towards the development of a proper fuel market for bioenergy from agriculture.

1.2 The goals of this work

The work has sought to compile and synthesise current knowledge, primarily in literature on agrifuel for energy production. We have restricted ourselves to plants larger than 2 MW, which is the normal area of interest for Värmeforsk. The compilation has primarily looked at experiences in the Nordic countries, supplemented by experiences inside and outside the EU where such has been considered relevant. When synthesising, we have put the emphasis on a total perspective in accordance with the visions and goals set out in the Värmeforsk publication "Grödor från åker till energiproduktion" (Agrifuel from field to energy production).

The aim has been to provide a snapshot of current knowledge, to identify knowledge gaps and to synthesise current knowledge in the form of future research needs. Measures considered appropriate for Värmeforsk research programme planning have been suggested.

1.3 Report structure

Chapter 2 contains synthesised knowledge related to energy crops and various steps in the chain. Existing knowledge gaps are also presented and prioritised and which will form the basis for research that will be pursued as part of the programme. Chapter 3 offers a brief overview of other current research programmes related to this area. Chapter 4 addresses "Production costs for agrifuel" as a complement to the knowledge overview. This is followed in chapters 5-13 by a compilation of the knowledge and experience related to the various stages in the chain.

2 Synthesis of current knowledge

The initial study has looked at knowledge gaps in the following nine sub areas:

1. Production related obstacles and opportunities for energy crops
2. How cultivation and harvesting affect fuel quality
3. Storage and logistics
4. Refining of the fuel
5. Preparation and feeding of the fuel at the plant
6. Combusting energy crops
7. Production of electricity from energy crops
8. Flue gas cleaning and emissions
9. Ash disposal and recycling of ash into the soil

The results of this synthesis offer guidelines for the direction the research programme should take.

During the course of the initial study, a workshop was organised with the project steering group (where the main representatives were from energy plant owners). The workshop aims included identifying new knowledge gaps and prioritising those knowledge gaps deemed more important by the project. Of the nine sub areas above, areas 1 and 3 were given the highest priority. Sub areas 2, 4 and 5 were considered to be of medium priority while areas 6 – 9 were judged to be somewhat less of a priority. There were only marginal differences between sub areas given medium priority and lower priority and they should not be considered definitive when deciding on project proposals. The clearest different in priority was between sub areas 1 and 3 and the rest.

The combustion of waste products from the production of biofuel and crops is a new sub area that has been identified and prioritised by the workshop. Proposals as to where research is needed have not therefore been included in the initial study but research into this sub area should be included in the programme however. The workshop also argued that projects that include or take into consideration systems thinking and total concepts should be prioritised within the programme. Cooperation between various parties in the chain, from producers to users should also be encouraged.

New types of hybrid aspen and poplar offer promising potential and can be planted on what is currently arable land. It will however take at least 10 to 15 years before any significant harvesting can be done. Technology and issues surrounding these types of tree are more closely related to forestry production than field crops. Which means that overall, issues that are more related to forestry production (e.g. hybrid aspen and poplar) on what is currently arable land have not been prioritised in this programme.

Although the knowledge reviewed in this study has been restricted to straw, energy grain, willow, reed canary grass and hemp, there is no reason why future projects should be restricted to these crops. They were chosen as knowledge and experience of them also largely covers other crops that can come into consideration within the programme. They also represent different basic types of crop, in terms of e.g.

cultivation, harvesting and handling issues and fuel properties. Hemp and energy grain are annual crops that must be established afresh each year. Hemp is a new crop, while energy grain is a traditional crop in which both the straw and grain can be used for fuel. Reed canary grass and willow represent two types of perennial crops with widely different properties. Reed canary is a grass that is harvested annually while an energy forest of willow is made up of fast growing types of willow that are coppiced at three or four year intervals.

The knowledge gaps that have been identified in this study are summarised in the various sub areas. The research needs for each sub area are set out in the form of proposed measures that are considered suitable for Värmeforsk's planned research programme on the combustion of energy crops. In several instances, these suggestions have been divided into two categories – higher and lower priority. This categorisation is also primarily based on the conclusions from the workshop with the project steering group. Proposals that have been classed as a lower priority can still, however, be of interest for the programme to implement if there are clear motives, new or other knowledge etc, for such.

2.1 Production related obstacles and opportunities for energy crops

A number of production related obstacles and opportunities for energy crops have been identified within the parameters of this report. To reduce production costs and achieve a functioning market the most important thing is to increase the acreage of energy crops under cultivation. Larger areas will enable the fuels to gain a market that is open to competition and provide financial incentives for e.g. the development of specialist machinery. In addition to economies of scale, a reduction in production costs can also be achieved through technological developments, greater knowledge and plant refinement. As the costs of these new energy crops can, in many cases, be significantly reduced via larger scale cultivation, implementation issues, i.e. how to make cultivation more appealing to farmers, are important and need further study.

How support systems are structured is also of major significance for implementation, and it is important that these are steered towards both large areas and high energy production. A better insight into what financial support would be required to persuade farmers to want to invest in energy crops is also relevant, e.g. when structuring support systems.

Apart from issues directly related to profitability, other factors influence why farmers do not invest in energy crops to a greater extent. Changes in the appearance of the landscape, changes in level of employment and tenant farming issues are examples that can presumably create obstacles. The perceived risk is another factor that can be alleviated by more information and knowledge, contract practices and financial support. Additional knowledge on how such measures can be structured to reduce obstacles is therefore of importance.

To achieve a functioning market and services for energy crops also requires more information on selling, processing and on various organisational structures for local parties. Different organisational structures that can e.g. be studied include:

- Contract and management of energy farming.
- Contracts to make a higher proportion of tenant farmed land available for crops.
- Whether energy forests can be an alternative to the leasing of land.
- Alternative possible contracts that enable individual farmers to gain energy crop support without going through big organisations. Obtaining energy crop support today requires a contract with a buyer or processor.
- Impact on employment i.e. how many jobs are created with energy crops over and above cultivation itself, e.g. further processing and distribution.

Systems studies that look at different crops and forms of production in a broader context, rather than looking at each crop or production method in isolation would also be of major benefit. Synergies between different crops can then be identified in order to achieve cost reductions.

2.1.1 Proposed measures – Obstacles and opportunities related to the production of energy crops

All these proposed measures within this area are assessed as high priority.

Perceived risks and obstacles to energy crops and measures to reduce such. Greater knowledge is required to shape potential growers' interest in and attitude towards energy crops and their perceived risks. This will enable the development of cost effective measures to address these perceived risks. For instance, projects could take a closer look at how potential growers see such risks and use the findings to develop next step measures and determine what additional knowledge is required. Such perceived risks can be reduced by greater knowledge or by including energy crops in a portfolio approach. This should help show how investing in energy crops can reduce risk for an enterprise. This can include research into the market risks, production risks and political risks and how these interface with existing agricultural production. If important obstacles and incentives for farmers can be identified, this can eventually lead to measures that stimulate the increased establishment of fuel crops. Projects shorter than 3 years possible.

Systems studies. Systems studies that look at the production of energy crops from a total perspective are important in helping to find ways of making them more profitable. Such studies could look at e.g.:

- The advantages of cooperative arrangements for technology, e.g. harvesting machinery.
- Coordination between the production of food and energy. How can competition between the two be addressed? For instance, can crop substitution be a way of increasing total production of food and energy.
- Potential for cost reductions on the production of different energy crops. What production costs can we expect in the long term? What measures will be worth investing in? What respective development is required in Sweden and internationally?

It ought to be possible to divide such systems studies into various parts, e.g. cultivation, processing and distribution, to enable the findings to be more applicable in other situations. The findings in terms of identified opportunities to increase income or potential cost reductions can be used as a basis for resource allocation and can persuade organisations to implement cost reducing initiatives.

Business opportunities and possible organisational structures in the grower and entrepreneur chain. More knowledge is required of what opportunities are available for farmers who are part of the chain from growing, processing, distribution and sales to the consumers, such as energy plants. Knowledge is also needed on how different organisational structures can be configured and the size of the related overheads. Different organisational structures can be looked at, e.g. for the management of energy farming, forms of energy crop support contracts, issues concerning the leasing of land. A greater understanding of the above factors can be obtained by studying experiences in this area, and also from other areas and sectors. The research findings can be used for e.g. information purposes and specific advice for farmers and other interest groups. Projects shorter than 3 years are possible.

Calculation methodology for the short and long term analysis of energy crop cultivation. Current subsidy calculations treat indirect costs, i.e. costs not linked to a specific crop, in different ways and on different scales. This makes it more difficult to compare different crops in terms of how much they impact on common company costs. This favours more resource intensive crops when you only look at the contribution margin in subsidy calculations. Current subsidy calculations therefore discriminate against the cultivation of energy woods and reed canary grass. A new calculation methodology needs therefore to be developed for the short and long term analysis of growing different energy crops and comparing these with traditional crops. There is an urgent need to develop such calculation methods for use by e.g. advisers, as this is one way to reduce the gap that exists between theoretical knowledge and practical application today. Such calculations could also then be used when structuring contracts or quantifying how risks can be shared between grower and consumer.

Disseminating information to potential growers of energy crops. Helping farmers and other potential organisations to gain a better understanding of different energy crops has been identified as an important tool for increasing the production of energy crops from the soil. It is important that such information reaches the right target group and that it is disseminated in an appropriate way. There are various ways of achieving this, such as via seminars, farmers meetings and local theme evenings. For instance one drawback to willow is that you have to tie up land for this for a long period. Here potential growers need more information on the financial implications of phasing out willow prematurely, and how this is done from a purely practical angle. Knowledge about this does exist, but such information is not available to farmers.

2.2 How cultivation and harvesting affect fuel quality

Practical experience and knowledge of how different energy crops work as fuel varies from crop to crop. However, generally speaking, the level of knowledge is low when it comes to how such things as using fertilisers, choice of crop and choice of growing

location can affect the quality of the fuel produced. Similarly very little is known about how growing conditions and type of soil affect the fuel properties.

The quality of the fuel, and even the costs, can be influenced by a conscious choice of harvest point. For instance, by deliberately leaving grain straw in the field, you reduce the content of substances that from a combustion viewpoint, are undesirable, in this case potassium and chlorine. Another example is hemp that can be harvested over an extended period between the time the leaves drop till the following spring. What changes occur in the properties of the fuel during this time is, however, unclear. From a cost viewpoint alone, it would be advantageous to have as long a harvesting period as possible, as this offers the opportunity to make the most effective use of existing equipment capacity. More in-depth research into how the fuel quality changes over the time period available for harvesting is needed for most crops.

We know that the fuel quality of energy crops can vary significantly, due to factors such as growing conditions, weather, type, soil etc. As a rule, such variations do not become apparent until the fuel is burned at which point it is no longer possible to do anything about them. It would therefore be advantageous to be able to identify or reject batches that could cause problems on combustion, at the earliest possible stage. As it would be desirable to be able to detect substandard batches before delivery to the heating plant, relatively simple methods/technologies for measuring quality in the field would be worth trying to develop.

2.2.1 Potential actions – how cultivation and harvesting affect fuel quality

Influence of growing conditions. Generally speaking, there is a lack of detailed knowledge of the fuel qualities of potential energy crops and how these are affected by e.g. growing conditions and soil type. More knowledge is also required on the potential effects of active farming measures or strategies, e.g. fertilising and type selection, being able to control the handling and combustion properties and emissions. For energy grain knowledge is also needed on how actions such as chemical pesticides affect its properties.

Influence of harvest time point. For each energy crop, there is a time window of varying length when it is possible to harvest the crop in purely practical terms. A wide window offers greater scope to keep costs down as it enables better utilisation of machinery. More knowledge is also required on how fuel properties change over the time period that is available for harvesting.

Proposals considered to have lower priority

Determining the fuel quality in the field. Development of a method/technology for detecting and rejecting substandard quality fuel at an early stage should be able to reduce the risks of problems at the combustion stage. Implementing such a project is assessed as being relatively high cost and high risk, however, and therefore is not considered to be the highest priority in the programme. The need for a method for quick

determination of fuel quality is considered to be of more importance once a fuel has become established.

2.3 Storage and logistics

Straw agrifuels (straw, reed canary grass and hemp) can be handled in the form of compressed bales or chopped up as loose goods. There are two basic types of bales: round bales where the material is pressed and rolled into cylinders or into rectangular bales. In bales, the straw material is relatively long while chopping results in a more bitty material in loose form.

The advantage of the chopped variety is that it is easier to handle by transport machinery and feeding equipment at heating plants. However it has a higher volume than bales, which makes for higher storage and transport costs. However, even in bale form, storage and transport costs account for a substantial proportion of the total costs. In the case of straw fuels therefore, there is a need for measures that can reduce handling, storage and transport costs. Alternative storage systems and/or increasing the degree of compression are potential measures here.

Agri-fuels grown for energy production are not subject to the same quality standards as products to be used for animal feed or human food. This can open the way to simpler and therefore cheaper storage and conservation systems, for e.g. grain. However the lowest quality requirement to be satisfied by energy crops has yet to be defined. Quality standards must therefore be taken into consideration when assessing alternative systems. Work environment aspects (dust, mould spores and accidents), risks of self-ignition and dust explosions must also be included in such assessments.

Various ways of reducing handling costs can be analysed in systems studies by identifying efficient logistics solutions within specific regions. In this context it is important to also take into account the possibilities of coordinating different energy crops. One such analysis ought to also include strategies and opportunities to meet security of supply requirements, plus the carbon footprint of systems.

2.3.1 Proposed measures – Storage and logistics

Measures linked to fields or farms

Greater volume by weight for straw fuels. The current handling technology for straw fuels produces a low bulk density. Measures to increase the density are important for reducing the relatively high costs of storage and transport.

Alternative storage methods. We need to know what the lowest quality standards likely to be required of energy crops, and to what extent simplified storage and conservation systems can be expected to meet these requirements. When assessing alternative storage systems, risks associated with the work environment, self-ignition and dust explosions must also be taken into account.

Systems studies. Analyses of the likely structure of efficient logistics solutions are required. In this context, it is important to also take into account security of supply,

environment footprint and how the management of different energy crops can be coordinated.

Measures linked to energy plants

Quality control. Quality control must be done quickly and accurately to ensure a simple flow from off loading to combustion. One or several projects evaluating quality control methods for different crops (moisture content measuring, removal of impurities etc) could address this within the parameters of the programme (< 3 yrs).

Proposals assessed to have a lower priority

Measures linked to fields or farms

Drying of willow chips. One way of improving the quality of the fuel and minimise storage losses would be to dry the chips in bin dryers on the farm, an established technology for grain. As this technology is well known it ought to be able to be applied for willow chips with minor modifications without too many problems. Farmers who have expressed an interest could apply this method also from now, which is why it has not been accorded a high priority within the research programme.

Measures linked to energy plants

Pneumonitis. Methods for handling agrifuels in closed systems in order to reduce the risk of pneumonitis lung inflammation can be investigated. However this is not being prioritised in the programme as there does not appear to be a serious problem with lung inflammation at energy plants.

2.4 Refining of fuels

The refinement of *straw fuels* is addressed in this work. Refining willow can be compared with the refining of wood chips that is being looked at in the current programme “Production technology platforms for the Swedish pellet industry” (2007-2010). Straw fuels used in Sweden are straw from various crops (e.g. wheat, rape), several years old grass (reed canary grass) and hemp. These have several properties in common but also differences, e.g. hemp has extreme fibre strength. Based on earlier systems studies we have assumed that the fuels will arrive in the form of large bales at refinement plant. On large scale combined combustion with e.g. pellets or briquettes from tops, roots and branches have been discounted with the assumption that only bales can be split up. Pelleting know-how has been largely obtained from the plant in Køge in Denmark and from the installation at the department of biomass technology and chemistry at the Swedish University of Agricultural Science.

Technologies and methods that have been developed for the refinement of wood shavings, planing shavings etc are not optimal for straw fuels. They physical differences in the materials demands other or modified methods. Hitherto, there has been little R&D into these materials or work done by machinery manufacturers on account of the lack of demand. This situation is now changing as there is a big demand for ways of refining straw fuels into a form that is environment friendly in terms of combustion, transport and handling properties. In particular, technology for refining hemp grown as an energy

crop has not yet been developed in terms of fibre separation, grinding, conditioning, pelleting etc.

If this area is to be developed, work mainly needs to be done in grinding, conditioning, addition of additives and pelleting. The development of new technology requires the involvement of equipment manufacturers, as such work is expensive. Measures related to fuel refining are expensive and comprehensive knowledge cannot reasonably be achieved within the programme period.

2.4.1 Proposed measures – Refining of fuels

Additives. Additives can (i) improve pelleting properties, (ii) improve combustion properties or (iii) bind dust particles. Some research into additives and combustion properties has been carried out and published. Evaluations of the combustion process can be done in projects < 0.5 - 2 yrs. There are big knowledge gaps in additives and the pelleting process and in binding dust, and the area will probably be more complicated compared with wood pellets. Trials with different types of lignin or press helpers are planned at the Swedish University of Agricultural Science BTC. These additives have previously been evaluated for their combustion properties. There is scope for lower cost systematic trials during the programme period. One area where projects can be supported if they deliver benefits during the programme period would be additives that make pelleting easier or improve the work environment as dust binders. The costs are unclear, but projects < 0.5 MSEK ought reasonably deliver some useable results. Comprehensive knowledge in this area will not be achieved in less than 3 years.

Pelleting process. A number of lab scale research projects or small trials have been published. Manufacturing of straw pellets has been successively improved at the pellet factory in Køge based on methods and equipment for wood pelleting, although scientific research into optimising the production of straw fuels in a wider sense has not been performed. Trials with reed canary grass indicate that totally different equipment is required compared with conventional pelleting machinery.

The development of new types of machinery requires cooperation between equipment manufacturers and is very expensive. Every change/modification of equipment takes time. The established manufacturers of pelleting machinery are not particularly interested in agrifuels today, which they see as a tiny and marginal market. Shorter research projects are required to persuade equipment manufacturers to become involved. Trials with new pelleting technology are considered cost intensive and comprehensive knowledge will not be achieved in 3 years. If measures of this type are to be included, some form of cooperative work with equipment manufacturers on the development of pelleting technology for straw fuel ought to be initiated during the programme period.

Grinding technology. Trials in the USA have demonstrated that significantly less energy is required to grind straw and grass compared with wood chips. Grinding straw fuels requires little energy and is not very expensive. However in time, measures will be required as the mills in operation today produce widely different sized particles and a lot of dust. However trial installations are expensive.

Knowledge gaps assessed to have lower priority

Conditioning of fibres. During the pelleting process, steam or heat conditioning long fibre materials such as straw can reduce the energy consumed substantially. To date, no research has been done in the pellet area, but certain experience is available from paper and pulp production, albeit with shorter fibres. The potential cost savings of lower energy consumption for pelleting is considered to be substantial.

A trial installation is currently under construction at the Swedish University of Agricultural Science BTC Umeå and is expected to be completed in 2007 (funded by the pellet platform). The completed installation can be used for agrifuel projects. Basic materials technology research and applied research at production plant are examples of measures that can provide greater knowledge of conditioning. Basic research performed at the trial installations built can be done within the programme period. The costs are unclear, but projects of < 0.5 MSEK ought reasonably be expected to deliver usable results. Applied trials are more cost intensive. Comprehensive knowledge in this area will not be achieved in less than 3 years.

2.5 Preparation and feeding of fuels at energy plants

Energy crops have many similarities with other biofuels, but there are also big differences. The emphasis in this report lies mainly in the differences between better known biofuels and energy crops.

Reception and handling of fuel. Before a fuel can be combusted it must be fed into the boiler. The handling of chipped and refined (powdered, pellets and briquettes) energy crops is no different from other fuels in the same form, except that the risk of arching can be slightly higher for certain straw fuels. Arching occurs when fuel particles clump together to form an arch at e.g. the bottom of a silo, which makes outflow more difficult. However certain types of grain sap have better in and out flow properties than powdered wood.

Straw fuel can also be delivered in the form of bales or as loose goods, which is a big difference compared to other biofuels. Bales require specially adapted fuel reception and combustion equipment but they can be shredded and then used in grate or fluid bed boilers. A common problem with straw fuels is that long straws catch in the fuel handling machinery, e.g. on screws or bolts. Hemp is particularly problematic in this respect, due to its strong fibres.

2.5.1 Proposed measures – Preparation and feeding of fuels at energy plants

Preparation and feeding of straw fuels. Handling equipment needs to be developed for straw fuels, especially for long fibre materials such as hemp. Fibres catching in screws, bolts and other transport equipment is a common problem. Once problems related to feeding the fuel in are resolved, larger scale combustion tests can be performed. It is important to be able to achieve an even flow of fuel that does not get caught or require similar maintenance. Such work could conceivably be done in

cooperation with fuel handling equipment suppliers and this is estimated to take more than three years.

Leaching/washing. What scope is there for leaching different crops to reduce the amount of e.g. sodium and potassium? What can be done in the field and what can be done at different processing stages? Length of time 3 years.

Blending. Improvements to methods for blending two or more different fuels.

Measures assessed to have lower priority

Grinding. Improvement of ground/powdered properties of grain. Powdered properties must be improved if 100% grain is to be combusted. Such work is cost intensive and is therefore not a current priority.

2.6 Combustion of energy crops

Common types of combustion equipment for biofuel are powder boilers, grate furnaces and fluid bed boilers. Depending on the boiler type, the different burning characteristics of the fuels have a big impact on how well combustion can occur.

Calorific value/moisture content. The calorific value is very much dependent on the moisture content of the fuel. Different boilers are suited to different calorific values, for example, the temperature and temperature profile in the boiler are affected by the calorific value of the fuel. For stable operation it is important that the calorific value does not vary too much. The moisture content and calorific value in energy crops depend on a number of factors and do not substantially differ from other biofuel.

Ash content. In general, energy crops have a higher ash content than more conventional biofuels (such as e.g. wood chips, stemwood and wood pellets). High ash content makes for lower calorific value and with it lower energy density in the fuel, higher risk of ash related problems and larger quantities of ash, which make for increased costs for ash handling.

Composition of ash. The alkali and chlorine content is often higher in energy crops than in stemwood from forests, which entails increased risk of coating and corrosion on heat transfer surfaces, sintering and agglomeration of ash particles and slag. The risk of coating and corrosion can be reduced with the help of additives or burning other fuel at the same time.

Size and shape. Size and size breakdown affect e.g. how fully a fuel burns. Here too, a homogenous fuel is best to enable the boiler to be optimised for a certain range of sizes. The shape can also affect the transport characteristics of the fuel and fall in pressure over a grate bed. If the proportion of fine particles in the grate and FB boilers is too high, this can lead to combustion occurring in the wrong part of the furnace and uncombusted fuel in the flue gas emissions out of the boiler. In the case of powder burners, in addition to the above factors, the volatile content is important, as the fuel must be ignited rapidly.

2.6.1 Proposed measures – Combustion of energy crops

Combustion of different crops. A systematic study that compares a large number of different agrifuels under the same well controlled conditions. This is estimated to take up to three years. This is considered to be a high priority measure in order to gain a clear picture of the various combustion characteristics of different crops.

Coating. Coating formation is very complex and there is a lack of knowledge of all the stages. Certain plants seem to be able to burn crops without any problems with coating, while others have big problems. A project should be able to identify the cause of coating and methods for eliminating it. Time required > 3 years. This is a high priority measure as coating is the single biggest problem when it comes to burning energy crops.

Corrosion when burning reed canary grass and hemp. There is a lack of information on corrosion formation on combustion of reed canary grass and hemp. Such information should be obtainable through combustion tests over an extended period with various blends of fuel and in different types of boiler, and possibly including tests using different additives. This work is estimated at up to 3 years.

Additives. To gain a better understanding of how additives affect coating formation and corrosion, work should be done on determining the effect of additives in terms of amount used, crop and costs. This work is estimated at taking around 3 years to perform.

Operating and maintenance costs for different fuels. Knowledge of the size of operating and maintenance costs in association with burning energy crops is limited today, but important for a plant. An example of one type of question is what must the price difference be to make it profitable to burn one particular crop (i.e. how would the additional operating and maintenance etc costs be of switching fuel). Running a project in this area is estimated to take longer than 3 years, and it could be expensive and impossible to generalise for all boilers. Execution could e.g. include some form of calculation tool and model for total calculations albeit based on practical experiences, in which a certain type of plant can report on the collective risks, investment requirements and costs that arise – compared with a known reference fuel most generally tops, roots and branches.

Operating strategies. How can (primary) combustion technology measures improve the combustion of energy crops? This work is estimated at around 3 years.

Knowledge gaps assessed as being low priority

Co-combustion. A large proportion of today's plants are coal-fired (from a European perspective) and from that perspective, it is important to find ways of burning coal together with biofuels (energy crops). One possible area can be to develop understanding on the connection between coating and corrosion when burning energy crops with other fuels, including wood fuels. This is a big area and is expected to take > 3 years.

Boiler design. A project directed at improving the opportunities for the different boiler types to burn one or several energy crops is important if the actual combustion process is to be optimised. Improving co-combustion opportunities in the different combustion technologies is also of interest but perhaps not the highest priority at present. Time required estimated as > 3 years.

New boiler concepts. The development of new boiler better suited to energy crops. This project is given a lower priority due to the high costs involved.

Control systems/measuring instruments. Improve the possibility of controlling combustion. As the Värmeforsk basic programme includes developing control and measuring technology this knowledge gap has been given a lower priority in the energy crops programme.

Bed material. Trials to find the best bed material for different energy crops. This work is cost intensive and therefore is seen as a lower priority.

Corrosion resistant plant material. Combustion trials and materials analysis to determine which materials prevent corrosion on boiler walls and tubes. This work is cost intensive and is partly being addressed by the Värmeforsk basic programme.

2.7 Production of electricity from energy crops

To produce electricity “directly” from combustion requires the production of high pressure and high temperature steam, that is then ducted to a turbine. As energy crops have a high alkali and chlorine content this entails associated risks for the plant plus high corrosion, and the risks rise with the temperature of the steam. Alternative methods for production electricity from agrifuels can therefore be advantageous.

- The problems can be partly reduced with the right design of boiler, for instance having more space between the superheaters, makes replacing the superheaters easier or by doing the superheating of the steam at the back of the boiler (when the temperature of the flue gases is lower).
- Co-combustion reduces the risks for plants and corrosion and can therefore be an alternative.
- Another way is to burn energy crops in a separate boiler and heat the water there without turning it into steam, or steam at a low temperature. The hot water produced can then be ducted to another boiler that is fired with a different fuel. The water is then turned to steam and superheated in the second boiler.
- Gasification of biofuel enables the synthetic gas produced to be combusted in a gas turbine and so produce electricity.

2.7.1 Proposed measures – Production of electricity from energy crops

Co-combustion. Systematic tests and documentation on how different energy crops can be burned together with coal or wood in order to produce more electricity. This work

should be done in cooperation with the co-combustion project discussed in the chapter on combustion. This is expected to take > 3 years.

Design. A project ought to be able to provide greater knowledge on how boilers and boiler materials should be designed to achieve high steam temperatures with little coating. One problem with this proposal is that it would require cost intensive research equipment and the work would take a long time, over 3 years.

Energy combines. Sector wide investigations into improving the cost effectiveness and efficiency of energy combines technology. A project on this is being done in the Värmeforsk basic programme. However the focus in this programme should lie on the total economy of different concepts and what volumes of energy crops can be applicable.

Knowledge gaps assessed to have a lower priority

Operating strategy. Identification of how different operating strategies can raise steam temperatures. At present, this is a lower priority as the potential for improvement does not offset the project cost.

Concepts for separate combustion. Identification of different concepts for burning energy crops separately but cost effectively. This work is considered to be very cost intensive and has therefore been given a lower priority.

Cleaning technology for gasification. Investigation into how tar can be removed via gasification technology. This is estimated as taking > 3 years.

Refined energy crops. This kind of project can evaluate how much additional power would result from using pellets and briquettes for producing electricity. At present, this measure has a lower priority because the potential improvement would not match the project costs.

ORC with energy crops. Introductory technology trial using energy crops as fuel with ORC (Organic Rankine Cycle) technology. A project like this would take a great deal of time and money and is therefore considered to be a lower priority.

2.8 Flue gas cleaning and emissions

Fast growing energy crops characteristically have higher nitrogen and ash content than stemwood. Sulphur, chlorine and the alkali metals sodium and potassium contents are also generally higher, although there are large variations. Fuel-related emissions that can be of significance for developing a market for agrifuels within the length of the programme are nitrogen oxides and dust. Dioxins should also be addressed, as many energy crops contain chlorine that is one of the sources of dioxin formation. Specific requirements for measures related to the emission of sulphur dioxide or hydrogen chloride on combustion of agrifuels are not considered to be on the agenda during the programme period. However hydrogen chloride ought to be looked at from a corrosion point of view.

Particle emissions are restricted today by emissions regulations. As ash rich fuel generates more particles there is a need for both combustion technology and flue gas cleaning measures to reduce emissions.

Emissions of nitrogen oxides from agrifuels are restricted at the licensing stage and by the charging system for nitrogen oxide. As nitrogen rich fuels can release nitrogen oxide contents of up to several hundred mg/MJ, there will be a need for both combustion technology and flue gas cleaning measures to reduce emissions. There is no indication that the NO_x charging system will be extended to smaller plants.

In addition to the presence of chlorine, the formation of dioxins depends on combustion conditions, flue gas cooling and chlorine containing fuel and catalytic surfaces. By learning more about what is required to maintain minimal content levels in emissions, can enable future expensive measuring and cleaning methods to be avoided.

2.8.1 Proposed measures – Flue gas cleaning and emissions

Limiting nitrogen oxide emissions. More knowledge is required on the levels of nitrogen oxides that are reached when burning agrifuels and fuel mixes and what reductions can be achieved with combustion technology measures (primary measures) and by the application of the secondary deNO_x methods SNCR and SCR. This is assessed as a high priority within the programme, and can be achieved through a project < 0.5 – 2 years by lab experiment and/or full scale trial, and by exchanging experiences in workshops etc.

Primary measures: More knowledge is needed on how far we can go with e.g. staged combustion, control of the surrounding excess air, temperature control, optimised blending, optimised stop times etc.

Secondary cleaning with SNCR: More knowledge is required on possible reduction with ammonia injection, possibility of including ammonia slip in the plant's emission licence, effect on economy, risk of salt increase and low temperature corrosion.

Secondary cleaning with SCR: At present, SCR offers the only possibility of low emissions as the crude gas has a very high nitrogen oxide content, or where existing emission conditions are low. Knowledge gaps exist on the chemical and physical characteristics of flue gas emissions from different fuels and fuel mixes, in both the gas and particle phases. Installation a catalyser after particle cleaning is recommended today. More knowledge is required on particle cleaning, on what causes deactivation, how regeneration can take place and the economic consequences of installation.

Knowledge gaps considered a lower priority

Formation of nitrogen oxides. A greater fundamental understanding of nitrogen oxide formation would require a long term research project and is therefore given a lower priority in the programme.

Fundamental research into SCR requires a more long term research project and is therefore a lower priority in the programme.

Limiting dioxin emissions. A better understanding of the formation and reduction of dioxins, and the possibilities of limiting emissions via choice of combustion technology and operation or via co-combustion can be obtained from research publications and measurements in lab and/or full scale trials. This can be achieved via a project of < 0.5 – 2 years plus workshops etc where experiences can be exchanged.

Fundamental research into the formation and reduction of dioxins requires a more long term research project and is therefore a lower priority in the programme.

Limiting particle emissions. Better knowledge of particle content and the chemical and physical characteristics of particles can be obtained by measuring in labs or in a full scale project < 0.5 – 2 years. Workshops where plant owners could exchange experiences would be an important element. Textile filters are currently used when combusting straw, and this technology can therefore be considered a top priority. Alternative technologies (flue gas condensing, wet electric filters etc) can also be of interest if licences for particle emissions cannot be obtained.

Primary measures: More knowledge on how particle emissions can be kept low via controlled combustions, temperature control, reducing/oxidising zones, use of additives etc. is required.

Textile filters: More knowledge is required on textile filters with different agrifuels, appropriate filter load, particle density, pressure drop over filter cake, temperature in filter to avoid acid dew point, hygroscopic effects etc. The durability of the hose material at different loads, impact of sulphur, new types of material are also of interest.

Electrostatic filters: Electrostatic filters are not in common use today when burning agrifuels. More knowledge of the restivity of particles from different fuels is required, and on flue gas flows and moisture content in flue gases on combustion/co-combustion of agrifuels. Reading research publications plus lab and/or full scale testing in shorter projects are recommended. Measures concerning electrostatic filters are considered a lower priority than ones addressing the textile filters currently used when burning straw.

2.9 Ash handling and returning ash to the soil

Ash from biofuels grown on agricultural land can be an important nutriment resource if it is of sufficient quality. An important parameter for determining whether or not ash recycling is possible is the content of heavy metal and other harmful substances in the ash and fuel, and also whether it contains important nutrients. The amount of uncombusted material in the ash is another important parameter in terms of how the ash is handled. The amount of uncombusted fuel ought to be minimised for several reasons.

Spreading ash affects both the crops and soil system, it could e.g. lead to an increased risk of nitrogen leaching. To avoid damages to plants and shoots, ash must be spread at

the time of ploughing, on bare soil or, in the case of crops that grow over several years, immediately after harvesting. Knowledge of how different farming crops react to the addition of ash from different energy crops is important if the ash is to be made optimum use of. Similarly, it is important to do further research into how different kinds of ash affect the soil and how accessible different nutrients, particularly phosphorus is for plants and possible ways of controlling this.

Making optimum use of ash requires it to be evenly distributed over the growing area. How different forms of storage affect the spreadability and fertilizer properties of ash, is also important to determine. Spreadability is very much influenced by the water content of the ash, which varies considerably depending on e.g. how and how long the ash has been stored. Suitable methods and strategies for ash storage that can enable the water content to be maintained at the desired level need therefore to be identified.

Generally speaking, ash recycling know how is higher in the forestry sector than in agriculture. It ought to be possible to transfer and apply some of this know how in agriculture. For ease of handling, the forestry sector has also experimented with pelleted and granulated ash. This kind of product is more uniform which aids even distribution.

2.9.1 Proposed measures – Ash handling and returning ash to the soil

Measures linked to plants

Returning fly ash and bottom ash. Standardised measures for returning fly ash and bottom ash to the soil are integral to recycling. Estimated time required up to 3 years

Removing heavy metals. The development of methods for cleaning fly ash of heavy metals would ease the recycling of fly ash to the soil. Costs and scenarios analyses can be done for different methods based on earlier research. Time perspective 3 years.

Measures linked to fields

Knowledge transfer from the forestry sector. One quick and effective measure to raise the level of knowledge would be to take an inventory of the ash recycling knowledge available in the forestry sector in order to see what could be applied within agriculture. A project like this could be done quickly in the form of reading publications and accessing expertise from both forestry and agriculture.

Effect of ash on arable land and cultivated crops. Knowledge is needed on how ash from different energy crops and different storage methods affect both the crops and the soil system. The suitability for different agricultural crops should be investigated in field trials, as should the risk of increased nitrogen leaching. This would take at least three years. Such knowledge is important if ash is to be made optimum use of and to avoid adverse environment impact.

Suitable crops after ash spreading. Different plants can have varying capacities to assimilate the nutrients in the ash, while certain crops could suffer a negative reaction. An orienting one year study with growing trials in the laboratory is considered sufficient initially.

Determining phosphorus accessibility in different ashes and the further processing of ash products. Knowledge of phosphorus in ash is of significance as phosphorus is considered to be one of the most important nutrients in the ash. An initial survey of how accessible phosphorus is in different ashes can be done as a pre study in the form of ash analyses. Field trials can be of interest as a second step, but this can take longer than three years. Such studies would be considered more urgent if granulation of ash were to be on the agenda.

Pelleting/granulation of ash. Further processing the ash can make for more even spreadability and better control of nutrient accessibility. How further processing affects the solubility of nutrients (primarily phosphorus) ought to be taken into account too. A project designed to evaluate and test technology developed for forest land combined with spreading trials are considered to be of certain interest within the research programme, and ought to be able to be done within three years. For instance, projects can be done in cooperation with chemicals/artificial fertilizer companies.

Knowledge gaps assessed to have a lower priority

Measures linked to plants

Hemp ash characteristics. As there is currently no detailed knowledge of hemp ash characteristics this could be the subject of a project. Time perspective 3 years.

Ash volumes. Energy crops create more ash than other fuels. It is therefore important to find methods of removing large quantities of ash from boilers efficiently. Time perspective is 3 years.

Leaching water. Strategies for dealing with leaching water when removing water. At present, this has been given a lower priority as the improvement potential does not offset the project costs.

Measures linked to the soil

Water content of ash from boiler to transporting to farms. Water content is an important parameter for spreading ash well. Knowledge on how different methods of storage affect the water content of ash is therefore important, and at the same time ash storage methods that deliver the desired water content need to be identified. Practical trials can be performed both in the lab and in field trials. It is estimated this would take about 12 months.

3 Current research programmes

This chapter provides a brief summary of current research programmes than in terms of subjects addressed are tangential to the Värmeforsk programme on burning energy crops. Please see table 1 for an overview of current research programmes, with the programme titles, period and budget. Specific current research projects are addressed by subject area in chapters 5-13. Current and completed European research and development initiatives within small scale bioenergy-fired heating and power production (less than 10 MW) are described in [1].

Table 1. Current research programmes within the area

Research programme	Period	Total Budget
Production and refinement of energy crops and energy savings within agriculture (SLF)	2005-07-01 – 2009-06-30	16 MSEK (+ ca 12 MSEK)
Rural development programme (SJV)	2007–2013	35 billion SEK
Sustainable supply and refinement of biofuel (Swedish Energy Agency) Sub programme: Production engineering platform for the Swedish pellet industry (Swedish Energy Agency)	2007-01-01 – 2010-12-31	160 MSEK+ additional funding
Small scale biofuel fired heating (Swedish Energy Agency)	2007-2010	40 MSEK+ 40 MSEK additional funding
High temperature corrosion centre of excellence (Swedish Energy Agency)	2006-2009	87 MSEK
TPS Sector research programme for energy plants	2006/2007	6.6 MSEK
Ash programme (Värmeforsk)	2006-2008	45 MSEK
Moisture content measuring of biofuel (Värmeforsk)	2004-2008	7.8 MSEK
ERA-Net-BIOENERGY	2006-11-01-2008-03-31	3,8 MSEK (from Sweden)
Värmeforsk basic programme	2005-01-01 - 2007-12-31	50 MSEK

Production and refinement of energy crops and energy savings within agriculture

The programme was started in 1 January 2006 and will run for four years till 30 June 2009. To date, the programme has released three publications (1 Feb 2006, 1 Oct 2006, 1 Feb 2007), with a total budget of 16 MSEK, of which SLF provided 60% and Swedish Energy Agency 40%.

Additional funding is being sought for the remaining period, where SLF can provide 7 MSEK and the Swedish Energy Agency 4.67 MSEK.

The programme goal is to improve opportunities for farming to increase its own use and sale of energy crops and bioenergy in refined form in the short and long term and so create new business opportunities for agriculture and help reduce the use of fossil fuels. A further goal is to achieve general energy efficiencies within main farming production.

The programme is divided into four sub areas:

- Farming company energy systems and energy supply
- Fuel raw materials for the market
- Raw materials for biofuels
- Farmers as energy entrepreneurs – logistics and business models

Projects are geared towards issues that have clear relevance to Swedish agriculture, energy companies and other consumers within the bio energy area. Projects are based on the opportunities and problems that exist within different parts of the country and industries/companies will benefit from being involved in shaping and implementing such projects. From the programme side, cooperation between producers and consumers is considered to be of great value, as it would facilitate the development of a market for biofuels from farming. Initiatives are divided into projects that are good for demonstration purposes, plus development and research projects. The programme is mainly geared towards relatively short term development projects as it is felt important to be able to apply the findings proactively quickly.

The rural development programme

A new rural (LBU) programme was launched on 1 January 2007 to provide support and financial compensation to rural areas. The programme is administered by the Swedish Board of Agriculture (SJV) and regional county administrations and will run till 2013 with a total budget of around SEK 35 billion, or around SEK 5 billion a year. The programme replaced the earlier environment and rural programme that ran from 2000–2006. The LBU programme includes support for:

- development of rural areas,
- environment improvement measures and
- increased competitiveness within farming, forestry, gardens, reindeer farming and food processing.

At time of writing (May 2007) the programme is still awaiting approval from the EU Commission and as such, changes can occur before this. However, applications for support can be made now.

The rural programme is directed at everyone interested in rural development or business enterprise in rural areas. Most forms of support are geared towards farmers, but some measures are available for small businesses, forest owners, not for profit and other organisations in rural areas.

The programme includes the following support:

Environment support – for farmers who wish to sell environment services to society. Support will be similar to that available in the earlier programme.

Project support – for companies, associations of companies, organisations, local authorities etc to implement projects in rural areas. Project results must benefit more than one party or contribute to achieving the rural programme goals.

Company support – available for new operations with a company, or to start a new farming or reindeer farming enterprise. As part of this, investment support can be available for e.g. fixed assets, machinery and equipment.

Skills development – covers training, advice, seminars and information campaigns to people actively engaged in farming, gardening, reindeer farming, food, forestry or rural development enterprise.

Regional support – for farmers in areas less favourable for farming. Skills development.

In addition to the above, the rural programme offers **other support** available for:

- forest-related measures
- nature and culture environments in reindeer farming areas
- endangered pet breed preservation societies

Leader

Leader is one way of applying part of the LBU programme support. The aim is to help achieve rural development goals with the aid of local knowledge and local involvement. To be eligible, a specific form of local partnership has to be formed, a so called *LAG group*. An LAG group has to include representatives from three sectors of society: the not for profit, public and private sectors. The LAG group is responsible for producing a common development strategy for a specific geographic area, and to decide which projects can be funded via the LBU programme. Leader projects implemented in line with the development strategy can get additional funding from the programme.

Sustainable supply and refinement of biofuel

The programme, which is managed and administered by the Swedish Energy Agency, runs from 1 January 2007 to 31 December 2010. The annual budget of 40 MSEK covers both basic research and industry driven development projects. This includes both individual projects and closely connected activities such as large interdisciplinary projects and externally managed development programmes. The programme includes three themed areas: *Forestry*, *Farming*, *Refining*, and the transverse area *Strategic knowledge*. The goals for the latter three areas are described below.

Farming includes the following goals:

- Commercial available coppiced willow to be improved in the medium to long term to meeting future market needs for new growth characteristics. Swedish commercial refining to be international leading and supported by know how from universities.
- Willow cultivation to be made more profitable in the short to medium term by improvements to machinery, farming management initiatives or other types of measures that help make it a more competitive energy crop.
- Production and the use of energy crops other than willow to be made more viable in a short to medium term perspective.

The programme also helps finance the *Production and refinement of energy crops and energy savings within farming* programme run by SLF (see earlier in this chapter).

The area of *Refining* includes the following goals:

- Development of resource efficient and cost effective pellet production in a good working environment
- Optimised quality in terms of input raw materials and end product, adapted to handling system and small and large scale application.
- Development of fuel characteristics and qualities in line with R&D findings within combustion technology.
- Pellet production from a broader, cost effective raw materials base.

Strategic knowledge includes the following goals:

- An environment consequences description for the forest fuels area
- Methods to enable different environment goals related to bio energy to be weighed against each other
- Meet the needs of government organisations for new knowledge when taking decisions within subject areas relevant to biofuels.

Sub programme: Production engineering platform for the Swedish pellet industry

The Swedish Energy Agency has awarded 18 MSEK to the Swedish University of Agricultural Science, for a research programme entitled “Production engineering platform for the Swedish pellet industry. This grant provides 40 percent of the total costs of the programme which will last four years (2007-2010). The total budget is 45 MSEK.

The overall goal of “Production engineering platform for the Swedish pellet industry” is to create the right long term conditions for the increased supply of pellets to the energy system . The main focus within the programme lies in forestry raw materials. This is to be achieved via cooperation between research and the pellet industry, in order to gradually develop a broader raw materials base for pellet production. Process costs and resources efficiencies are also important as is the need to adapt and further develop pellet quality to varying combustion technologies.

Small scale heating with bio fuels

The Swedish Energy Agency has allocated 40 MSEK for the period 2007-2010 for the “Small scale heating with biofuels” programme. The goal is to develop secure small scale heating supply based on bioenergy in plants up to 10 MW. The programme aims to contribute to the development of a sustainable energy system and at the same time boost the competitiveness of Swedish industry on the international market by developing know how and expertise within industries and to improve cooperation between universities, colleges, institutes and enterprise. The programme is split into six project packages. Project funding applications are currently being invited within the programme up to a total of 35 million. Applicants are required to submit project outlines that will form the basis for formulating the project packages: Small scale pellet engineering, small scale communal heating, biofuel, solar energy, wood fired boilers and local combustion furnaces, technology watch and system aspects and synthesis.

High temperature corrosion (HTC) centre of excellence

The high temperature corrosion centre of excellence, Värmeforsk and Materials Technology for thermal energy processes (KME) are organising a programme from 2006-2009 that seeks to contribute to realignment to a sustainable energy system via materials development for new efficient thermal processes. The goal is to solve materials problems related to more efficient power production from renewable fuel and to help develop new materials for future energy systems. The HTC research is being structured into a handful of *large projects* each covering several different *application areas* and that can consist of several *sub projects*. The large projects are:

- Large project 1 – Better steam data when burning biofuel and waste/CO₂ capture
Application areas include:
 - o Power and heating from biofuel
 - o Power and heating from waste
 - o “Advanced processes”
 - o Combustion with CO₂ capture.
- Large project 2 – Gasification and gas turbines
Application areas include:
 - o Gasification of biofuel and black lye
 - o Material for steam reforming
 - o Gas turbines for combustion of synthetic gas in combi cycle installations
 - o Gas turbines for higher reliability and greater fuel flexibility
- Large project 3 – New technologies for energy conversion, energy savings for vehicles, industry and households.
Application areas include:
 - o High temperature materials for household and processing industry heating
 - o Carrier material for exhaust catalysers, systems for exhaust gas after treatment
 - o Recuperators for processing industry
 - o Construction materials for fuel cells (SOFC)
 - o Small scale combustion of biofuel

TPS Sector research programme for energy plants

The TPS sector research programme runs 12 month projects with the active participation of energy works. The programme is divided into four technology areas, the three common combustion technologies of grate boilers, powder combustion and fluid beds and one area that is combustion technology independent.

Ash programme

The Värmeforsk ash programme includes research into the use of ash, including recycling of ash from burning different fuels. This recycling is mainly focused on the recycling of wood fuels to various types of forest land but also to energy crop fields e.g. willow and hemp. The ash programme for 2006-2008 follows on from earlier ash programmes with the goal of creating more long term security, assuring and extending

findings where required such that they can be applied in practice. Research is being pursued in the areas of:

- Geo engineering
- Fly ash in roads and other surfaces
- Fly ash in concrete and mortar and to complement/replace cement
- Bottom ash
- Deposits
- Environment and chemistry
- Ash for forests and land

Measuring moisture content of biofuel

The overall goal of this research programme is to:

- develop a standard measurement technique based on NIR technology or radio frequency for the automatic moisture content measurement of fuel on delivery to plants.
- on-line measurement with NIR for boiler control

ERA-Net-BIOENERGY

ERA-Net-BIOENERGY is a network of national R&D financiers within the area of bioenergy. The overall ERA-Net goal is to promote European research cooperation within the area of small scale combustion ($< 3\text{MW}_{\text{th}}$) of biofuel. The participating countries are Austria, Finland, Germany, Sweden and Great Britain. Five projects are currently in progress, four of which with Swedish involvement. Projects address the areas of development status for small scale combustion of pellets from new ash rich raw materials, possible methods for controlling small scale pellet combustion, clean combustion of biofuels in small scale heating plants: particle measurement and sample taking plus physical/chemical and toxicological characteristics determining, development of testing methods for small scale equipment for the combustion of solid fuels apart from wood and small scale cogeneration of power and heating.

Värmeforsk basic programme

Värmeforsk (www.varmeforsk.se) is a sector organisation for research and development within the energy sector, especially oriented towards fuel based power and heating production. Its research programmes are dictated by the needs perceived to be most important by the sector, which are largely dependent on external factors such as environment targets established. In terms of structure Värmeforsk is divided into the basic programme, where basic research is carried out, and an applied programme. The Värmeforsk basic programme is structured into four research areas:

- Plant and combustion technology
- Materials and chemicals technology
- Process management
- Interdisciplinary

The timetable for the basic programme is currently 2005-01-01 to 2007-12-31. The annual budget is estimated at around 17 MSEK, i.e. 50 MSEK for the entire period.

3.1 References

- [1] Gustavsson, L., Kjellström, B., Kovács, P., 2007 “R&D for small scale bio energy application – a European overview” Swedish Energy Agency

4 Production costs for agrifuel energy

This section reports the results of cost calculations for different crops intended for energy purposes. One of the calculation aims has been to use a methodology that makes the calculations for different crops as comparable as possible. The main aim has been to evaluate production costs for different field crops. The results, see table 2, are, with the exception of straw, the same as in “Evaluation of agriculture as a bioenergy producer, Jo 2005:05”.

Table 2. Production cost in SEK per MWh for energy crops. The figures should be regarded as approximate rather than exact costs.

Production area	willow	Hemp	Reed canary grass	Common wheat	Oats	Straw
Götaland southern plains (Gss)	130	318	222	296	303	150
Götaland middle (Gmb)	160	318	225	327	341	
Götaland northern plains (Gns)	140	325	228	354	354	
Svealand plains (Ss)	153	330	232	384	386	
Götaland forests (Gsk)	168	345	236	390	427	-
Mid Sweden forests (Ssk)	188	351	239	396	439	-
Lower Norrland (Nn)	-	362	239	-	631	-
Upper Norrland (Nö)	-	362	239	-	603	-

The costs for straw has been estimated as 150 SEK per MWh. The calculations for straw have been done in the EU RENEW project using the same methodology and cost as for other crops, which means the costs in the table are comparable. Straw for energy is considered feasible only on plains and intermediate areas.

From table 2 it is clear that energy forests have the lowest production costs by far per MWh compared with both existing traditional crops and other energy crops. In the case of low yield soil the production cost per MWh between willow and reed canary grass is not much different to in high yield soil. One explanation for this is the high harvesting, storage and handling costs for straw fuels. The production costs for hemp seem to be far too high for a large scale energy crop.

Of the straw fuels, straw is the cheapest as the cost of growing falls on the core harvest. Reed canary grass seems to be the cheapest of the straw fuel energy crops to produce and offers the biggest competitive advantage on the least fertile fields. However, at today's energy prices, it would be hard to grow reed canary grass profitably. Grain has higher production costs per MWh than willow and reed canary grass but can have a higher value per MWh for smaller energy users due to the relatively low costs of equipment and operation at small plants, especially compared with unrefined straw fuels.

Table 3 shows the cost breakdown in percent for the different crops. This can provide an indication of the significance of different costs for the various crops. As the table illustrates, the costs of harvesting, storage and transport add up to the bulk of the costs for straw fuels. In the case of willow harvesting and transport make up a substantial cost, too. For the annual crops, the cost of establishing them makes for a relatively high proportion of the costs for obvious reasons. It is crucial to reduce handling costs for willow and straw fuels after harvesting. Another finding that is not apparent from the table however, is that in the case of straw fuels, it is more important to reduce the harvesting and handling costs than to increase the yield.

Table 3. Example of the distribution of costs in percent for different crops at certain yields, indicated in the table. Land costs are not included. The share of costs related to harvest and transport increase with an increase of the yield.

	willow	hemp	Reed canary grass	Common wheat	oats	Straw
yield, tons/ha	8	6	5	5	4	
Cost type						
Establishment	20	29	6	20	35	0
Feeding	18	9	23	22	14	9
Harvest and field transport	25	24	28	14	15	39
Storage	0	11	12	9	5	22
Road transport	16	12	10	4	3	18
Sales	6	3	4	4	3	6
Maintenance etc	6	4	6	19	14	1
Overheads	10	7	12	9	10	5

4.1 Cost assumptions for calculations

All calculations include direct costs, all heavy goods transport, costs for entrepreneurs' own work, and capital with a real interest rate of six percent, 30 km transport. Storage costs have been accounted for with straw fuels. A brokerage cost of six percent has been accounted for on fuel revenues. The calculations relate to shipments to large users. Land costs and support are not included in the calculations. Modified total step calculations have been used [2] for all crops. Which means the same method has been able to be used for annual and perennial energy crops. Using the same method enables better comparability between the various alternatives.

Yields are of major significance for production costs. Table 4 shows what yields have been used in the calculations for the various crops [3].

Table 4. Summary of estimated average yields for various energy crops, cultivated on average farmland within each production area, in tonnes per hectare and year [3]. The column to the right shows the crops energy content in MWh per tonne dry matter [4].

Energy crop	Average yield per hectare and year								MWh/ ton ds
	Gss	Gmb	Gns	Ss	Gsk	Ssk	Nn	Nö	
Wheat kernel	6.4	5.5	4.8	4.2	-	-	-	-	4.5
Oat kernel	4.8	4.1	3.6	3.2	3.0	2.8	1.9	1.9	4.85
Reed canary grass	5.4	5.2	5.0	4.8	4.6	4.5	4.5	4.5	4.5
Hemp	6.5	6.5	6.2	6.0	5.5	5.3	5.0	5.0	4.5
Willow	9.5	6.5	8.2	7.0	6.0	5.0	-	-	4.4

4.2 Comments on the calculations

From a costs perspective, having to establish crops every year is negative and raises the production costs for annual crops. It is also costly to handle straw fuels in bale form compared with e.g. energy forest chips and grain kernels. Hemp is both an annual crop and also needs to be handled in bale form which means it is expensive to produce for large scale energy purposes. Straw fuels are expensive to handle and store which means the costs rise if they cannot be shipped in association with harvesting. Energy forests are harvested in the winter months when energy needs are at their highest, which reduces storage costs.

The different crops are at different development stages in terms of both, refining cultivation, cultivation technology and post harvest handling. Which means the greatest potential for cost reductions lies with least developed crops such as e.g. willow. It also means that traditional farming crops do not offer the same cost reducing potential as the new energy crops, assuming these are to be grown on a large scale.

One advantage of using traditional crops for energy purposes is that there is a tradition of growing them and existing resources that can be exploited, which means greater acceptance amongst farmers to grow these crops. The disadvantage compared with energy crops such as willow and reed canary grass is that the cultivation costs are higher per MWh for traditional farm crops. Based on this, we can say that from a short term perspective, certain farmers could possibly be interested in exploiting existing resources for energy production. In the long term, when these existing resources need renewing, the competitiveness of crops specially adapted for energy e.g. willow and reed canary grass will be boosted. However grain is cheaper to handle than straw fuels, which means there are cost savings available in the post harvest chain. Willow does, however, have the advantage of being harvested when the need for heating and power is at its greatest, which reduces the need for long term storage.

4.3 References

- [2] Rosenqvist H., willow cultivation – Calculation methods and profitability, Silvestria 24, Swedish University of Agricultural Science, Uppsala, Sweden. 1997.
- [3] Börjesson P., Production costs for biofuel in Swedish agriculture, sub report 1, 2007.

4.3.1 Personal messages

- [4] Börjesson, Pål. Environment and energy systems, Lund University Faculty of Engineering

5 Obstacles to and opportunities for the production and use of energy crops

Håkan Rosenqvist

There are a number of production related obstacles and opportunities for energy crops. Several of these are described below.

Obstacles to crops

- Small growing acreage
- No functioning market outlet
- No functioning market for energy crop related services
- Reduced employment
- Reduced use of own machinery and equipment
- Tied in for a long period
- Leasing
- Change of landscape view
- Energy crop support
- Crop know how
- Perceived risk
- Technology

Opportunities

- Increased income
- Reduced employment
- Further processing
- Hunting
- Expanded income portfolio

5.1 Obstacles to crops

5.1.1 Small growing acreage

A small acreage of willow, reed canary grass and hemp leads to high costs and is an obstacle to both market growth and technological development. A small growing area can also need other market solutions and other technological solutions. Examples of this can be briquetting straw fuels when the conditions are not in place for large scale consumption, e.g. small scale briquetting of hemp [6]. In order to reduce costs for bioenergy it is important to address issues related to how the various energy crops can be grown on a sufficient scale to ensure the fuels can be sold on an open market, financial incentives for development and sufficient acreage for special machinery. Costs can be reduced by economies of scale and through the development of machinery and know how, technical developments and cultivation refinements [21]. In the case of new energy crops like willow, reed canary grass and hemp, costs can be cut substantially in many instances if these crops could be grown on a large scale [21]. In which case, implementation issues become important and need further research. The points below are of major significance for implementation. In addition to the below, support systems

are also of major importance for implementation. How support systems are structured is important to ensure they not only promote large acreages but above all, promote high energy yield production. The reasons why farmers do not invest more in perennial crops need further research.

5.1.2 No functioning market outlet

This can be of a structural nature, such as in the willow area where there is virtually only one supplier, namely Lantmännen Agroenergi. Knowledge is required here on how sales and structure can be done by local companies. Another difficulty is the lack of customers for such fuels within reasonable distance, which is particularly the case for straw fuels. This leads either to a need for further processing e.g. ready heating or the creation of a local market for the biofuel. One step towards creating local consumers can be local briquette or pellet manufacturing for local distribution.

5.1.3 No functioning market for energy crop related services

When there is little acreage under cultivation the start up phase is simplified if standard farming machinery can be used. You need a sufficiently large growing area in order to keep costs at a reasonable level when using special machinery for e.g. willow harvesting and planting. Small acreages also generate uncertainty for machinery owners. With only one machinery owner to rely on, there is also the risk that the service will be priced higher, if there is no competition.

5.1.4 Reduced employment

Individual businesses can reduce their labour force with certain energy crops such as e.g. willow, and also in certain cases for reed canary grass. The alternatives to energy crops and possible further processing will have a major say in how employment changes [27] [29].

The employment effect would need to be divided into employment for farmers, and employment for others.

One way of increasing employment is to further process the crop and distribute it to customers. It is appropriate here to divide employment and costs into 1) growing 2) further processing and 3) distribution. This would enable the findings from each area to be applied in other situations.

A comparison also needs to be done with the alternatives to energy crops. We have pretty good data on how much time is spent in the field but less well informed about other time and overheads.

5.1.5 Reduced use of own machinery and equipment

Moving existing production of e.g. grain to perennial crops, such as willow and to a certain extent reed canary grass, means a change in the resource set up. This can be perceived as existing resources not be made proper use of. This line of reasoning calls for a closer look at the costs associated with the time such equipment is used. This can be done by simulation with models in association cooperative machinery [4]. This

methodology could also be applied to changing areas under cultivation on individual farms where energy crops are grown on part of the farm.

There is also a need to differentiate between short term and long term analyses. Current support calculations, such as those published by the Agriwise Swedish University of Agricultural Science, HS for southern Sweden and the county of Västra Götaland, include a lot of costs that have not been taken into consideration. Not including all costs in support calculations makes comparisons more difficult between crops where the costs are very much company common costs and crops that have less impact on common costs for the company. This favours more resource intensive crops when contributions are looked at in isolation in support calculations. By the same token, energy forest and reed canary grass farming get less favourable treatment in today's support calculations.

If the calculations were done in a different way the calculations that use common resources would not have been advantaged by a low cost for using existing resources. The pros and cons of the various calculation methodologies are illuminated in [24], but work needs to be done on implementing a new calculation methodology in practice that can be used for both short and long term analyses of growing different energy crops and for comparisons with traditional crops.

5.1.6 Tied in for a long period

According to preliminary results from an ongoing study, that is looking at e.g. reasons why energy crops are not cultivated, one huge obstacle to energy forestry is having to tie in to this for such a long time [14]. One way to tackle this would be to take a close look at the financial effects of premature termination and how such termination could be done in practice.

5.1.7 Leasing

For various reasons, the leasing of land is an obstacle to the establishment of willow farming. About 45 percent of arable land in Sweden is leased. Only around 9 percent of willow grown is on leased land [22]. It is not known what proportion of this 9 percent that is leased is done so by so called operating companies and what proportion is leased to or from relatives. To help increase the proportion of other leased land available for energy forests, research needs to be done on how this should be structured, communicated and agreed between different organisations. The question of whether energy forestry can be an option for the land owner when leasing out land, and if so, how this should be structured, should also be looked at.

5.1.8 Change of landscape view

A very big obstacle to the desire to plant willow is that willow grows so tall [14]. As such it is important that willow planting is sympathetic to the landscape [26].

5.1.9 Energy crop support

To be eligible to receive energy crop support of 45 Euros per hectare, you need a contract with either a purchaser or refiner. This can create an obstacle if sales are made other than through companies that are already established today, such as Lantmännen

Agroenergi. The way this is structured needs to be looked at and described in a way that reduces this obstacle.

5.1.10 Crop know how

It is important that anyone investing in a new crop has knowledge and understanding of the crop. This is addressed in the current project “*Market analysis of the range and future range of energy crops for heating production*”, that is designed to help provide information related to farmers’ attitudes to the cultivation of energy crops, see section 5.3 [14].

In order to pass on knowledge and information on crops it is important to know which farms are most likely to grow which crops. Research in the willow area has shown that this is mainly larger farms, farms without livestock, farmers between 40 and 65 years of age, farms in the area with medium good soil plus energy forest growers are often more highly educated than the average farmer [15][16][17][18][22].

5.1.11 Perceived risk

Enterprises act in accordance with perceived risk. An increased risk is perceived by most business people as a demand for an increase in the expected financial return. In the financial calculations for different energy crops, one can include a cost for risk that differs in magnitude for different crops [21]. The scale of the perceived risk is made up of the actual risk and the perceived risk that can differ from the actual risk and can therefore be influenced. The actual risk is also affected if the return for the item concerned is seen as an isolated phenomenon or set in a portfolio perspective. The combined risk can be reduced if the risk associated with different activities has a low covariation. Based on this, we can conclude that there are at least two ways of reducing the perceived risk. Partly by setting energy crops in a portfolio perspective. [24], and play by seeing how we can reduce the perceived risk with better knowledge and information. To do so, requires further investigation into how potential growers perceive the risk and how the perceived risk can be reduced in a cost effective way. Studies have been performed on which farmers grow willow [22].

5.1.12 Technology

Technologies are at different stages of development for different energy crops. This affects the future cost reduction potential of the crops and how difficult it is to introduce new crops. In the case of hay, studies have been done showing the costs of handling straw fuels [1][7][10][11]. The cost reduction potential of different energy crops has also been studied [21]. In the case of straw fuels such as hay and reed canary grass existing technology used outside the energy sector can be used. This makes these crops easier to introduce but at the same time there is less potential for cost reductions. The scale of the cost reducing potential available for different crops will influence whether or not these crops will be economically competitive in the future.

5.2 Opportunities

5.2.1 Increased income

If farmers are to invest in energy crops it is important they choose a crop that meets their goals. One of the most important goals is higher earnings. Production costs and the profitability of different energy crops have been investigated in a number of studies [5][12][13][19][21]. A study has also been done on the profitability, potential and structure of supplying straw fuels to a larger consumer [9]. It is also important to look at what cost reductions can be expected in the future and how these can be achieved, an area which has been investigated in part [21].

Profitability and yield per hectare can be improved via a combination of energy crop cultivation and slurry and drainage water measures [19][20]. To further enhance profitability within the energy crops sector, there is a need for systems studies that do not look at each crop and production method in isolation. By putting the various crops and forms of production in a wider context solutions that are most effective at achieving additional cost reductions can be identified.

If the use of bioenergy increases in the world, the alternative value of the land will rise and grain prices will climb [8]. In this scenario it would be interesting to look at how production per hectare could be increased for both food and energy purposes. This in order to ensure there will be sufficient space for both energy and food production. Production can rise for a given crop with different production technologies but it can also be done with crop substitution. In theory higher yields on food and fodder crops means more arable land can be freed up for energy production. Assuming that the need for food and fodder crops is constant, assessments suggest 29% of arable land can be used for energy crops by 2020, which corresponds to a production of almost 30 TWh of bioenergy [3].

5.2.2 Reduced employment

Reduced employment can be both a goal and an obstacle to energy crops depending on the circumstances of the individual farmer. Acreages of energy crops could rise by looking at whether businesses looking to reduce employment would be prepared to grow energy crops. Energy crops can also be an alternative to leasing out land. For this to happen, it must be evaluated how different organisational structures could be established, including contracts and energy farming management.

5.2.3 Further processing

Studies have looked at how farming enterprises sell heat from biofuels and so make the enterprise more profitable [25][28]. Information on selling heating services is available in several popular science brochures. Briquetting of straw fuel for local consumption can both increase farm earnings and create a market for straw fuels where there is no large local user [6].

5.2.4 Hunting

Improved hunting opportunities can be an argument in favour of planting energy forests. Approximate calculations of the net benefits of hunting to energy crop farming have been done [2][24]. A more in-depth analysis of how energy crops impact on hunting ought to raise interest in energy crops for some farmers.

5.2.5 Expanded income portfolio

Adding additional strings to the production bow is a way of reducing the risks to a company [24]. Market risks, production risks and political risks and how they interface with existing agricultural production, all need further analysis. Please also see the section on “Obstacles, perceived risk”.

5.3 Current research

The ongoing IVL research project *Market analysis of range and future range of energy crops for heating production*, is expected to be completed by June 2007. Göteborgs Energi, Eskilstuna Energi & Miljö, Lunds Energi, Örnköldsvik Energi, Ena Energi AB, country authorities and Energigården are also involved in the project. The overall aim of the project is to see what current and possible future obstacles and prerequisites there are for energy crops in four geographical areas in Sweden – Skåne, Västra Götaland, Mälardalen and Västernorrland – from a farmer’s perspective. The project seeks to provide information on how farmers view growing energy crops. Another aim is to analyse the value farmers put on different characteristics for the various crop options and to determine the potential for energy crops in terms of farmers’ decision-making processes. The results are based on a choice experiment questionnaire survey sent to 2,000 farmers [30].

5.4 References

- [1] Bernesson S. & Nilsson D., Straw as a source of energy Report - environment, technology and agriculture vol 2005:07, Swedish University of Agricultural Science, Sweden. 2005.
- [2] Börjesson Pål, Hedar Erik, Herland Erik, Jonasson Lars, Larsson Marcus, Rosenqvist Håkan and Westin Paul (Ed.). Evaluating the prerequisites for the continued introduction to market of energy forestry report, Final report, Government resolution 2002-12-05, N2002/11666/ESB, Swedish Energy Agency, Eskilstuna. 2003.
- [3] Börjesson P., Production costs for biofuel in Swedish agriculture, sub report 1, 2007.
- [4] de Toro A., Rosenqvist H., Machinery cooperatives – three case studies. Report – environment, technology and agriculture 2005:03, Inst. of biometry and technology. Swedish University of Agricultural Science Uppsala, 43 sidor. 2005.
- [5] Ericsson, K., Rosenqvist, H., Ganko, E., Pisarek, M. and Nilsson, L., An agro-economic analysis of willow cultivation in Poland. Biomass and Bioenergy. 30, 16-27. 2006.

-
- [6] Forsberg M., Sundberg M., Westlin H., small scale briquetting of hemp. JTI-report 351, JTI – Swedish Institute of Agricultural and Environmental Engineering. Uppsala. 2006.
- [7] Jesper T. Graversen & Morten Gylling, Energy crops for combustion – Production economics, handling costs and supply plans, SJFI – Working Paper no. 7/2002. Statens Jordbrugs- og Fiskeriøkonomiske Institut. Copenhagen, Denmark. 2002.
- [8] Johansson D and Azar C., A scenario based analysis of land competition between food and bioenergy production in the US. Accepted for publication in Climatic Change. 2007.
- [9] Mattsson J. E., Business development – Local straw fuel for combined power and heating plant. Report 2006:8 Inst. of landscape and gardening technology, Swedish University of Agricultural Science, Alnarp. 2006.
- [10] Nielsen V., Hay gathering technology since 1950. DJF Raport Markbrug nr 95, Danmarks JordbrugsForskning, Forskningscenter Folum, Tjele, Danmark. 2003.
- [11] Nilsson D., Harvesting, transport, storage and upgrading of straw as a fuel: methods, energy needs, costs, Report / Swedish University of Agricultural Science, Institutionen för lantbruksteknik, 150. 1991.
- [12] Olsson R., Rosenqvist H., Vinterbäck J., Burvall J., Finell M., Reed canary grass as an energy and fibre raw material. A systems and economics study. BTK-report vol. 4. 2001.
- [13] Parsby M. & Rosenqvist H., Production economics of energy crops – with particular focus on willow, SJFI – Working Paper no. 3/1999. Statens Jordbrugs- og Fiskeriøkonomiske Institut. Copenhagen, Denmark. 1999.
- [14] Paulrud S., Pågående project, IVL Svenska Miljöinstitutet. 2007.
- [15] Roos, A., Rosenqvist, H., Ling, E. & Hektor, B., Factors influencing the adoption of short rotation willow coppice production among Swedish farmers. *Acta Agriculturae Scandinavica B* 50(1):28-34. 2000.
- [16] Roos A. and Rosenqvist H., Experiences of commercial energy crop production – A study of willow growers in Sweden. 1st World Conference and Exhibition on Biomass for Energy and Industry, Seville 5-9 June 2000. 2000a
- [17] Roos, A., Rosenqvist, H., A survey of short rotation willow growing in Sweden. Abstracts: XXI IUFRO World Congress 2000, 7-12 August, Vol II (Eds. IUFRO Vienna, Jandl, Devall, Khorchidi, Schimpf, Wolfrum, Krishnapilly) p 11. Kuala Lumpur, Malaysia. 2000b.
- [18] Roos, A. & Rosenqvist, H., Experiences and lessons from large scale energy forestry in Sweden – findings of a survey of willow farmers. Paper presented at Energitinget 2000 14-15 March 2000, Eskilstuna, Sweden. 2000c.
- [19] Rosenqvist, H. and Dawson, W. M., Economics of using wastewater irrigation of willow in Northern Ireland. *Biomass and Bioenergy* Volume 29, 2005 83-92.
- [20] Rosenqvist, H. and Ness, B. An economic analysis of leachate purification through willow-coppice vegetation filters. *Bioresource Technology* 94: 321-329. 2004.

-
- [21] Rosenqvist H. and Nilsson L., Energy crop production costs in the EU. Report in EU project RENEW. 2007.
 - [22] Rosenqvist, H., Roos, A., Ling, E., Hektor, B. willow growers in Sweden. Biomass and Bioenergy 18(2):137-145. 2000.
 - [23] Rosenqvist, H. and Dawson, W. M., Economics of willow growing in Northern Ireland. Biomass and Bioenergy Volume 28, Issue 1, January 2005, Pages 7-14.
 - [24] Rosenqvist H., willow growing – Calculation methods and profitability, Silvestria 24, Swedish University of Agricultural Science, Uppsala, Sweden. 1997.
 - [25] Rosenqvist, H. & Uhlin, H-E. Small scale communal heating from forestry – A commercial concept for farming enterprises. U(B) 1992/2. Vattenfall, Vällingby. 1992.
 - [26] Skärbäck E., Svensson, I., Krigström P., and Hultenberg S., Energy forests in the landscape, advice and directions for starting. Swedish National Board for Industrial and Technical Development, Stockholm. 1993.
 - [27] Stridsberg, S., The total employment effect of biofuels, The Swedish Farmers' Foundation for Agricultural Research, January 1998
 - [28] Svensson J., Farmers as energy producers – A case study in energy initiatives in farming, Dissertation No 459, 2006. Inst. of economics, Swedish University of Agricultural Science, Uppsala. 2006.
 - [29] Uhlin, Hans-Erik and Themppillai, Dodo, 2001, Regional heating provision: a study of regional economic effects for individuals and society of wood based fuels for heating production in WX region (counties of Dalarna and Gävleborg), University of Gävle.

5.4.1 *Personal messages*

- [30] Paulrud, S. IVL.

6 How cultivation and harvesting affect fuel quality

6.1 Straw

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6.1.1 Water content

The water content of cut straw must be less than 20% to prevent mould growth and temperature rise in bales [1]. Straw shredders and other handling equipment are less effective if the water content in the straw is higher than the figure above. If the straw is too moist, cakes of mould are easily formed, which can interrupt production in shredding machinery.

6.1.2 Basic constituents

6.1.2.1 General

The various elements contained in straw are pretty well documented. For instance, the Fuel handbook published by Värmeforsk says straw contains C, H, O, N, S, Cl. The same source gives the main elements of its ash as Al, Si, Fe, Mn, Mg, Ca, Na, K, P, but not , on the other hand, Ba or Ti. The fuel handbook also states the effective calorific value of straw. The elements contained in straw and its ash are also listed by various research projects that have been done [1].

6.1.2.2 Chlorine and alkali metals

Straw has a high content of chlorine and alkali metals such as potassium and sodium that can cause problems on combustion [2][3] through the formation of sodium chloride and potassium chloride, which are highly corrosive, especially at high temperatures. See also chapter 10.

As straw is widely used to produce electricity in Denmark today, a number of studies have looked at ways of reducing the amount of potassium and chlorine in straw [4]. It is worth noting that high levels of these elements cause a variety of problems in power plants, such as.

- Corrosion in superheaters
- Slag formation and blockages
- Shorter life expectancy for catalysers for NO_x –reduction

The Danish trials showed a positive correlation between the levels of potassium and chlorine in straw [4], which was also demonstrated by Hansen and others [5].

6.1.3 Cultivation specific characteristics

6.1.3.1 Influence of crop species

Danish research has included comprehensive studies of the various elements found in straw, such as silicon, calcium, potassium and chlorine [4]. In terms of species of grain

(wheat, rye, corn) they proved to largely have the same make up. With the exception of wheat however, that had a significantly higher level of silicon.

In the case of rape straw, the levels of potassium and chlorine were the same as grain straw. On the other hand, the silicon content was comparatively low and calcium content high. The latter could suggest comparatively good combustion properties. The ash melting point for rape straw is also higher than for grain straw [6]. This means that the risk of sintering and coating rises in the boiler is also lower when burning rape straw. One disadvantage of burning straw from oil plants however is that they have a high nitrogen content, which means you lose nutrients on combustion and NO_x emissions go up.

6.1.3.2 Affect of type

In addition to the differences between species the Danish research also looked at type specific variations [4]. Comparisons of a couple of types of barley and rye revealed no differences in the chlorine and potassium contents. However statistically valid differences were found in three types of wheat.

6.1.3.3 Location

There does not appear to be any connection between geographic location and the chemical composition of straw [4].

6.1.3.4 Soil

The Danish studies found no connection between the type of soil and the respective potassium and chlorine contents of the straw [4]. On the other hand, a higher clay content showed clear tendencies towards a higher silicon content and lower nitrogen content respectively in the straw. In this context, it is worth mentioning a research project that performed comprehensive analyses of 38 different batches of straw, that revealed e.g. that straw from very fertile soil had a higher ash content than straw grown on less fertile soil [7].

6.1.3.5 Nutrients

The Danish trials showed that using chlorine free supplements significantly reduces the chlorine content in straw [4]. In practice, this means using K₂SO₄ rather than KCl as potash supplement. Analyses of straw samples showed that even though this meant additional sulphur, it did not increase the sulphur content in the straw. The studies also showed that neither nitrogen nor phosphorus application (amount of nutrient elements) affected the potassium content of the straw.

6.1.3.6 Chemical treatment

A survey of four fungicides containing chlorine applied to grain crops demonstrated that in all cases, the chlorine content in the straw increased in the magnitude of 100-1000 percent [8]. Other trials with six different fungicide protectants did not, however, find any clear link between the composition of the straw and the chemical treatment applied to the crop [4].

6.1.4 Harvesting

6.1.4.1 Equipment and technology

Technology that shapes straw into round or rectangular bales sized for machine handling is generally used when harvesting straw for energy. The straws therefore largely retain their original shape which means that the theoretical length of the straw is the height of the crop minus the stubble height, i.e. up to about one metre. However, the straw suffers certain damage between the combine harvester and straw press and possible straw laying. If shorter length straw is required, the infeed channels of the presses can be fitted with cutters.

An alternative harvesting method is shredding the straw. If the straw must be shredded, e.g. for briquetting or pelleting, it can be an advantage to shred it in the field. In which case it is not necessary to bale it and then break up the bales. However the low density and relatively complicated handling make transport and storage expensive [1].

6.1.4.2 How long a crop stays in the field

As part of the Danish trials, straw samples were taken at regular intervals for analysis while at the same time the accumulated rainfall was monitored during the time it was in the field [4]. Figure 1 shows the measured leaching of chlorine, potassium and calcium from barley straw. The graph shows that 100 mm of rain reduced the chlorine and potassium contents to low levels while the calcium content largely remained constant. Equivalent trials with wheat straw returned similar results.

Key to graph: Kalium = Potassium, Calcium = calcium, klor = chlorine

Andel av vikt, Percentage of weight

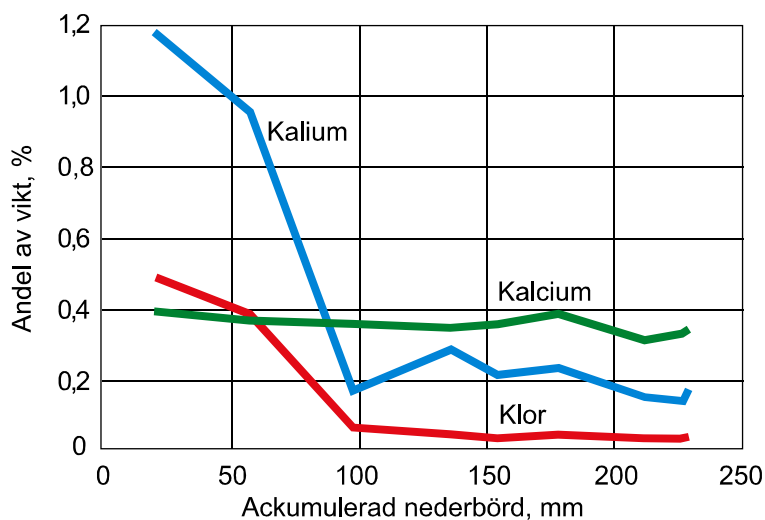


Figure 1. Leaching from barley straw during duration on the field. After Sander, 1977

Substantial leaching of potassium has also been noted in studies that investigated changes in straw placed in fibre bags from September to May [9].

Trials have shown that the energy losses on washing straw in the form of drying energy and the loss of organic material are in the order of some 8% of the straw's calorific heating content [3].

Comprehensive sample taking was done in the Uppsala region of wheat straw that remained in the field 3-4 weeks after combine harvesting. The straw was then analysed for levels of sulphur, chlorine, minerals and ash content [10]. In the case of chlorine content, this was found to generally fall over time that that this process was hastened by rain. The alkali content also fell over time but here rain had less significance than in the case of chlorine.

These field trials have shown that noteworthy changes to the levels of different elements in the straw occurred in the period immediately after combine harvesting independently of rainfall [10]. During dry periods lasting longer than three days after combine harvesting these changes became insignificant. In this context it is worth noting that straw can become grey with mould simply from exposure to night dew and warm weather without any elements having leached out. [1].

The results from the field trials show that mechanical processing of straw probably accelerates leaching [10].

6.1.5 Ashes

The amount of ashes produced on burning straw can vary significantly depending on the origin and technology with which it is burned. Material published on this show ash contents of between 2.5 and 10%, which cover valued determined both in the laboratory and on practical combustion [3][6][10][11][12][13].

One problem with burning straw is that the ash starts to soften at relatively low temperatures [3], often at just 800-850°C, but even at temperatures as low as 600°C. When ash is soft it can have a tendency to sinter and stick to different parts of the furnace and on heat transfer parts of the boiler.

The ash content in straw can vary hugely depending on the quality and where it was grown. Straw contains very free reactive silica and also contains substantial amounts of alkali, which entail a big risk of potassium silicate glass formation in the ash. At the same time, as the Na content is negligible, the melting point for this K silicate glass is assumed to be around 770°C [14].

Calcium is also present, but to a smaller degree. Which means Ca probably could not push up the melting point of the glass to the higher values typical for Ca-K-silicate glass (> 800°C) [14].

Chlorine is present on such a scale that almost 25% of the alkali content can be presumed to vaporise as chloride and give rise to salt deposits. The sulphur content in straw is not sufficient for complete sulphating of alkali chloride [14].

6.2 Current research on fuel quality of straw

To our knowledge there is no research in progress within this area.

6.3 References

- [1] Bernesson S. & Nilsson D., 2005. Straw as an energy source. Review of existing knowledge. Report environment, technology and agriculture 2005:07. Institution of biometry and technology, Swedish University of Agricultural Science. Uppsala.
- [2] Hadders, G., Flodén, S. 1997. Spreading ash from straw fuels on farmland. Requirements and recommendations. JTI report Lantbruk & Industri No 234, Swedish Institute of Agricultural and Environmental Engineering Uppsala. 33 s. ISSN 1401-4963.
- [3] Nikolaisen, L.(ed), Nielsen, C., Larsen, M.G., Nielsen, V., Zielke, U., Kristensen, J.K., Holm-Christensen, B. 1998. Straw for Energy Production. Technology – Environment – Economy. 2nd edition. The Centre for Biomass Technology, Copenhagen, Denmark . 53 p. ISBN 87-90074-20-3.
- [4] Sander, B., 1997. Properties of Danish Biofuels and the Requirements for Power Production. Biomass and Bioenergy. Vol 12, no. 3, p 177-183. Great Britain.
- [5] Hansen M.W., Hansen A., Jensen L.R. & Nielsen C., 1987. Survey of straw-fired combined power plant. Dk-teknik, TR-sagmr 1986-/352-86356.Søborg.
- [6] Stridsberg, S., Christensson, K. 1994. Fuel mixes with straw. Combustion trials at five plants. SLF Report no 10, The Swedish Farmers' Foundation for Agricultural Research, Stockholm. 47 p. ISSN 1104-6082.
- [7] Thellesen H., 1988. Combustion characteristics of straw as fuel. Slag formation. Statens jordbrugstekniske forsøg. Report no 40. Horsens.
- [8] Ravn T., 1986. The farming value of Danish straw. II Chlorine content of barley straw. Report from the Biotechnology Institute, A.T.V., 22 årg., no. 1-4. Kolding.
- [9] Christensen B.T.,1983. Straw decomposition. I. The loss of nutrients and dry matter in barley straw after washing in water. Tidskrift for planteavl 87, 477-487.
- [10] Hadders, G. 1994. Changes in fuel characteristics in straw over the harvest period. JTI-report No 186, Swedish Institute of Agricultural and Environmental Engineering Uppsala. 51 p. ISSN 0346-7597.
- [11] Ekström, N., Jonsson, C. 1985. Straw and ash handling on straw combustion. JTI report No 67, Swedish Institute of Agricultural and Environmental Engineering Uppsala. 55 s. ISSN 0346-7597.
- [12] Nilsson, C., Carling, H., Ekström, N., Ivarsson, E. 1988. Burning straw. The latest from the Swedish University of Agricultural Science 364, Technology. **the** Swedish University of Agricultural Science, Uppsala. 53 p. ISSN 0347-9293. ISBN 91-576-3298-7.
- [13] Henriksson, A., Stridsberg, S. 1992. The potential of using straw as a fuel forenergy in the agricultural areas of southern Sweden. Report 161, Inst. of lantbruksteknik, Swedish University of Agricultural Science, Uppsala. 93 s. ISSN 0283-0086. ISRN Swedish University of Agricultural Science-LT-R--161-SE.

- [14] Strömberg, B. Fuel handbook. Värmeforsk. Fö-324. ISSN 0282-3772. Stockholm, 2004.

6.4 Grain

Hugo Westlin, JTI – Swedish Institute of Agricultural and Environmental Engineering

Grain has traditionally been grown for food purposes. Five different types of grain are most commonly grown in Sweden. In 2005 379,000 ha barley, 355,000 ha wheat, 200,000 ha oats, 50,000 ha triticale and 21,000 ha rye [15]. Other types of grain are found, but are grown on a very limited scale. Interest in using grain as fuel has been growing in recent years, mainly on smaller farms. This increased interest is partly due to high energy costs and low market prices for grain. Grain is also combusted today in around 20 small scale communal heating plants, in which farmers process their grain for heating. The LRF energy scenario for the year 2020 is that the use of grain for fuel is likely to rise in the future. It is assumed there is greater potential for larger plants than for internal use on farms [16].

6.4.1 Fuel characteristics

Earlier studies have shown that there are relatively big differences in the quality of different types of grain as fuel. Surveys done by e.g. Hadders and others. (2001) [17] and Lindström (2004) [18] show that the ash melting temperature of grain is affected by both the elements contained in it and the relationship between the different elements, primarily, calcium, potassium and silicon.

Grain quality is also affected by many other factors, and the importance of these various factors differs from year to year. For instance, the weather conditions during the year and cultivation measures can be at least as important as type of grain [19]. Studies also show that neither nitrogen or phosphorus feed, type or dosage of fungicide could influence the potassium content of the straw.

The water content in the grain kernel and its significance for the effective calorific value has been investigated by Westlin and others (2006) [20]. Their research findings show that the output calorific value of the grain kernel falls if the water content is higher, and that combustion efficiency becomes poorer (the combustion trials were done in a boiler with an approximate output of 20 kW without flue gas condensation).

6.5 Current research on the quality of grain as fuel

JTI is currently running, in partnership with the faculty of biometry and engineering at the Swedish University of Agricultural Science, an SLF funded project on growing energy grain. The project is looking at the opportunities for farming to increase profitability when growing energy grain. As part of the project, a number of types of farms are going to be built and where different strategies for farming energy crops will be applied and the economics of these farms will then be studied. The project started in autumn 2006 and is expected to be completed in the first half of 2008.

Within the Alnarp Partnership a number of project are being pursued on feeding bioenergy crops with waste water products.

6.6 References

- [15] SCB.; Farming statistics year book 2006 with data on food. Örebro, 2006.
- [16] Herland E.; LRF:s energy scenario up to 2020 Renewable energy from farming and forestry offers new business opportunities and a better environment. 2005.
- [17] Hadders G, Arshadi M, Nilsson C, Burvall J.; Fuel characteristics of grain kernels. JTI-report Lantbruk&Industri 289, 2001.
- [18] Lindström E; Evaluation and development of AgroTec grain burner. Energy engineering and the thermal process chemistry (ETPC), Umeå University. 2004.
- [19] Fogefors H (ed); Plant production in farming. Nature and Culture Borås. 2001.
- [20] Westlin H, Lundin G, Rönnbäck M, Österberg S, Johansson M.; Combustion of undried oats and oat husks – how do they burn and what are the financial implications? JTI-report Lantbruk&industri 352. 2007.

6.7 Willow

Pär Aronsson, Swedish University of Agricultural Science

Willow is cultivated on around 15,000 ha of arable land in Sweden, today. The majority (approx 55%) of this was planted before 1996 [21]. Each year around 2,500 ha willow is harvested [26], which generates around 12,000 tons ds chips that are sent to heating plants. Little research has been done on variations in ash content and chemical composition of harvested willow chips. However a study of this was done in 1993 by Ledin and Vigré at the Swedish University of Agricultural Science, but the findings have not been published. Analysis data have been made available for presentation in this report. The samples came from harvested shoots in 28 commercial willow farms in different parts of the country. The samples represent different ages of shoot, clones and growing locations. Unfortunately there is no information on how the samples were taken and how the analyses were performed. Data from commercial willow farms have been obtained from Lantmännen Agroenergi AB who handle virtually all harvesting and sales of willow chips in Sweden.

6.7.1 Dry substance content

Willow is chipped immediately on harvesting and transported directly to heating plants for burning. In some cases, the chips are stacked on the edge of the field for later transport to heating plants. It is unclear how this affects the dry substance content.

The average value for the dry substance content in the 28 samples taken (Ledin & Vigré, unpubl. data) was 44.1 % with relatively wide spread (Figure 2). This can be compared with the levels in willow chips analysed at heat-only boiler stations between 2002-2006 (Figure 2). These values represent analyses of around 2,100 chip loads from some 1,250 willow farms in Sweden [26]. For 2002-2006, on average the DS content was 50.0 % with 52.4% (2003) and 48.7% (2005) as the highest and lowest values. The low DS content in 2005 can be partly explained by the very deep snow in mid Sweden

which meant a great deal of snow was fed into the harvesting machinery. That there are still such big differences between data from Ledin & Vigré and samples from heat-only boiler stations could possibly depend on differences in drying methods. Another possible factor is the time the samples were taken. It has been shown that the DS content is at its highest in early winter, i.e. shortly after the leaves have fallen and after which it continues to drop [22]. The DS content in a clone fell from 52 to 48% from November-April.

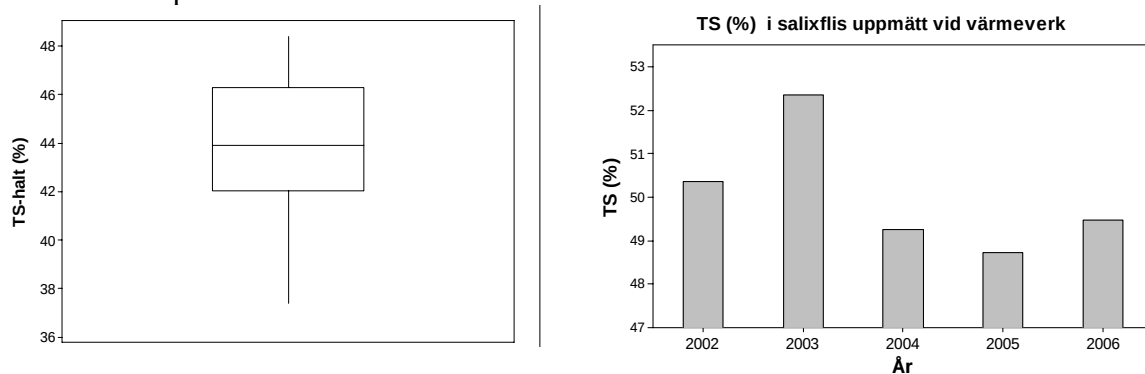


Figure 2. Content of dry substance (left) in 28 samples of willow presented as median value (from Ledin & Vigré, unpublished data), and average content of dry substance (right) in willow chips supplied to plants during 2002-2006 [26].

6.7.2 Ash content

The ash content in willow chips varies somewhat, but in the case of the samples from the 28 willow farms the average was 1.6% with a spread of 1.3 to 2.1% (Figure 2, Ledin & Vigré, unpubl. data.). This ash content is broadly in line with data presented by Strömberg (2004) from analysing a few chip samples. There is a slight tendency in the data for the ash content to be lower the higher the age of the shoot (Figure 2).

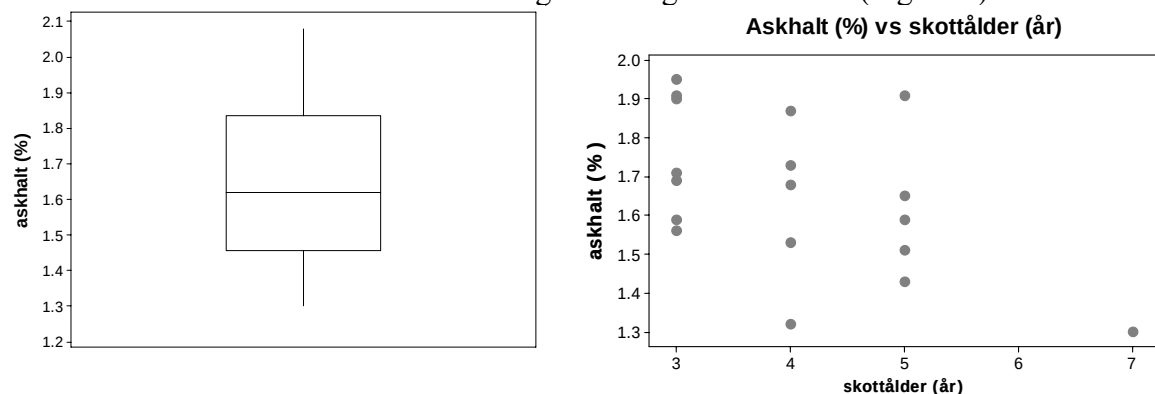


Figure 3. Ash content in 28 samples of willow presented as median value (left) and ash content of the same samples plotted against the age of shoots (right) (from Ledin & Vigré, unpublished data)

Particle size and fraction breakdown are addressed in section 7.7 on storing willow.

6.7.3 Chemical composition

Strömberg [23] presents the results of several separate chemical analyses of willow wood and these are compared in table 5 with analyses done by Ledin & Vigré (unpubl. data). The N and S contents largely agree, but there is a big difference for chlorine.

Table 5. Content of some elements in willow chips according to Strömberg (2004) and Ledin & Vigré (unpublished data).

Source	C	H	O	N	S	Cl
Strömberg (2004) (% ash free)	48.9	6.22	44.4	0.41	0.04	0.03
Ledin & Vigré (unpubl. data) (% of DS)				0.33	0.036	0.003

Willow has a documented good capacity to absorb different heavy metals. This has been noted from both a fuel quality perspective, and from the vision of being able to use willow plants to cleanse ordinary arable land of cadmium for the subsequent production of high quality food. The cadmium content in willow chips varies between different clones and depending on various soil factors (including the cadmium content of the soil) but is usually in the order of 1-4 µg/g DS [24]. In the study by Ledin and Vigré (unpubl. data) the median content of cadmium was 2.4 µg/g DS (Figure 4 and Figure 5).

The proportion of bark in the willow goes down with increasing shoot age and the levels of different elements differ markedly between wood and bark [25]. From this one can speculate that the average levels of various elements in chips are affected by the age of the plantation on harvesting. No clear such trend can be seen in the material (Figure 4). Nor does there seem to be any clear correlation between the annual biomass growth and the level of different elements (Figure 5).

skottålder = shoot age

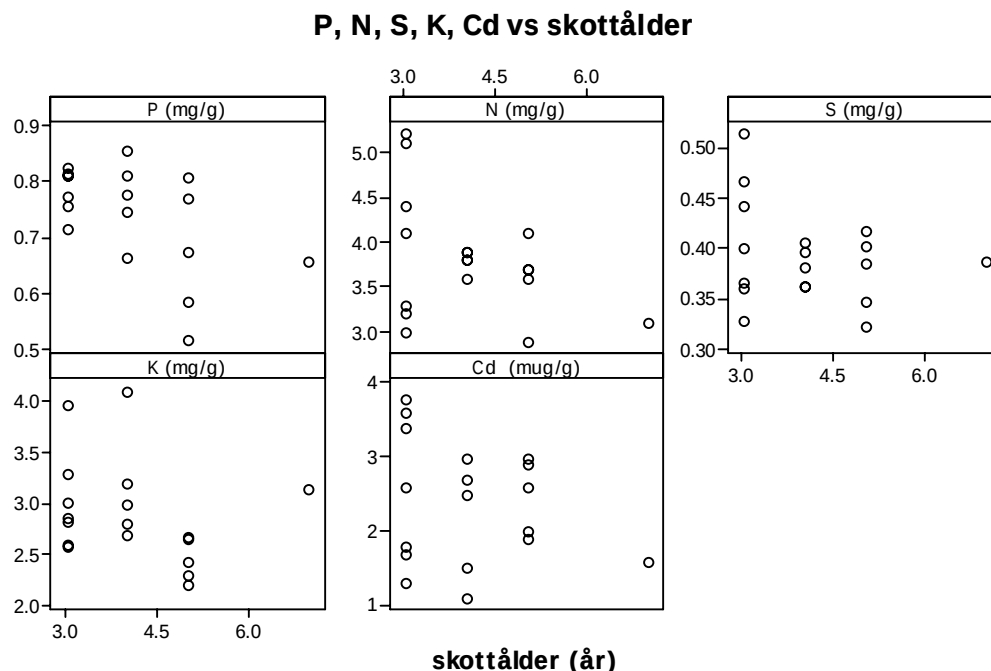


Figure 4. Content of P, N, S, K and Cd in stemwood from willow related to the age of the shoot (from Ledin & Vigré, unpublished data)

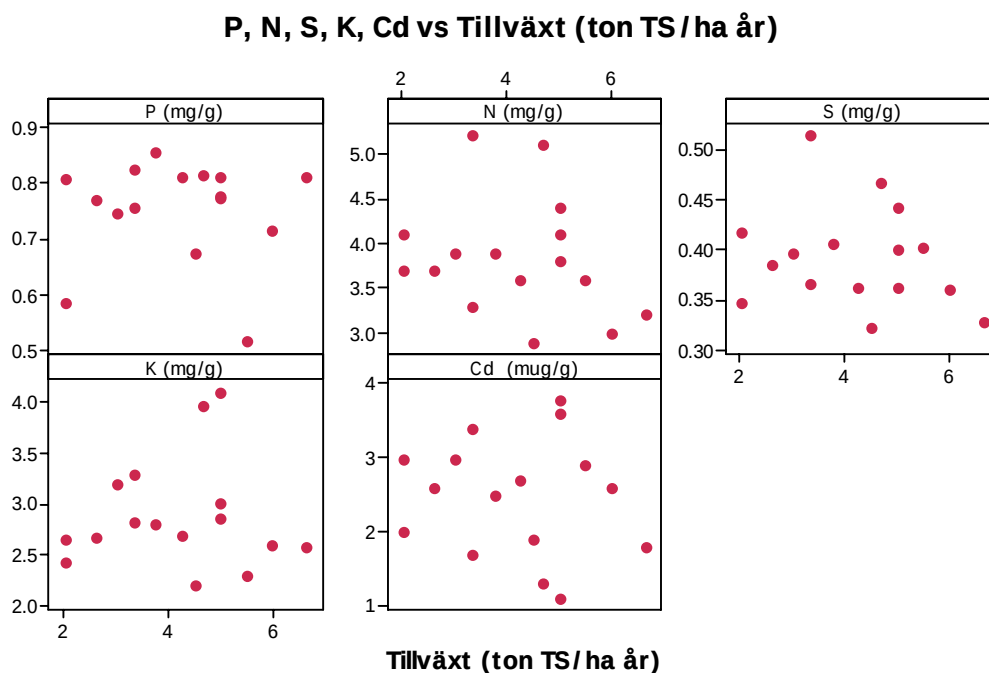


Figure 5. Content of P, N, S, K and Cd in stem wood from willow related to growth (from Ledin & Vigré, unpublished data)

When it comes to the content levels of different elements in willow shoots, there has been no explicit study of any correlation between these content levels and various environmental factors. This was one of the original aims of the study by Ledin and Vigré from which data are presented in this report, complementary soil analyses were also included in the study. It is not clear why no scientific report was made, but one suspicion is that this was because it was not possible to correlate soil factors with the levels of various elements in the willow shoots.

6.8 Current research on willow in terms of fuel quality

ENA Energi, Swedish University of Agricultural Science and Lantmännen Agrobränsle are currently doing cultivation trials with willow. The main angle is looking at the effects of feeding and the results are expected to be available in a few years.

6.9 References

- [21] Mola-Ydego, B. & Aronsson, P. 200X. Yield models for commercial willow biomass plantations in Sweden. Manuscript submitted to Biomass and Bioenergy.
- [22] Telenius, B. 1997. Implications of vertical distribution and within-stand variation in moisture contents for biomass estimation of some willow and hybrid poplar clones. *Scandinavian Journal of Forest Research* 12:336-339, 1997.
- [23] Strömberg, B. Fuel handbook. Värmeforsk. Fö-324. ISSN 0282-3772. Stockholm, 2004.

- [24] Eriksson J. Blombäck K., Perttu K., Greger M., Göransson A., Klang-Westin E., & Landberg T. Amounts and flows of cadmium in the soil-willow system. Swedish Energy Agency, report ER 19:2003. ISSN: 1403-1892, 2003.
- [25] Adler, A., T. Verwijst & P. Aronsson, 2005. Estimation and relevance of bark proportion in a willow stand. *Biomass and Bioenergy* 29:102-113.

6.9.1 Personal messages

- [26] Slagbrand, Rolf. Lantmännen Agroenergi AB.
- [27] Eklund, U. Ena Energi AB.

6.10 Reed canary grass

Rolf Olsson, Swedish University of Agricultural Science

Reed canary grass was identified in project Agrobioenergi [28] along with willow as the perennial crop that offered the highest yield under Swedish conditions. However, with conventional summer harvesting technology, it was estimated that some 10% of the harvest would require artificial drying and storage in store houses to satisfy the quality requirements for straw fuels. As this meant productions costs would be far too high, willow was prioritised in future agrifuel programmes.

A new production system for reed canary grass, the so called spring harvest system, was unveiled in 1990 [29]. At that time, the concepts were very tenuously based on experimental data. In the agrifuel programme that followed, initiatives were concentrated on evaluating the agronomical requirements for spring harvesting. The results showed that the method could be applied throughout Sweden. The harvesting technology subsequently proved to be usable in the whole of northern Europe [30]. The method means that seeds that are sown in year 1 are then first harvested in the winter/spring of year 3 and then harvested at the same time year after year provided driving damage does not result in too uneven fields. There is often a long period between harvest and use and unsuitable storage techniques can affect the fuel quality. As winter/spring harvesting delivers the cheapest and most durable production of reed canary grass the bulk of the analysis will concentrate on the analysis of factors in the spring harvest model that affect the fuel quality.

6.10.1 Fuel characteristics

Common to all rhizome grasses, of which reed canary grass is a member, is that winter/spring harvesting is possible and delivers a shrivelled and dry products provided dryness and/or frost cause the parts of the plant above ground to die off. In the case of reed canary grass, in our climate you also have to wash away the wax layer that protects the plant against drying out in winter, so the product becomes dry and brittle. Washing off the wax layer also means the biomass quickly changes moisture content in response to the weather conditions. As reed canary grass is pressed into bales in dry weather conditions, this means the bales retain a high level of dry substances (85-90%) in all vegetation areas where frost means the plant shuts down for winter [31], [32], [33].

Types and cultivation conditions that produce high blade harvests provide a significantly lower quality fuel in terms of e.g. high ash content and a high number of fine pieces when handling and breaking up reed canary grass bales. Winter/spring harvesting of dead material also means that the amount of nutrients and process interrupting elements in the fuel are also reduced. In the case of readily soluble elements such as chlorine and potassium the above can go down by a factor of 6 and for e.g. nitrogen, sulphur and magnesium by around 50%. The levels of not very soluble elements such as heavy metals are unchanged or increased [31], [32], [33]. Standard fuel data for spring harvested reed canary grass are given in the Värmeforsk Fuel handbook.

According to the above, spring harvesting means that much of the nutrients added recirculate in the growing system and in other words, not found in the fuel. The chemical composition of the harvested biomass is affected by the levels of elements in the soil available to the plant. A high level of calcium available in the soil can double the calcium content in the fuel according to trials in project Norrfiber (Ås and Röbäcksdalen respectively). High levels of water soluble silicate in the soil, a common feature of e.g. poor stiff clay soil, drastically increased the level of silica dioxide and with it the total ash content of the fuel [46],[48]. The link between clay content and ash content is shown in Figure 6 and the respective ash content and silicon content in Figure 7 [34].

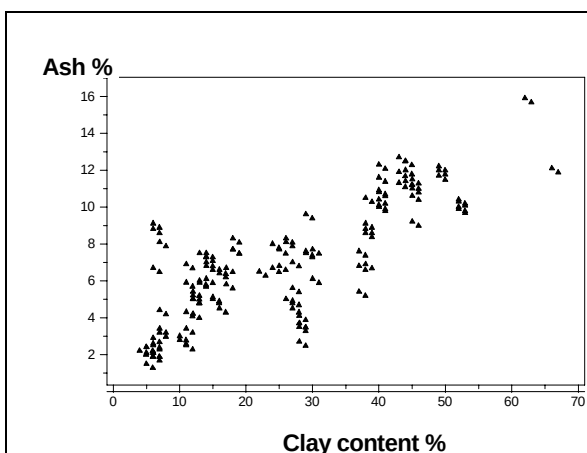


Figure 6. The effect of clay content on ash content.

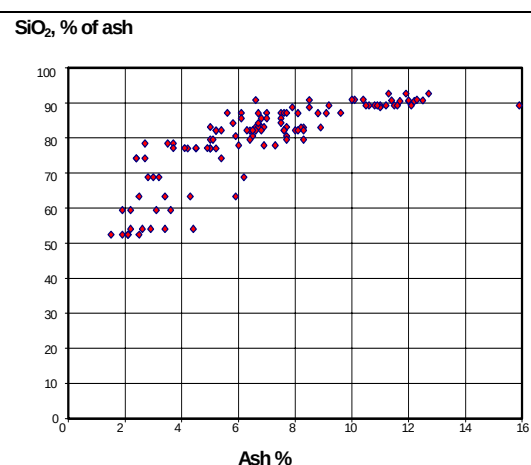


Figure 7. Content of silica dioxide in ash.

The initial melting temperature of the ash has a good correlation with the quotients: Silicon/calcium + potassium + magnesium [35].

6.10.2 Effect of type and growing conditions

The reed canary grass types that have been available on the market so far have their origins in livestock fodder and have therefore been refined to produce large blades that are qualitatively best for animal fodder. Refining reed canary grass for energy purposes is in progress in Sweden and Finland and apart from high yield, this is oriented in the opposite direction, namely high straw proportion. The proportions of blade and straw

are affected by type, harvesting technology, age of the pastureland, weather conditions for the year, type of soil and geographic growing zone. The variation in blade/straw from place to place and year to year in the grades can vary from 26.6 to 78.5%.[30] Other important parameters that can affect the fuel quality are winter hardiness and resistance to pests. A first industrial type, Bamse, has been introduced and is being evaluated at the Swedish University of Agricultural Science Rönneby and elsewhere. The grade, which was evaluated against other refined lines in northern Europe, produced around a 10% higher yield here than the best fodder grade, Palaton [30]. Svalöf Weibull's upgrading programme includes lines from northern Sweden with at least 30% higher yields than Palaton [36]. The field age variation measured as the total ash content in a trial spanning 15 populations at 11 trial sites was between 2 years 6.5 resp 7.4% ash [30] while the variation between the 11 trial sites reflecting the differences in types of soil, weather conditions for the year and incidence or lack of a protective snow layer, varied between 0.9 and 6.7% for straw and 3.1 and 15.1% for blade fraction [30]. The ash content in reed canary grass fuel is reduced with rising field age. In a trial spanning 10 different trial sites the average ash content fell from 5.8% in a one-year-old field to 3.2% in a five-year-old field [37].

6.10.3 Effect of weather conditions in the year and winter hardiness

In a field of reed canary grass the stem part of the crop normally increases during the first field years. This is of major significance for spring harvesting as the biological loss of biomass is reduced and the ash content falls at the same time. In cultivation areas where the crop is not protected by a blanket of snow in the winter, autumn storms also cause large blade drop which further increases the winter losses but at the same time reduces the ash content in the fuel. In the trial with 11 sites across the whole of northern Europe with 15 different populations/types, the median figure for stem proportion for all types increased from 68.5% in one year fields to 72.5% in two year fields. For the refined line that now comprises the commercial grade, Bamse, the difference in straw proportion was 64% in the one year fields and 77% in two year fields [30].

The first industrial grade, Bamse, is undergoing long-term evaluation by the Swedish University of Agricultural Science-BTC Rönneby. In spring 2006 (field age 4) the yield fell drastically and in small boxes the measured crop had more or less halved. The crop was straw poor and very blade rich in the 2005 growing season. The biomass that grew in 2006 (harvested spring 2007) has shown the same growth pattern which is why the yield is expected to be very low this year too [38]. A similar trend is also found in the Palaton grade, where large scale trials with spring and autumn hay making respectively show corresponding reductions in yield and straw quantities in recent years. Late autumn hay making has here returned slightly better results. Over the past few years the autumns have been very mild and rainy and the winters snow poor and cold.

Rhizome growth occurs in spring and summer while shoot establishment for the production of fertile (seed bearing) shoots mainly occurs in autumn and early spring. Shoots that grow along the ground do not survive the winter [41].

In order to assess the possibility of increasing the available harvest time, without damaging shoot growth in the spring, trials have been done on late autumn hay making at Röbbäcksdalen. So far, reed canary grass appears to overwinter well [39] but the trials with local materials that were done in the 1960s and 70s revealed that the local plants were hardier than the North American variety and that the difference grew bigger with the age of the field [40]. The difficult autumns and winters that we have had in recent years confirm these earlier observations and show the need for frost resistant plants.

In the existing plant refining material there is a wide range of strategies for shoot establishment in the autumn [42], which is why the chances of being able to develop high yield hardy grades of reed canary grass suitable for the spring harvesting system are good.

6.10.4 Effects of harvest technique

The development of the delayed harvest technique has meant that production costs and fuel quality have been significantly improved for reed canary grass. Operating experiences from burning summer harvested reed canary grass are available from Söderköping. Several technical operating problems arose such as e.g. substantial dust formation made up of potassium chloride that spread throughout the entire plant. One weakness that has been observed for traditional spring harvesting is the drop in quality that cutting early developing annual shoots entails, with a substantial increase in ash content and higher fine parts in the fuel in future harvests as a result of the increase in blade quantity that occurs. The alternative of raising the cutting height in spring results in a drastically reduced harvest if the cutting height is increased from 5 to 10 cm the harvest goes down by 25% [43].

Harvest losses in round baling trials have amounted to 20-30% [43], [44] and in practice can reach 50-60% when harvesting [45].

Both round baling and rectangular baling entail vigorous mechanical processing of the brittle spring harvested material, which also results in higher harvesting losses. Shredding and milling bales causes further increases in the proportion of fine material. A ball milling trial produced reed canary grass 33.2% smaller than 90 micrometers. Growing and harvesting measures that increase blade proportion will result in a further increase in the proportion of fine fractions [47].

6.11 Current research on the fuel quality of reed canary grass

One project with an association with this research area is in progress, SLF: Bioenergy project V0640005 Reed canary grass – plant refinement, type development and seed production. The project is evaluating the new lines developed at SWAB in terms of yield, leafiness and hardiness. The trials will perform late autumn harvesting and record the biological harvest. The project will look closely at issues of major significance for fuel quality as discussed above.

6.12 Referenser

- [28] Westermarck.S. Energy crops – Fuels from farm crops. Results and evaluations from the government energy research programme. Statens Energiverk 1987-12 09
- [29] Olsson. R, Reed canary grass: Energy crops for energy and biomass production 1990. Scandinavian Energy and Environmental Conference, Stockholm 21-23 november 1990
- [30] Olsson. R et al The Reed Canary Grass Project. BTK Report 2004: 7
- [31] Landström S, Lomakka L, Andersson S. Harvest in spring improves yield and quality of reed canary grass as a bioenergy crop. Biomass and Bioenergy Vol. 11, No.4, pp.333-341,1996
- [32] Strasil,Z.;Vana, V.; Kas,M. The reed canary grass (*Phalaris arundinacea* L.) cultivated for energy utilisation. Research in Agricultural Engineering 51 (1): 7-12 2005
- [33] Christian, Dudley,G; Yates, Nicola,E.; Riche, Andrew B: <The effect of harvest date on the yield and mineral content of *Phalaris arundinacea* L. (reed canary grass) genotypes screened for their potential as energy crops in southern England. J Sci. Food Agric. 86: 1181-1188 (2006)
- [34] Burvall, J. Hedman, B. Perennial rhizomatous grasses-The delayed harvest system improves fuel characteristics for reed canary grass. Sustainable Agriculture for food, energy and Industry, pp.916-918, 1998, James and James (Science Publishers) Ltd.
- [35] Burvall,J. Influence of harvest time and soil type on fuel quality in reed canary grass. (*Phalaris Arundinacea* L) Biomass and Bioenergy vol.12, No.3, pp.149-154, 1997
- [36] Andersson,B.; Lindvall,E. Developent of new reed canary grass types. Final report from STEM project no. 12289-2; dno. 511 OP-2001-02713
- [37] Landström,S.; Olsson,R. Perennial rhizomatous grasses-Cultivation experiments with reed canary grass for bioenergy in Sweden Sustainable Agriculture for food, energy and Industry, pp.942-944. 1998, James and James (Science Publishers) Ltd.
- [38] Samulsson,R. (2007) Oral information from current trials with ash feeding on reed canary grass fields
- [39] Andersson,.S. Nitrogen feeding on different grass species. Växtodling 19, Inst. for växtodlingslära.1990 Swedish University of Agricultural Science Uppsala
- [40] Andersson,S. Reed canary grass. Types for northern Sweden 1977-78 Aktuellt från lantbruksuniversitetet.252 Uppsala 1977
- [41] Evans, M.W. and Ely, J.E. Reed canary grass. Jour. Amer. Soc.Agron.33: 1017-1027. 1941
- [42] Hellquist, S., 2007 Oral communication
- [43] Pahkala, K. Et.al.2002 Ruokohelven viljely ja korjuu energian tuotantoa varten. MTT Farming and food economy .Plant production: Eva Björkas, Svenska lantbrukssällskapens förbund.

-
- [44] Larsson, S., Örberg, H., Kalen, G., Thyrel, M. Reed canary grass as energy crop. Experiences from full scale trials at Biomass Technology and Chemistry (BTC) in Umeå between 2000- 2004. BTK Report 2006:11.
 - [45] Isolahti, M.; Ruokohelpi on satoisa energiakasvi. Teho. No.2 :8-10, pp.37-38, 2006
 - [46] Jones, L.H.P; Handreck, K.A. Silica in soils, plants and animals. Advances in agronomy 19, 107- 149 1967
 - [47] Bridgeman, T.G. et al. Influence of particle size on the analytical and chemical properties of two energy crops. Fuel. Vol.86, Issues 1-2, January 2007 pp.60-72
 - [48] Pahkala, K. et al. Production and use of agrofibre in Finland. IN Final report of the Study, Part 1. Production of Agrofibre crops: Agronomy and Varieties, pp.84, Agricultural Research Centre of Finland, Jokioinen, Finland. 1996.

6.13 Hemp

Martin Sundberg, JTI – Swedish Institute of Agricultural and Environmental Engineering

After a long ban, following a ruling by the EU Court, permission was again granted to grow hemp in Sweden in 2003. However several provisions were attached to cultivation. For instance, only types with low levels of the narcotic substance THC are permitted. Although there is substantial interest in hemp, it is still only being cultivated to a very limited extent in Sweden. In 2006 there were 155 registered growers with a combined acreage of 527 ha.

Interest in hemp in Sweden is not restricted to its use as a pure energy crop, the potential is also seen to use the various parts of the plant for other purposes. Its fibre can be used for textiles, paper, insulation and as reinforcement in concrete, plastic etc. The seeds can also be pressed for oil that has a variety of application areas. The seeds can also be used directly in food products and as animal feed. The woody material remaining after fibre extraction can also be used in the building industry, animal litter or as fuel.

As the production costs for hemp are high at the present time compared with other energy crops, many judges view growing hemp *solely* for combustion as barely a realistic option for energy production in a broader perspective [49]. Work is therefore being done in several parts of Sweden to extract the fibres and/or seed parts before using the remaining woody parts for energy purposes [50][51][52][53]. However this report is restricted to considering the whole plant for combustion. As the goal here is a large quantity of biomass, the fibrous types are the ones of interest.

For several reasons, hemp intended for combustion is best harvested after the leaves have fallen, which happens after frost has set in. The nutrients in the leaves can then be returned to the soil and benefit future crops. Apart from the leaves generating a great deal of ash, they also contain high levels of potassium which can cause problems on combustion. Winter frosts cause the stems to dry, which means the water content gradually goes down. As a rule, the stems become very dry towards spring and only

contain 10-20% water [50][53], which means the material is suitable for storage without additional costs for drying.

In well managed plantations in suitable soil potential yields for types of fibre hemp can be up to 10 ton ds/ha in the autumn when the leaves have dropped [55]. There are significant losses of biomass during the winter/spring, which means that the yield on spring harvesting is estimated to be around 6 ton ds/ha [56]. In very good, rich earth, it should however be possible to achieve higher yields [55].

6.13.1 Fuel characteristics

Available analyses of hemp show wide variations. Fresh hemp generally has high levels of potassium, sodium and chlorine, and associated risks of sintering and build up with the risk of corrosion on combustion. In the case of spring harvesting, when the plant has dried and lost its leaves, the alkali and chlorine content is much lower. Analyses done on late harvested hemp show high ash melt temperatures and this is therefore seen as being able to be burned without problems [53][52].

Spring harvested hemp can normally be brought in with low moisture content. In a series of trials over several years the moisture contents recorded were between 13 and 24%, with the variations mainly caused by the proportion of green growth that came with the harvest [50].

No major differences in fuel characteristics or inorganic composition have been reported between fibre and oil hemp [50]. However no research has been done to determine any possible differences in fuel characteristics between different *types* of hemp. On the other hand, differences have been reported in hemp grown on different kinds of soil, where hemp grown on earth rich sandy soil offers better fuel characteristics than hemp grown on more clayey soil [50]. Future studies are going to look more closely at this (see section 6.14).

The department of biomass technology and chemistry at the Swedish University of Agricultural Science in Umeå performed pelleting and combustion trials with a variety of different biofuels in 2005 and 2006 including hemp [58][59]. The primary aim of the project was to look at ash forming characteristics during combustion. The project included hemp with low ash content and with high ash content. The results showed that almost 80% of the ash from the hemp with high ash content formed slag on combustion. The corresponding figure for hemp with low ash content was just 20%. The combustion trials revealed relatively low particle emissions from pelleted hemp, 30-60 mg per Nm³, compared with bark and tops, roots and branches, 100-140 mg per Nm³.

Operating experiences from large-scale combustion of hemp remain very limited at present. The word from energy plants is that the fuel is very space intensive as the bulk density is low. Prior to the 2005/06 heating season, a number of combustion tests were planned with chopped hemp at larger plants [55]. However several of these never happened, partly due a lack of financial resources and partly due to problems associated with the harvest. Although a company called Neova (ex Sâbi) burned chopped hemp mixed with chips at one of its works, no fuel analyses or tests were performed on this

batch. The amount of chopped hemp was so limited, it was all combusted in a couple of hours [61]. Under similar conditions, Mälarenergi burned around 10 tons of chopped hemp with an 8% water content in one of its boilers [60].

Hemp has been used for several years at Visby Energi's district heating plant in Visby. However the combustion characteristics of the hemp has neither been measured nor documented [63].

6.14 Current research on the fuel quality of hemp

From 2007-2009 a project "Production and characterisation of hemp as raw material for solid biofuel" will be implemented at the department of biomass technology and chemistry, Swedish University of Agricultural Science, Umeå. The primary aim of the project is obtain more in-depth knowledge of the fuel characteristics of hemp. The following areas will be studied:

- the effect of harvest time on the fuel quality of hemp (autumn/spring harvest, plus several other occasions in between)
- the effect of soil type on the fuel quality of hemp (mineral-/earthy soil)
- the effect of type of hemp on the fuel quality of hemp (fibre/oil)
- the effect of harvest technique on the fuel quality of oil hemp (picking/no picking)
- appropriate preprocessing methods for briquette and pellet production of hemp (type of mill)

During winter/spring 2007, Eslöv-Lund Kraftvärmeverk AB is planning two test combustion trials with winter harvested hemp at heating plants with two different types of boiler. One is to be done in a straw boiler in Denmark, where an initial step will also be to look at how the hemp works with the existing handling equipment at the plant. The second trial is planned for Svalöv heat-only boiler station [62].

6.15 References

- [49] Mattsson, J. E.; Business Development – Locally grown straw fuels for combined power and heating plant. Report 2006:8, Faculty of landscape and park technology, Swedish University of Agricultural Science Alnarp, 2006
- [50] Finell, M., Xiong, S. & Olsson, R.; Multifunctional industrial hemp for northern Sweden. BTK-report 2006:13. Department of Biomass technology and Chemistry Swedish University of Agricultural Science, Umeå, 2006
- [51] Svennerstedt, B. & Svensson, G.; Industrial hemp – cultivation, harvest, preparation and market. Fakta jordbruk no 7, Swedish University of Agricultural Science, Uppsala, 2004
- [52] Johansson, S. & Olofsson, R.; Hemp's potential as an energy crop. Final report. Energinätverket Green4u, 2006
- [53] Norberg, P. Industrihemp-X. Final report. University of Gävle, 2006
- [54] Pasila, A.; The dry-line method in bast fibre production. Academic Dissertation. University of Helsinki, Publications of Department of Agricultural engineering and household technology 15, 2004

- [55] Sundberg, M. & Westlin, H.; Hemp as a fuel raw material. Initial study. JTI-report Lantbruk & Industri 341. JTI – Swedish Institute of Agricultural and Environmental Engineering, 2005
- [56] Forsberg, M., Sundberg, M. & Westlin, H.; Small-scale briquetting of hemp. Initial study. JTI-report Lantbruk & Industri 351. JTI – Swedish Institute of Agricultural and Environmental Engineering, 2006
- [57] Strömberg, B.; Fuel handbook. Värmeforsk report F4-324. Stockholm, 2004
- [58] Öhman, M., Gilbe, R., Boström, D., Backman, R., Lindström, E., Samuelsson, R., Burvall, J.; Slagging characteristics during residential combustion of biomass pellets. Proceedings from the second world conference on pellets, Jönköping, Sweden 30 May – 1 June 2006
- [59] Öhman, M., Lindström, E., Gilbe, R., Backman, R., Samuelsson, R., Burvall, J.; Predicting slagging tendencies for biomass pellets fired in residential appliances: A comparison of different prediction methods. Proceedings from the second world conference on pellets, Jönköping, Sweden 30 May – 1 June 2006

6.15.1 Personal messages

- [60] Nerén, Jens. Mälarenergi
- [61] Oscarsson, Andreas. Neova
- [62] Ottosson, Peter. Eslöv-Lund Kraftvärmeverk AB
- [63] Pettersson, Leif. Visby Energi

7 Storage and logistics

7.1 Straw

Gunnar Lundin, JTI – Swedish Institute of Agricultural and Environmental Engineering

7.1.1 Forms of handling

Complete handling chains for straw for energy from field to energy plants have been published in a recent report on practical experiences [1]. The studies cover every step from field to heating plant as follows.

- Harvesting
- Bringing in to the farm
- Farm storage inc loading in and out
- Transport to heating plant
- Storage at heating plant inc unloading and preparation

The methods, bulk densities and costs for five forms of handling are specified in the study: large rectangular bales, small rectangular bales, round bales, field chopped loose straw and field briquetted straw. Both outdoor and indoor storage of straw were looked at. Systems with large bales were found to be cheapest followed by systems with smaller large rectangular bales and field briquetted straw. Indoor storage affected costs quite significantly. Field briquetted straw proved to offer cost advantages for long transport journeys and indoor storage as the high weight by volume is more efficient for transport vehicles and storage space.

Handling chains for complete straw fuel systems are also presented by other researchers [2][3].

7.1.2 Changes during storage, micro organisms hazardous to health

Losses during storage are partly losses caused by microbial activity, partly by material that must be discarded after storage [2]. Loss caused by handling the straw is also included here.

The most important factor limiting the shelf life of vegetation at our latitudes is probably mould. There is extensive published knowledge concerning how mould attacks grain kernels but far less on what mould does to straw.

Certain types of mould, usually listed as fungi, grow on the crops in the damp conditions that occur during growth and ripening in the field. Other related moulds are better adapted to drier environmental conditions (14-19% water content) than fungi. These storage moulds are the dominant source of damage after harvesting [4].

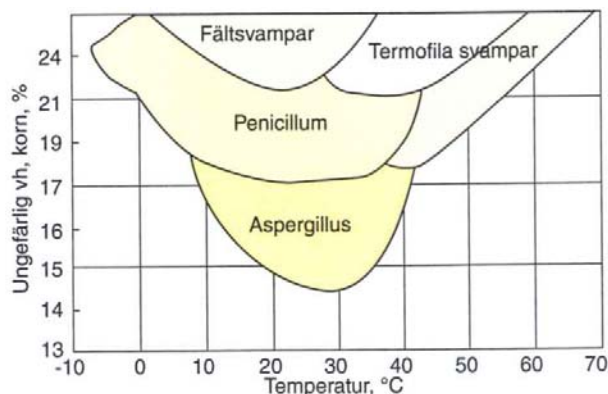


Figure 8. Conditions of temperature and moisture in which different fungi can grow in stored grain (Jonsson 1999, after Lacey, Hill and Edwards, 1980).

On exposure to organic dust, one inhales mould spores and other particles. The current safe threshold for organic respirable dust is 5 mg/m^3 . Dust with an aerodynamic diameter of less than $4 \mu\text{m}$ can reach all the way to the alveoli where they overload the body's defence system and cause a powerful reaction 4-8 hours after exposure, known as acute alveolitis. One can then suffer fever, shivering fit and feel generally unwell, in certain cases even severe coughing and shortness of breath [5].

Anyone who has breathed in dust with high mould levels for an extended period can suffer chronic problems, allergic alveolitis. This condition is far more serious than acute alveolitis, and many people never fully recover [5].

The risk of personnel falling ill from alveolitis can be reduced if the straw is handled in closed systems. This would be very expensive in most cases and mould formation should therefore be prevented as far as possible. Bales that have been attacked by mould often have more mould on the inside of the bales than on the outside. As such, breaking up bales before combustion entails greater risk than burning bales whole. Bales containing mould will also be more difficult to break up as the straw in the mould-affected area often clumps together. This is another reason to aim for mould free straw [1].

The Swedish autumn climate, particularly in the central Sweden, can make it difficult to bring in the straw with sufficiently low water content [2]. Data indicate that straw with a water content of max 18% ought to be suitable for storage. Straw-fired heating plants in both Sweden and Denmark do not normally accept straw with a water content higher than 20%.

7.1.3 Forms of storage

Uncovered outside storage is by far the cheapest means of storage but the one with most risks attached [2]. The method can occasionally even be the most expensive when you include wastage. Round bales are more tolerant of outdoor storage and more resistant to rain compared with rectangular bales that are sensitive to rain and should therefore be brought undercover as soon as possible.

As an example of outdoor storage one study presents conditions at the heating plant in Svalöv where rectangular bales are stored uncovered [1]. These are stacked about 10 m high and built on the concept that the higher the stack the fewer the bales affected by overhead rain. The uppermost bale protects the bales underneath from rain. These bales can be used for protection for 2-4 years depending on how soon they were rained on after harvesting and baling.

Covering outdoor stacks with plastic can be a cheap option, but it does have drawbacks [2]. It can be difficult to fix the plastic sheeting in place to prevent wind blowing it away, birds can peck holes in it, and condensation often forms at the top of the stack. To avoid condensation, the sides of the stack can be left partially open, but one then risks the straw getting wet from driving rain. The plastic can be held in place better if it is covering by netting. This netting can then be held in place with sandbags, car tyres or similar. High demands are placed on the quality of the sheeting and how it is secured.

There has been a machine on the market for some time that can sheet over two rectangular bales on top of each other laid in a long string, called a tube liner. The bales are lifted onto a platform with a front loader and then wrapped in plastic to form a long sausage as more are added. Bales that can be wrapped in this way can have a water content of max 14%, otherwise condensation forms [1]. Round bales can also be wrapped in this way.

Tarpaulin is less susceptible to wildlife damage, and not as affected by wind as it is heavier [2]. The most weather resistant and durable type of material is PVC. The downside is that it can be blown off and the stacks need keeping an eye on.

A building offers numerous advantages when storing straw [2]. The straw remains dry and does not need watching. It is, however, a much bigger investment compared with outdoor storage.

Some farmers have built cheap and simple barns with poles [2]. The poles can be impregnated telegraph poles. The roof overhang should be at least 1 metre to provide adequate protection. Adding walls on one or more sides, preferably on the west and north sides, offers greater storage protection.

7.1.4 Self-ignition

When mould and bacteria breakdown the straw, heat and water build up [2]. If the temperature in the store rises above 60°C a chemical reaction starts that can cause the temperature to rise several hundred degrees. There is then a huge risk of self-ignition.

7.1.5 Accident risks

Handling straw entails risk of accidents on machine handling of large bales, e.g. when loading into store. Drivers are often very experienced in how the stability of the loading machine is affected by differing weights in the load arms. However they rarely think of the load's weight by volume and shape. As the centre of gravity of large bales is a comparatively long way forward of the loading attachment the machine can be less stable

than first thought [6]. Involuntary machine movements in the machine used for lifting can cause serious personal injuries. It is important to ensure that the valves and seals in hydraulic systems are in good condition before use [7].

7.2 Current research on straw storage and logistics

“Costs, access and quality of fuel straw – the effect of local variations in weather and geography and choice of handling systems” (Project number SLF H0640048). Current investigation (2007-2009) at the institute of biometry and technology, Swedish University of Agricultural Science. Accessible quantities of straw will be studied by looking at the relationship between kernel and straw. The drying time of the straw in the field will also be studied under different weather conditions, by simulating weather data for 15 years, along with the costs for straw.

“Farming as a supplier of agrifuel to large-scale combined power and heating plant – Case study Värtan” (Project number SLF H0640055). Studies of possible logistics and handling chains for the agrifuels willow and straw, related costs and business critical parameters for suppliers of agrifuels. The project is being led by JTI – Swedish Institute of Agricultural and Environmental Engineering, and being done as a case study of Fortum Värme’s planned biofuel plant in Värtahamnen. Other project partners are LRF, Fortum and the institute for biometry and technology, Swedish University of Agricultural Science. The project is funded by SLF (The Swedish Farmers’ Foundation for Agricultural Research) and will finish in September 2007.

7.3 References

- [1] Bernesson S. & Nilsson D., 2005. Straw as an energy source. Review of existing knowledge. Report-environment, technology and agriculture 2005:07. The institute for biometry and technology, Swedish University of Agricultural Science. Uppsala.
- [2] Nilsson, D. 1991. Harvesting, transport, storage and upgrading of straw as a fuel – methods, energy needs, costs. Report 150, Inst. of farming technology, Uppsala. 102 p. ISSN 0283-0086. ISRN Swedish University of Agricultural Science-LT-R--150--SE.
- [3] Stridsberg, S., Christensson, K. 1995. Handling of chopped straw II. SLF Report no 16, The Swedish Farmers’ Foundation for Agricultural Research, Stockholm. 31 p. ISSN 1104-6082.
- [4] Jonsson J. & Pettersson H., 1999. Evaluation of different conservation methods for grain. Report no 263 from JTI. Uppsala.
- [5] Andersdotter M., Filipsson A., Hansson R., Sjö Dahl L. & Thelin A., 2000. Work environment and safety in agriculture. LT:s förlag. Södertälje.
- [6] Hemming J.-G., 1984. Straw feed bales. Pratiskt Lantbruk 43. LT:s förlag, Borås.
- [7] Lundin G., 1995. Ergonomic checklist for technical equipment for large bale handling. Report no 206 from Swedish Institute of Agricultural and Environmental Engineering Uppsala.

7.4 Grain

Hugo Westlin, JTI – Swedish Institute of Agricultural and Environmental Engineering

The storage of grain for food and animal feed purposes is an area that has been the subject of a great many research and development initiatives. Changes in moisture content and dry substance losses in store have been studied by e.g. Jonsson & Pettersson (1999) [8]. They evaluated the most common conservation methods for grain used on farms. The safe storage time for grain i.e. time available within which buffer stored, ventilated grain should be dried to avoid mould growth and with it the risk of impaired quality – has been studied in a number of projects, including an EU funded project “OTA-Prev” [9]. This produced guidelines for safe storage times for grain, Table 6, at different temperatures and water content levels in the grain. A further development of this model is being done in a current doctoral thesis (see section *Current projects*).

Table 6. Safe storage times for grain according to Jonsson, 1999 (preliminary)

Temperature	Time available, days, at harvest water content, %				
°C	18	20	22	24	26
25	9.7	4.4	2.7	2.0	1.6
20	10	6	4	3	2
15	35	14	8	5	4
10	40	20	12	9	6

Virtually everything known about the drying and storage of grain has concerned grain intended for human or animal consumption. However in recent years various question marks have arisen concerning whether or not the requirements for energy grain should be the same as for food grain. Regardless of this, one can assume that the requirements on grain for fuel will look different to those for food grain. Several projects related to the use of alternative and to a certain extent older technology for grain conservation and storage of energy grain have therefore been started (see section 7.5).

As grain have been, and still are, a very important farming product, there is a well developed and thought out logistics system for them. Costs, for both conservation, storage and handling of grain, have also been well researched and analysed. Several projects related to this have been implemented in recent years to take a closer look at the potential for cheaper and more efficient ways of drying and storing products. Logistics and transport have been similarly studied.

The bulk density of grain kernels can be considered well documented. A number of different studies have analysed how bulk density is affected by how stores are filled, the height of the storage and the water content of the grain. These studies have found that

there is some potential for influencing the bulk density of grain in storage, but not much. In many contexts, the weight by volume of the grain is used as a measure of quality and in certain cases, also the grounds for pricing.

7.5 Current research on grain related storage and logistics

Researcher Nils Jonsson at JTI is currently working on a doctoral thesis in which he is looking at the microbial activity in grain during storage, and what effect this has on the safe storage time for the grain.

Nils Jonsson has also been granted funding by SLF to look at low energy conservation of bioenergy grain with the aid of chilled air-drying. An earlier project assessed the standards for chilled air-drying in England [10], very similar to the one now to be done in Sweden.

7.6 References

- [8] Jonsson N, Pettersson H.; Evaluation of different conservation methods for grain. JTI report Lantbruk & Industri 263. JTI – Swedish Institute of Agricultural and Environmental Engineering, 1999.
- [9] Jonsson N, Johnsson P, Ritzzo A, Olsen M, Gustafsson L.; Modelling the growth of *Penicillium verrucosum* in cereal grain during aerobic conditions. In “Prevention of Ochratoxin A in Grain” Final Report of Project No. QLK1-CT-1999-00433 in Quality of Life and Management of Living. 2007.
- [10] Bruce D.M, Jonsson N, Armitage D.M.; Practical strategies for minimising the production of ochratoxin A in damp grain. Project Report No. 399. HGCA. 2006.

7.7 Willow

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7.7.1 Storage problematic

Harvested willow (chipped or unchipped) sometimes needs to be stored during the heating season even though it is harvested in wintertime. The length of storage can vary from a week to several months for various reasons. The fuel characteristics of the biomass can change when freshly harvested willow is stored. Such changes during storage are dictated by a number of factors that are related to the properties of the material, including moisture content and particle size, along with external variables such as form of storage, length of storage and stack size.

Willow can be harvested as whole shoots or cut and chipped directly. Which means willow can be stored as whole shoots in a pile or in chipped form in a stack. Storing willow whole in a pile can lead to lower moisture content and lower substance losses, which can enhance fuel quality. A number of problems are associated with storing willow chips in a stack on the other hand. It is a well-known fact that freshly harvested chips stored in a stack break down faster due to microbial activity. Micro organisms also generate heat via their metabolism. This increase in heat can be even more

vigorous if there is limited airflow in the stack due to a high proportion of fine particles in the stack. This leads to substantial substance losses and a significant increase in the number of mould spores. All these factors adversely affect fuel quality and work environment.

One reason the quality of the fuel deteriorates when stored in chip form is that the moisture content shifts in the stack, which makes for non-homogenous fuel. The ash content of the fuel can also increase as a consequence of material breaking down. The work environment can be adversely affected by spore formation on the stored chips. These spores can easily become airborne when infected chips are e.g. loaded or transferred. Exposure to high concentrations of these spores can trigger allergies [11].

How the characteristics of materials and fuel quality are affected by different forms of storage has been investigated on both laboratory scale and in full scale field trials. The quality parameters that can be affected during storage include the fuel's moisture content, ash content and calorific value. Studies have shown that high substance losses can occur during storage. The scale of these substance losses depends on several factors such as the material's chemical composition, moisture content, how finely it is chipped and the proportion of fine particles (<5mm).

7.7.2 Forms of willow storage

7.7.2.1 Pile storage

The advantage of coppicing is that the wood can be stored as bundled shoots or loosely in piles. Storing willow shoots in a pile reduced the moisture content from 54% (raw weight) till around 35% between March-September. Covering the pile results in even drier fuel [12]. The same study shows that the substance losses were minimal and that the temperature in the pile was close to the ambient temperature during most of the storage period. A Danish study produced similar results [13].

7.7.2.2 Storage of willow chips

Willow is usually stored in chipped form in stacks. Storage in stacks under various conditions has been studied [11] [13]. If the ambient and stack temperature drops below 0°C microbial activity is restricted and there are minimal problems. If willow chips are stored when the air temperature is above 0°C, microbial activity can be triggered and cause problems.

The effect of the storage conditions on dry substance losses in freshly harvested willow chips, and what proportion of these losses can be due to microbial activity have been studied in a laboratory experiment [14]. Three storage temperatures (5, 10 and 15°C) and three particle sizes (3-7, 7-16 and 16-22 mm) were studied over 73 days. The results show that substance losses that arose despite the low temperature, were significantly reduced at lower temperatures and larger particle sizes. The losses are assumed to be due the turnover in the plant material's own cells and in the micro organisms that grow in the material. However most of the dry substance losses are caused by microbial activity [14].

The effect of particle size on substance losses during storage has also been studied in large-scale field trials [15]. The report conclusions were that chip stacks with smaller particle sizes show faster breakdown, a higher proportion of micro organisms and greater substance losses. These changes can lead to higher ash contents in smaller stacks [15]. Figure 9 below shows a typical stack distribution and dry weight of willow chips before and after storage in stacks.

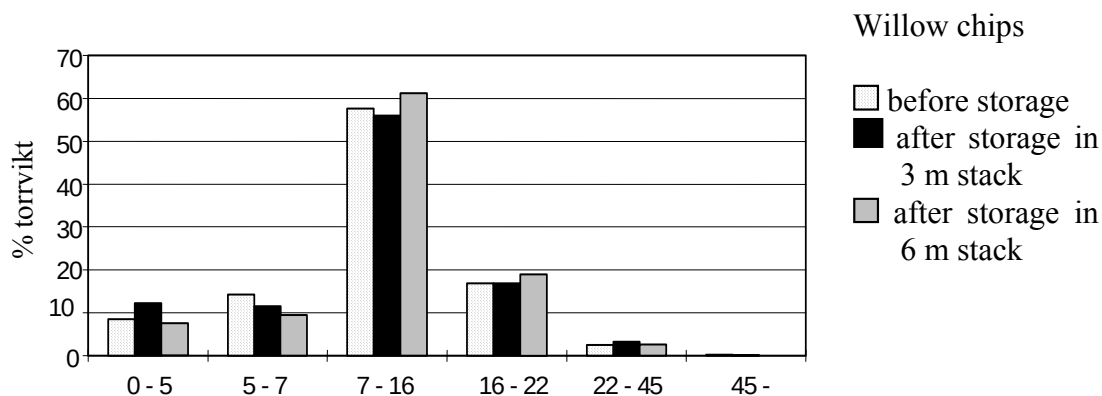


Figure 9. Distribution of fractions (mm) in willow chips before and after storage in 3 m and 6 m high stacks [15].

How storage affects ash content in willow chips was investigated in the same experiment. The changes in ash content mirror the breakdown of the material, i.e. greater substance losses lead to higher ash content.

Temperature change in the stacks partly depends on the stack height and partly on the particle size of the stored chips. The ambient temperature is less significant for temperature changes in the chips if it is a large stack. The temperature in the stack is very significant for the moisture content of the material which means the average moisture content in the chips can be lower in large stacks or in chip stacks with a high proportion of small particles [15].

Storage of chips for extended periods can adversely affect fuel quality and cause substantial losses [16]. Long term storage is being investigated in a study in which willow chips are stored in a 85 m³ chip stack for one year. The moisture content, which was about 48% at the end of the trial, was redistributed in the stack together with a very moist area (70%) on the outside of the stack. This area made up 48% of the stack volume. The average substance loss was 14.1% of the dry weight [16].

7.7.2.3 Cold storage of willow chips (Ventilated storage)

Several investigations in which the chip stacks have been ventilated with cold air have been published [17][18][19]. One study of willow chips stored in three metre high ventilated stacks chilled with outside air did not show a marked reduction in the material's moisture content [17]. The study spanned three trial stacks: a) storage with continuous ventilation under cover, b) storage with continuous ventilation uncovered, and c) a control stack with no ventilation or cover. The material's moisture content

before storage was about 54%. In May, after five months storage, this value had fallen to 32.5 and 37.5% respectively in the ventilated material that had been stored with and without cover respectively. The average moisture content in the control stack was about 62% [17].

The temperature in the continuously ventilated stack was very close to the ambient temperature, 6-22°C, while the temperature in the control stack was around 60°C. Intensive microbial activity in the control stack led to high substance losses of 8.9% of the dry weight. The substance losses in the ventilated stacks with and without cover were 6.5 and 7.1% respectively. There were marginal changes in ash content [17].

7.8 Current research on willow storage and logistics

Various commissioning bodies were contacted in the project, including the Swedish Energy Agency and the Federation of Swedish Farmers. There proved to be no current storage project on willow at the moment.

The current project “Farming as a supplier of agrifuel to large-scale combined power and heating plant – Case study Värtan” is looking into possible logistics chains for straw and willow (Project number SLF H0640055), see also 7.2.

The project “The development of a willow harvester from existing standard machinery for harvesting forestry wood chips” is developing a prototype for willow harvesting, with funding from the Swedish Energy Agency. The project is aiming to develop a harvester for willow that is more suitable for harvesting thicker willow. Such a harvester should offer high availability and be able to harvest branches up to 15 cm in continuous operation. This new harvester is to be ready for the 2007/2008 harvesting season. The project is being led by Lantmännen Agrobränsle AB in partnership with Silvaro AB and two willow harvesting entrepreneurs from Skog och Salix AB Nora and Maskin & Entreprenad Enköping respectively.

7.9 References

- [11] Jirjis, R.; Microbial activity during the storage of willow. In: Storage and handling of willow from short rotation coppice. Ed. P. D. Kofman and R. Spinelli. Printed by ELSAM PROJECT A/S, Denmark, 1997, p. 89-101.
- [12] Jirjis, R.; EU-project: AAIR SRF Harvesting, storage and drying. Contract no. AIR3 CT94-1102. Third year internal report. 1996.
- [13] Kofman P, Spinelli R. Storage and handling of willow from short rotation coppice. Report from ELSAM project, ISBN 87-986376-2-2, 1997.
- [14] Jonsson, N. & Jirjis, R.; Torrsubstansförluster and microbialaktivitet vid storage of willow chips. Summary: Dry matter losses and microbial activity during storage of willow chips. Swedish Institute for Agricultural Engineering and Environment (JTI) report, Lantbruk & Industri no 237. 1997.
- [15] Jirjis, R.; Effects of particle size and pile height on storage and fuel quality of comminuted willow viminalis. Biomass and Bioenergy 28/2005, p. 193-201.

- [16] Thörnqvist, T.; Storage of fresh willow spp. Faculty of Forest Sciences, Swedish University of Agricultural Sciences, Uppsala. Report no 133. 1982.
- [17] Elinder, M., Almquist, A. & Jirjis, R.; Cold storage of willow chips ventilated with cold outside air. The Swedish Farmers' Foundation for Agricultural Research, SLF, Report no. 18, 1996.
- [18] Rice B., O'Donnell B. & Lyons G., 1990. Study of alternative harvesting-drying-storage strategies for short rotation forestry and forest residues. Report on Contract No. EN3B-0072-IRL. TEAGASC, Carlow, Eire.
- [19] Nellist M.E., Bartlett D.I. & Moreea, S.B.M., 1995. Storage trials with arable coppice. Proceedings of IEA/BA, Task IX workshop "Preparation and supply of high quality wood fuels", held in Garpenberg, Sweden, 13-16 June, 1994. Research Notes No. 278. Department of Operational Efficiency, Swedish University of Agricultural Sciences.

7.10 Reed canary grass

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The dominant production method for reed canary grass entails harvesting in late winter/spring depending on the snow conditions and state of the fields. Harvesting must be done before new green shoots can be damaged by harvesting machinery. The most prevalent harvesting method in the forest counties including northern Sweden is round baling, while large rectangular bales are more common in plain areas where this is also used for straw. In many cases there are not enough machine hours for straw baling in terms of cost sharing of machinery, which makes for high baling costs. Increased reed canary grass cultivation that can employ this machinery in complementary seasons can help reduce the baling costs for all straw fuels. Volume increases can also create scope for more rational baling, such as the Arcusin system, which is used for baling hay in Britain.

Theses two baling systems were evaluated at the Biomass Technology Unit between 2000- 2004 [21], see Table 7. The density and other properties of the bales were very dependent on the experience of the driver. When the baling could be done repeatedly with the same machinery and driver the general performance and density increased in the baling system.

Table 7. Measures, weights and densities using different bale systems.

Press	New Holland D1201 (stora fyrkantbalar)	Hesston 4700 (små fyrkantbalar)	Krone Combipack (rundbalar)
Balmått (m)	2,5 x 1,2 x 0,9	1,2 x 0,8 x 0,8	Ø:1,4 b:1,2
Volym (m ³)	2,70	0,79	1,85
Medelvikt (kg/bal)	390	144	280
Densitet (kg/m ³)	144	182	152
Kapacitet vid rörflenspressning (ton/h)	12 - 19	ingen uppgift	5 - 7

Round bales withstand rain showers in the field better than rectangular bales, but are more expensive to transport as the load weight on transport is lower with round bales than for large rectangular bales. Storage is also more costly as the storage by volume is lower per surface area and ready storage areas are a relatively large cost (well drained and raised storage areas or storage barns).

If properly covered with plastic sheeting and raised and ventilated from below, the moisture content and other fuel characteristics are not affected by this type of storage and the moisture content is normally around 15+/-5%.

Preliminary estimates for outdoor storage with plastic sheeting indicate costs of 20 SEK/MWh for the round bale system (pillar stack) against 9 SEK/MWh for rectangular bales [26]. Central storage in buildings for square bales of reed canary grass is estimated as 35 SEK/MWh [21].

7.10.1 Loose harvesting technique

Baling and bale handling represent over 50% of the production costs for reed canary grass [25]. For a similar grass *Panicum virgatum* (switchgrass), the main energy crop in the USA, it has been determined that forage harvesting can be an alternative method that has fewer handling steps and therefore lower production costs [22]. Non-baling techniques with forage harvesters for reed canary grass have been studied in Finland [24]. Others studies have determined that the forage harvesting method reduces harvesting losses to the stack [20]. Storage of chopped straw fuel in stacks has been studied for *Panicum virgatum* [22], straw [23] and reed canary grass, pure or mixed with milled peat [24]. In none of these cases did the mown material pick up any moisture provided it was dry when stacking (moisture content max 24%) and no microbial activity was noted. When mixed with milled peat, the moisture content of the reed canary grass rose through water being absorbed from the milled peat and the temperature rose by up to 40-50°C which is normal for milled peat stacks, without any impairment to quality being noted [24]. Limited trial findings concerning the effect of storage on the quality of reed canary grass are still awaited. Both straw and *Panicum virgatum* were summer harvested and had protective wax coatings which counter moisture reabsorption which is common in spring harvested reed canary grass that lacks such protection. The loose system can also be assumed to produce a smaller proportion of fine particles thanks to fewer handling stages, which can also have a positive effect on the post storage quality. Cost estimates for different harvesting chains for reed canary grass have been done in a Finnish study [20]. The harvesting chain for round baling amounted to 86.29 Euro/ha while the round baling chain in the commercial chain came to 72.32 Euro/ha.

In terms of economics, the best system up to intermediate storage was loose harvesting, rotary rakes, flail mower, forage harvester and trailer. The cost for this system came to a total of 40 Euro/ha. Storage and transport to the end customer proved to be a bottleneck in this study. In the case of loose stored switchgrass a study has been performed on loading loose stored, chopped grass with a front loader tractor. A total of 13 tons of chopped grass were loaded in 30 minutes on a 40 foot moving bed trailer while unloading took 20 minutes [22].

These studies indicate developing loose handling systems for reed canary grass offers good potential and that they can reduce production costs.

7.11 Current research on reed canary grass storage and logistics

A project is in progress in Västerbotten, Sweden, that is aiming to develop new fuel from field and forest raw materials via the demonstration of technology, cultivation and organisation, large-scale production. About 415 hectares of reed canary grass have been cultivated as part of the project, which started in autumn 2006 and is expected to conclude in autumn 2007. Organisational and contract issues have been emphasised during the work. The project has involved Umeå Energi, Skellefteå Kraft, Norra skogsägarna, LRF and county authorities what have funded the work along with support from the Swedish Energy Agency and the EU [32].

7.12 References

- [20] Pahkala, K. Et.al.2002 Ruokohelven viljely ja korjuu energian tuotantoa varten. MTT Agriculture and food economics. Crop production: Eva Björkas, Rural advisory services for Swedish speaking farmers in Finland.
- [21] Larsson, S., Örberg, H., Kalen, G. Thyrel, M. Reed canary grass as energy crop. Experiences from full scale trials at the Biomass Technology Unit (BTC) in Umeå from 2000- 2004. BTK Report 2006:11.
- [22] Bransby, David, I. Field chopping as an alternative to baling for harvesting and handling switchgrass., Proceedings of the fourth biomass conference of Americas: Biomass a growth opportunity in green energy and value added products. Vol 1, Edited by Overend, R.P. and Chornet, E. Oakland California USA August 29- September 02, 1999. Elsevier Science.Ltd.
- [23] Stridsberg, S.Christensson, K. Stack storage of straw, The Swedish Farmers' Foundation for Agricultural Research February 1997
- [24] Leinonen, A. et al, Cultivation and production of reed canary grass for mixed fuel as a method for reclamation of a peat production area; International Symposium Peatland Restoration and Reclamation, In Duluth, Minnesota, USA 14-18 July 1998
- [25] Olsson, R.et.al. Reed canary grass as an Energy and Fibre raw material Systems and Economics Study; BTK Report 2001:4. "001 ISSN 1650-5115
- [26] Örberg, H. Oral communication 2007

7.13 Hemp

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The harvesting methods used for hemp create either a relatively long material pressed into round or square bales, or loose material chopped into small pieces.

One potential problem when harvesting and handling hemp is that the tough base fibres can easily get wrapped round rotating machinery. Even hemp harvested with forage harvesters contains long bunches of fibre as these are so tough the harvester cannot cut

them. This can limit the possibility of handling chopped hemp in e.g. screw feeders [Johansson & Olofsson].

As with other straw material, it is also important to be able to compress hemp to keep down storage and transport costs. The data available on weights by volume of bales with unchopped hemp range from 125-180 kg ds/m³ [27][28][29][30]. Practical trials testing various methods of compressing forage harvested hemp to improve transport economics have achieved weights by volume ranging from 146-184 kg ds/m³ (assumed moisture content 10%) [27].

Data on weights by volume for loose chopped hemp are sketchy. According to the practical experience of a machinery owner on Gotland, the weight by volume increases with a shorter nominal chopping length. He supplies loose chopped hemp to heat-only boiler station where the quantities delivered are weighted in. On the basis of this along with known transport volumes the weight by volume on transport has been assessed as around 70 kg ds/m³ for a cut length of 26 mm and as 115 kg ds/m³ for a cut length of 18 mm [31]. According to the same source, it is possible in practice to store winter harvested chopped hemp outdoors uncovered in staves for several months without any adverse effects. This provided that proper effort is put into creating a well shaped conical stave and that harvesting can be done without getting snow mixed in when cutting. When the latter had occurred, fungal growth had been observed.

As spring harvested hemp has a very low moisture content it is fragile and breaks up easily. A large quantity of small particles is formed, especially when using a forage harvester and these can also become embedded in the material. This dust is given off when handling loose stored hemp, which means that workers handling the material must ensure they use appropriate protective equipment to avoid inhaling it.

7.14 Current research on hemp storage and logistics

There is no known research into the storage and logistics of hemp in progress at present.

7.15 References

- [27] Johansson, S. & Olofsson, R.; Hemp's potential as an energy crop. Final report. Energi network Green4u, 2006
- [28] Norberg, P. Industrial hemp-X. Final. University of Gävle, 2006
- [29] Pasila, A.; The dry-line method in bast fibre production. Academic Dissertation. University of Helsinki, Publications of Department of Agricultural engineering and household technology 15, 2004
- [30] Hansson, I. 2005. Harvesting methods for industrial hemp. Dissertation Swedish University of Agricultural Science, JBT Alnarp.

7.15.1 Personal messages

[31] Nilsson, Benny, Farmer. Bondarve Lantbruk & Maskin, Gotland

[32] Lindström, Arne. LRF Västerbotten.

7.16 Storage of fuel at plants

All plants need to hold fuel stocks as just in time delivery cannot always be guaranteed. How much fuel is stored depends on the fuel and operating strategy but also on how much storage space is available. A common strategy is to store enough fuel to be able to operate the plant at full capacity for a couple of days, i.e. to manage a weekend without any deliveries. However this varies significantly from plant to plant. Which is the most appropriate method for storage and unloading depends on what form the fuel takes. Chips, pellets and briquettes are delivered in the same way as other biomass. Normally the fuel is tipped into a hopper or a fuel bay.

7.16.1 Unloading

The first station for the fuel is the unloading point. Fuel in powder form delivered in bulk to the plant is unloaded into a buffer silo. Certain powdered energy crops can cause problems when being emptied. For instance, reed canary grass can require special emptying arrangements while experiences of milled grain indicate that this fuel is easier to unload. [33]

Straw in bales has a somewhat low energy density, which means it is very space intensive to store at a plant. Delivery should therefore preferably be done in line with a delivery programme. The programme would then specify date of delivery, quantity, price and the quality standard the fuel should correspond to. On site, the straw is offloaded by forklift truck or crane, see Figure 10 When unloading from trucks by crane, it is important the bales are correctly positioned on the truck to ensure the crane can work efficiently. Bales should also be the right size and not too heavy. [34]



Figure 10. Bridge crane unloading a trailer [35]

Straw bales are weighed on unloading, either by weighbridge or platform scales. The truck is driven onto the weighbridge, where the weight of the truck is subtracted from the total weight. With platform scales, the front wheels of the truck are manoeuvred

onto the platform and weighed each time a bale is offloaded. While this is more time consuming, platform scales cost about two-three times less to buy than a weighbridge [34]

The moisture content of the straw bales can be measured with a tool with a probe that is inserted in the bale. The resistance between two electrodes is measured and converted into a value that shows the percentage water content [34]. Another method of measuring the moisture content is to use a microwave system, see Figure 11.



Figure 11. Bale crane with moisture sensing device [35]

Other straw fuels such as reed canary grass and hemp can be unloaded in a similar way. However there is limited experience of these crops and there is no documented material on unloading hemp or reed canary grass bales.

7.16.2 Storage

The fuel sometimes goes into intermediate storage at the plant before being sent for combustion. A number of factors ought to be taken into consideration to reduce the risk of fire, shrinkage and to ensure efficient unloading and loading, see previously in chapter 7.1.3. At the same time, the costs of storage should also be taken into account. It is more expensive to construct and maintain storage facilities than an outdoor area, but they are less prey to the weather. On average, plants have storage capacity for eight days fuel requirements [34]. Figure 12 illustrates typical straw storage facilities.

The form a fuel takes also plays a part in determining storage needs. Straw fuel, such as straw and reed canary grass can be stored in bales. The bales can be stacked and stored indoors or outdoors. As described earlier (chapter 7.1.3) bales should be sheeted if stored outdoors. While straw bales, especially round bales, can withstand rain, reed canary grass straw has to be protected from rain and ground moisture. Pallets can be used as a well-drained platform [37].



Figure 12. A crane moves the bales to storage [35]

7.17 Fuel handling work environment at plants

All biofuels carry the risk of self-ignition due to microbial activity. As there is a big risk of fire when the moisture content of the fuel is uneven, fire-extinguishing equipment should also be available at storage points to minimise the consequences of a fire. [36] [38]

To avoid the risk of alveolitis to personnel, mould formation should be prevented as far as possible. If possible, straw should be handled in a closed system. However this entails high costs for plants. Bales that have been attacked by mould often have more mould inside the bale than on the surface. As such there are higher risks associated with bales that are broken up before combustion than when bales are burnt whole [36].

7.18 Fuel quality requirements of the plants

To achieve good combustion, plants have a number of fuel-related quality requirements. Different types of fuel are required, especially in terms of fuel form, depending on the type of boiler in which combustion takes place. This is described in more detail in chapter 10.1.

Many plants have quality criteria concerning the moisture content of fuel. When straw fuels, especially hay, are combusted in roaster boilers, they have to be dry. Sätenergi has set the moisture content limit for its roaster boiler at 18% [40]. Studies of Danish plants have shown that a moisture content above 20% makes combustion slightly uneven [34].

Other quality requirements can restrict the use of certain fertilisers that adversely affect the combustion characteristics of crops [40]. Flintrännen in Malmö (fixed roaster boiler at 40 MW heating) cocombusts willow, but only if freshly harvested, to meet its quality specifications [41]. Other plants accept all types of willow and see it as a price issue when willow with poorer combustion characteristics is purchased [42].

Price is clearly the most significant factor determining what fuel is combusted in the boiler. Here a number of factors come into play along with the purchase price of the fuel, such as transport costs, possible storage costs, coating and corrosion risks, environmental criteria and the quality of the fuel relative to the amount of energy that can be extracted from the crop.

7.19 Current research on energy plants' storage and logistics

The Värmeforsk programme on moisture content sensing of biomass involves several projects that are evaluating technology for automatically measuring the moisture content of incoming fuel.

Near infrared (NIR) has proved to be a method that can measure the moisture content in fuel with good accuracy. A current research project addressing automatic moisture content measuring of fuel deliveries with NIR, is developing a sample taking method that will be representative of the entire load. A simple type of probe for measuring the moisture content directly in or above the load via an optic fibre NIR sensor equipped with probes linked to bolts/drills is to be calibrated and tested at an energy plants that takes delivery of different biofuels.

Automatic moisture content measuring of fuel deliveries by radio frequency (RF) can be used to measure the moisture content of whole containers of biomass. Earlier measurements have been done with reasonable precision and it should be possible to perform moisture content analyses directly in containers holding up to 40 m³ of fuel. In order to be able to take measurements on this scale, the container needs to be calibrated to be able to differentiate the signals desired. Antenna design also affects output signals. Automatic moisture content measuring of fuel deliveries with RF is a matter of finding the optimal frequencies for the purpose, determining an appropriate method of scaling away interference from different containers and taking measurements at a fuel reception station.

7.20 References

- [33] Stridsberg S & Segerud K; "Powder combustion charcoal/reed canary grass/ground fuel kernels", Värmeforsk report 566 March 1996
- [34] Nikolaisen L (ed); "Straw for Energy Production – Technology - Environment - Economy", second edition The Centre for Biomass Technology Copenhagen 1998
- [35] Williams R; "Project 1.1 – Technology Assessment for Biomass Power Generation – UC Davis", TASK 1.1.1 Draft Final Report October 2004 http://biomass.ucdavis.edu/pages/reports/UCD_SMUD_DRAFT_FINAL.pdf
- [36] Bernesson S & Nilsson D; "Straw as a source of energy", Swedish University of Agricultural Science report 2005:07 Uppsala 2005
- [37] Burvall J; "Reed canary grass as fuel raw material", Fakta Teknik, Nr 1 1997
- [38] Johansson H; "Straw fuel research programme findings" Stockholm May 1997
- [39] Nilsson K; "Summary of fuel data for willow and forestry biomass", Vattenfall Utveckling AB, U-V 96:Ö1 June 1996

- [40] Jirjis R; “Effects on particle size and pile height on storage and fuel quality of comminuted *willow viminalis*”, Biomass and Bioenergy 28 2005, 193-201

7.20.1 Personal messages

- [41] Green, Sven-Göran, Lantmännen Agrovärme AB
[42] Resmark, Martin, E.ON
[43] Björklund, Ulf, Eskilstuna Energi & Miljö

8 Fuel refining

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8.1 Refining straw fuels

The need to refine agrifuels coincides with the need to optimise production economics, transport, handling, combustion, and to minimise environment impact at all these stages. This initial study is restricted to straw and willow-based agrifuels.

The system in force for willow in Sweden is based on harvesting and chipping the willow which is then continuously combusted on its own or mixed with another fuel (wood, peat) during the heating season. This system means that once the willow is chipped it can be compared with other forestry fuels that require drying before undergoing some form of processing into pellets. Comprehensive research has been done in this area and willow is also part of the current STEM funded project focused on refinement into pellets. As such, only straw fuels are addressed below.

8.1.1 *Straw fuels*

In addition to various sorts of hay (wheat, barley, oats, rape etc), the area of straw fuels in Sweden today includes the perennial energy crop reed canary grass and the annual crop hemp. These different straw fuels have several characteristics in common that mean research and development needs related to them can be described as one. There are a number of differences, however. This is especially the case with hemp, whose extremely tough fibres differentiate it from the other straw fuels. There are also differences in terms of physical characteristics depending on how long the hay or energy grass has been exposed to wind and weather. The breakdown of organic fatty acids and resins on the outside of hay and energy grass during storage in the field affects surface characteristics and shelf life.

8.1.2 *Large bales*

Systems studies performed at the Swedish University of Agricultural Science have exclusively looked at various forms of large baled material [1]. Farm access to machinery for baling and the development of more efficient large baling machinery suggest that material from the field and to the gates of industry will be handled in the form of large bales. Rectangular bales are the optimum shape for this with approximate dimensions of 120x100x240 cm and with an individual bale weight for straw of around 400-450 kg [2].

This report will assume that the basic shape arriving at refining plants is the large bale.

In the case of large-scale co-combustion with e.g. peat, tops, roots and branches etc, processing into pellets or briquettes can be excluded and breaking up the bales enables a sufficiently adequate mix.

8.2 Existing knowledge

There are a number of straw pelleting factories in Europe (none in Sweden) of which the largest owned by Eon is in Køge, Denmark. The Køge factory has a system for producing pellets from large bales. Some of the procedures have been especially developed for straw, although much of the technology comes directly from processing wood products into pellets.

At the Swedish University of Agricultural Science Biomass Technology and Chemistry Unit (BTK) and the Swedish University of Agricultural Sciences research pilot BTC a system for manufacturing briquettes and pellets from large bales has been developed and evaluated over several years. Research has been done on parts of the various areas that make up the entire refining chain. The work that has been done enables the level of current knowledge to be very well defined.

8.2.1 Breaking up bales

Equipment for breaking up bales that factor in hay as a dry material has been developed. There are several designs available that can deal with the twine that holds the bale together. One solution employed at Køge cuts and gathers the twine to prevent it causing problems further down the line. The twine can tend to get wound round axles and damage storage seals etc. There are solutions for this, however.

A great deal of dust is generated when breaking up and roughly chopping bale, which must be dealt with via suitable ventilation equipment. There are no dimensioning standards for this as yet, but the findings at BTC form the basis for new designs.

Capacity calculations at various sieves and measurements of energy consumption for different types of straw and grasses and/or hemp have not been performed.

Hemp bales that are broken up in coarse grinders without first removing the base fibres result in extensive intertwining of fibres and other parts. Technology for breaking up hemp has not yet been developed.

8.2.2 Separating out foreign objects

Stones and other objects that can interrupt processing can be caught up in bales when crops are baled in the field. Metal objects from farming machinery etc are particularly troublesome. Foreign objects of this nature simply have to be removed before the bales are broken up. Equipment for detecting metal objects has been developed. Separation methods based on density differences are also well-developed. In this respect, technology developed for wood and waste recovery can also be used for straw fuels.

8.2.3 Removing dust

Technology for removing dust in industrial processes is widely known and equipment for dealing with all kinds of dust is available on the market. However, there are no dimensioning data available on dust quantities and necessary airflows with regard to a safe working environment when processing and pelleting/briquetting different straw fuels. The Swedish University of Agricultural Sciences research pilot BTC has

developed a system for handling such dust and there were no known data on dust volumes that would be generated when coarse grinding/transporting/blending straw and energy grasses etc prior to designing the equipment. The system is made up of different components and works well but the dust filter was sized inadequately. However the Swedish University of Agricultural Science BTC now possesses experience on this technology.

8.2.4 Fine milling

The energy consumption in kWh/ton when fine milling grain straw, maize straw and switchgrass has been studied with 2.8-3.2 mm sieves by researchers at the University of British Columbia, Canada [3] [4][5] that shows the energy consumed when milling these types of raw material is much lower compared with milling wood chips.

Hammer mills tend to be used when upgrading raw materials for pelleting. Research has been done on other types of mill [6] that have shown that different particle size distributions are obtained with different types of mill. How this would affect quality and the manufacturing process has not been studied. The potential for milling straw fuels prior to pelleting with pulp industry refiners has not been looked at.

8.2.5 Conditioning

Conditioning covers the treatment of the raw material with steam and heat at different levels and different time intervals. This treatment is very important for long fibre materials such as straw. This is because the fibres are realigned and deformed on pelleting. Conditioning helps reduce energy consumption for this process. This is done to a certain extent in the industry. There has been no research in this area in relation to pelleting technology, but research and development work is planned, primarily for wood containing fuel within the so called Pelleting platform. On the other hand there is a great deal of fundamental knowledge on fibre characteristics and fibre processing within “wet” environments in paper and pulp manufacturing. However, this mostly concerns relatively short fibres compared with straw fuels. There is big potential here for research into pellet manufacturing to come up with results and methods that can significantly reduce energy consumption and increase production capacity.

8.2.6 Addition of additives

Additives can be added to pellet raw material for three main reasons: (i) to improve pelleting properties (press helpers), (ii) to improve combustion characteristics (combustion aids) and (iii) to bind dust. A number of reports have been published on combustion characteristics including one from the Umeå University Faculty of Energy Technology and Thermal Process Chemistry that points to the positive effects of various additives from a combustion viewpoint [7]. Several studies have also demonstrated favourable combustion related effects from mixing peat with straw fuels. Little has been published on pelleting characteristics and dust binding. There is no known research on various additives and associated techniques. There is a large knowledge gap especially concerning these raw materials that are more complicated to pellet than wood raw materials.

8.2.7 Pelleting process

A research project at REAP Canada (Resource Efficient Agricultural Production) has looked at pellet production from switchgrass in small trials. No systematic work on different forms of preconditioning has been done. Several scientific articles have been published by the University of British Columbia, Canada, mainly by researchers Mani, Tabil and Sokhansanj who have studied fundamental characteristics in different types of straw and grass and compressing them into pellets and briquettes on a lab scale. No full scale trials under practical conditions have been performed. The pelletizing factory at Køge, which produces pellets from straw, has successively improved its pelletizing process based on wood pelletizing methods and equipment. No scientific work to optimise production of straw fuels in a broader sense has been done.

One project “Pelletizing of reed canary grass” [8] has performed trials on pelletizing spring harvested reed canary grass under different conditions and found that this raw material has characteristics that require totally different equipment compared with conventional pelletizing machinery. Further research and development is suggested.

According to data from [9] the pelletizing of reed canary grass with conventional presses works well until matrices and press rollers become hot, at which point the dry content rapidly increases and the material burns solid. Oriented trials for pelletizing grass in presses with cold technology such as ECo Tree in Italy have worked well. Here the material is kept chilled by large airflows that cool the press rollers and matrix [10]. New cold technologies from China that are being developed (e.g. High Zones) and new technology in which matrices and press rollers are cooled with water and air have also delivered promising results. Raw materials with a higher water content can then be used which would also improve the potential to develop semi mobile technologies that are not so sensitive to variations in moisture content. Which means the dry content in the finished pellets can be increased if required by post production drying in large sacks without inner sacks [10].

8.2.8 Cooling, dust removal, packaging

Machinery and methods for cooling pellets made from straw fuels will probably not be that different from wood pellet equivalents. The research findings and know-how available there will probably be applicable to straw fuel pellets.

8.2.9 Process control and optimisation

Pellet process control and optimisation in terms of moisture content, ash content and ash composition (alkali and silicon) with NIR (Near Infrared Spectroscopy) and XRF (X-ray Fluorescence) technology is currently underway in the research programme “Production engineering platform for the Swedish pellet industry”. This programme is looking at forestry raw materials in the first instance, but the findings should be applicable for agrifuels too.

8.3 Current research

The STEM, pellet industry and Swedish University of Agricultural Science funded programme “Production engineering platform for the Swedish pellet industry” (2007-

2010) includes the research areas “New raw materials” and “Pelleting technologies and systems” where fundamental stages concerning the density of raw materials and friction studies of raw materials are also included, and also as part of a doctoral degree. Interesting new pelleting technologies will also be tested, partly in consultation with a larger equipment supplier. However the general guidelines for this R&D programme are that the main focus should be on wood raw materials with straw only addressed to a limited extent in a research pilot for survey and characterisation purposes. A future programme on straw fuel refining ought, however, to be coordinated with the “Production engineering platform for the Swedish pellet industry” programme as synergies can then be achieved.

An SLF funded project just started, will take an initial look at hemp over a three year period. In addition to cultivation technique aspects, the project will also look at different types of milling to enable further processing into pellets or briquettes.

Another current two year SLF funded project at the Swedish University of Agricultural Science Biometry and Technology, is a systems analysis of the costs and effectiveness for the refinement chain of briquettes versus pellets for agri raw materials.

It is difficult to get a clear picture of what work is being done in other EU countries in this area. The aims of the research programmes that are now being established within the 7th framework programme include coordinating the know-how situation and research where an important area can be refining technology for environment friendly and effective utilisation of straw fuels”.

One project designed to support the production of agrifuels with local refining at smaller units is being prepared by STEM with the participation of individual farmers and producers of briquettes and Västerbotten county authority.

8.4 Knowledge gaps

Within technology for refining straw fuels for pelleting and briquetting, there are major knowledge gaps in the following main areas:

- Milling technology for improving the physical and chemical properties of raw materials for pelleting
- Conditioning of raw materials to reduce energy consumption and increase production capacity in manufacturing
- Addition of additives (press helpers, dust binders and fuel improvers)
- Pelleting process. New or adapted technology for pelleting straw fuels that has other characteristics than the wood raw materials for which today’s technology has been developed.

Generally speaking, this area is undeveloped. The technologies and methods that have been developed for refining sawdust, shavings and the like are not ideal for straw fuels. The physical differences between the materials call for different or adapted methods. The lack of demand hitherto has meant that R&D and equipment manufacturers have not addressed these materials. The situation has now changed and there is a big demand for ways of refining straw fuels into some form that is environment friendly in terms of

combustion, transport and handling characteristics. In particular, technology for refining hemp grown for energy purposes is undeveloped in terms of fibre separation, milling, conditioning, pelleting etc.

Table 8. Compilation of knowledge gap.

Knowledge gap	Type of measure	Time required	Priority within the programme
Milling technology	Combination trials mills/Pelleting	> 3 years	Low
Conditioning	Basic research on material characteristics with different conditioning Applied trials at manufacturing works	> 3 years	Medium
Additives	Systematic trials with different additives. Evaluation of pelleting process Evaluation in combustion process.	> 3 years	Medium
Pelleting process	Trials with new pelleting technology. Modified physical processing environment for pelleting.	> 3 years	Medium
Comments Milling technology Expensive to set up trials. Labs with different types of mill not available today. Milling of straw fuels requires little energy and is not so costly. However, in the long term, measures will be needed as today's mills create a wide range of particle sizes and a great deal of dust. Conditioning Construction of research facility underway at the Swedish University of Agricultural Science BTC Umeå, and due to be ready in 2007 (funded by the pellet platform). When open, the facility will be available for agrifuel projects. Additives Trials planned at the Swedish University of Agricultural Science BTC. Various lignins will be evaluated as press helpers while combustion related additives evaluated in earlier research projects will be verified [7]. Evaluation in the combustion process can be done in projects < 0.5 - 2 years. Pelleting process Development of new types of machinery needs to be done in partnership with machinery manufacturers and is very expensive. Every change/modification to machinery takes time. Established manufacturers of pelleting machinery are not particularly interested in agrifuels today, as they view this as a small and marginal market. Shorter research projects are required that can eventually attract equipment manufacturers.			

8.5 References

- [1] Nilson, D., *Harvesting transport, storage and refinement of straw for fuel - methods, energy requirements, costs* Faculty of Farming Science. Report 150, 102 p. Swedish University of Agricultural Science, Uppsala. 1991.

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- [2] Olsson, R., Rosenqvist, H., Vinterbäck, J., Burvall, J., Finell, M., *Reed canary grass as an energy and fibre raw material – a study of systems and economics*. BTK-report 2001:4. 60 s. Biomass Technology and Chemistry Unit, Swedish University of Agricultural Science, Umeå. 2001.
 - [3] Mani, S., *Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses*. Elsevier. University of British Columbia. January 2004.
 - [4] Miles, T.R and Miles, T.R. Jr, *Densification systems for Agricultural Residues*. In: Thermal Conversion of solid wastes and Biomass p.p. 179-191. American Chemical Society, Washington, DC. 1980.
 - [5] Samson, R., Drisdelle, M., Mulkins, L., Lapointe, C., and Duxbury, P. *The use of switchgrass biofuel pellets as a greenhouse gas offset strategy*. In: Bioenergy 2000: Proceedings of the 9th Biomass Conference of the Americas, Buffalo, New York. October 2000.
 - [6] Paulrud, S., *Upgraded biofuels - effect of quality on processing, handling characteristics, combustion and ash melting*. Doctoral thesis, Swedish University of Agricultural Science. 2004
 - [7] Öhman, M., Hedman, H., Danielsson, B., Boström, D., *Effect of low level addition of additives on combustion of stemwood pellets to counter slagging in combustion equipment*. STEM project P 13674. Sept 2002.
 - [8] Örberg, H., Kalén, G., Thyrel, M., Finell, M., Andersson, L-O., *Pelleting of reed canary grass*. Swedish University of Agricultural Science. BTK report 2006:12, 2006.
 - [9] Oral information Bo Lundmark, Glommers Miljöenergi AB
 - [10] Oral information, Rolf Olsson Swedish University of Agricultural Science Umeå
 - [11] Hansson and Nilsson. Current project. *Optimal pellets and briquettes – a systems study*. Swedish University of Agricultural Science 2007.

9 Preparation and fuel feed

Fuel preparation and fuel feed are dependent on the combustion process and the fuel's physical form. At the moment there are effective equipment available for the preparation of wood fuel in chipped or powder form and dosing it into the boiler, while whole bales require special firing and in-feed technology.

Grabs, rotary vane feeders, screw conveyors, conveyor belts and scrapers are commonly used for the in-feed of material of a slightly larger particle size. In-feed to grate boilers can also be done by always having the fuel chute full and the fuel delivery rate controlled by the combustion speed. In these cases it is necessary for the fuel to fully pack out the fuel chute so that it is air tight and there is no ingress of air into the boiler through this route.

No further preparation of wood chips is necessary if they are of the right size and they are sufficiently free from contamination. Oversize material can be separated by screening and the reject material crushed before feeding in to the boiler. Crushing and screening are more necessary in the case of uneven fuel quality and is not critical for straw fuel use. [1]

Bales can be fed in as they are but in practice the bales can be shredded, disintegrated and/or chopped prior to feeding into the boiler. A disadvantage with bales is that they differ physically from other fuel and thus require special equipment for feeding in and preferably even for combustion.

In order to minimise variations in firing during bale combustion, there is a trend for weight and moisture content to be taken account of during in-feed to give an energy-related feed speed instead of one based on volume as is usual. [5]

Debalers have been developed to achieve a more continuous combustion of straw. A knife divides the bale into 30 cm. thick layers which are fed continuously into the boiler. A machine equipped with a debaler breaks up the bale prior to combustion so that loose straw is automatically fed into the boiler. [6]

The handling of baled straw fuel requires a good deal of space and special equipment for the receiving, handling and break up of the bales. Only a few combustion plants in Sweden have this type of equipment. Danish plants have started to discontinue whole bale combustion and go over to shredded in-feed to the boiler to maximise efficiency. [7]

Pellets and briquettes have the advantage of being pre-prepared, have consistent quality and are easy to feed in and dose. They can be used as they are in some grate and fluid bed boilers and if the base material is powder, they can even be used in powder boilers if milled first. An important parameter for pellets and briquettes is that they remain intact right up to milling if that is done.

Powder is normally fed in using a pneumatic conveyor together with the primary air to the burner. There is a fire risk with all types of powder conveyor systems caused by dust explosion. Conventional technology is used to prevent fires and to quickly extinguish them if they nevertheless occur.

The following lists the properties of energy crops which are of importance in terms of fuel feed into the boiler:

Straw	Occurs in the form of powder or pellets and straw. Problems can occur when straw is handled with screw conveyors as straw stalks are long and wrap round the hopper screw. Straw fuel can give rise to problems in the fuel chute due to the stalks hanging when they pass through. This problem can be reduced by improved chute design. Pulverisation of straw requires milling or conversion to chip form to enable complete combustion during the short dwell time in powder boilers. Milled straw has similar properties to wood powder. The properties of straw can be improved by leaving it in the field for a time to let it be “washed” by rain. This reduces the amount of chlorine and potassium present, which otherwise cause corrosion and surface deposits. Alternatively, if newly-harvested straw is sent immediately to the combustion plant it can then be washed in specially-designed facilities at a temperature of 50-60°C. This also raises the moisture content in the fuel. [9] Straw can be combusted in a grate boiler, either disintegrated or in whole bales. Combustion of disintegrated straw requires a disintegrator, fan or suction conveyor, cyclone, a cell wheel to prevent burn back and a feeder to the boiler. A disintegrator will often not handle straw which has been damp or showing fungal growth nor straw containing couch grass. Some disintegrators cannot handle flax straw but rape straw gives no problems.
Grain	Defined as wheat, barley, wheat-rye hybrid or oats’ chaff with husks but no stalks. Grain is easy to handle in terms of transport, storage and in-feed. [4]
Grain stalks	Pellets of grain stalks can be milled and combusted in powder boilers. During a trial with grain stalks together with wood fuel in Norrtälje the fuel handling grab was sealed to prevent stalk loss. [4]
Willow	Willow is always used in chip form and is similar to “normal” wood chips in volume density, angle of repose and other fuel parameters. Chip size is often larger than that of normal wood chips and the amount of fine particle size material is generally low. Willow in chip form can even be more homogeneous than woodland chip fuel. [4] Willow in milled form has been tested for powder boilers. This resulted in significant problems with fuel in-feed, for example build-up in the fuel silo and static electricity which caused a stop in the handling process. [8]

Reed canary grass	Can also come in the form of whole bales, pellets (powder) or loose straw. Reed canary grass (RCG) has a low bulk density and build-up is commonly a problem. [2]
Hemp	One reason for cultivating hemp is its strong fibre which can cause problems with screw feeds and other types of in-feed equipment by jamming and entanglement. The high fibre content means that there is always a risk of build-up above the screws etc. [3] Hemp is difficult to separate and can create significant problems when disintegrating in bale splitting equipment. “Cigar” combustion has been used as an alternative. See Section 10.1.2. Hemp has also been shown to have two significant disadvantages in that its volume is too high and it is far too dry to be fired as the sole fuel in a boiler with a movable grate. To avoid this, hemp has been blended with wood chips to maintain suitable moisture content. [11]

A full scale trial is essential in order to establish how an energy crop will function in a plant’s fuel handling equipment.

9.1 Mixing

Thorough mixing is essential if two or more different fuels are to be co-fired simultaneously. The advantage with well-mixed fuel is that combustion is more stable with a reduced risk of sintering due to local superheating, providing a basis for getting the most out of the positive properties of the different fuels and promoting synergy effects.

Normal methods for mixing fuels are either on a fuel floor with the help of a grab loader, requiring a driver for the loader, or using a grab in the fuel hopper, which can be programmed or operated manually. In a number of plants which co-fire straw and other fuels, there are normally problems in achieving efficient mixing. [1]

A mixing strategy which has proved successful is to use a sufficiently large tipper hopper with place for four different fuel types and a grab. The grab is programmed to take fuel from the different sections according to a pre-determined pattern and then unload onto a mixing stack just in front of the in-feed hopper. When the grab then takes the fuel to the in-feed hopper, it takes a fraction of the required fuel blend which undergoes final mixing on discharge from the hopper and in the chute to the in-feed screw conveyor to the boiler. It is essential that the tipper hopper can handle a sufficiently large volume. [1]

Another alternative for mixing is to have a stoker plate in two sections with the facility to control each section’s speed separately. The mix of different fuels falls from the plate edge down in to a scraper conveyor. The scraper conveyor then discharges in a chute down to the in-feed hopper, where the fuel is blended. [1]

9.2 Handling of impurities

All fuels which have not been handled on a hardened surface carry the risk that impurities, for example gravel, are mixed up in the fuel. Depending on the combustion technology used, this can result in a range of significant problems to the process but there is always a risk of increased wear on conveyor equipment. Powder boilers are most sensitive to gravel but this is normally separated out by screening before it reaches the powder burners. Metal fragments and stones can also be separated out before the mills and screens, using a cyclone separator or stone trap, for example.

9.3 Current research

A four-year EU project has been underway since February 2006 known as NextGenBioWaste. The overarching goal is to increase the use of renewable fuels and the terms of reference of the project are to look at the whole chain, from fuel handling and combustion to ash and ash handling. SP1 is focused on fuel preparation and mixing. The total budget for the project is 29 M€. Further information can be found on the project's website: www.nextgenbiowaste.com.

9.4 References

- [1] Stridsberg, S. *Anpassning av värmeverksutrustning till halminblandning*, Värmeforskrapport #673, October 1999
- [2] Burvall, J. Tillverkning och proveldning av reed canary grass-pulver –ett fullskaleförsök. Sveriges Lantbruksuniversitet, Rapport 9:1993
- [3] Finell, M. et. Al. *Multifunktionell industrihampa för norra Sverige*, Sveriges Lantbruksuniversitet, Enheten för Biomassateknologi och Kemi, Umeå. BTK-rapport 2006:13
- [4] Strömberg, B., *Bränslehandboken*, Värmeforskrapport # 911, 2005
- [5] Sørensen L H; “Straw-fired Combined Heat and Power Plant”, Gülzower Fachgespräche Band 17 Energetische Nutzung von Stroh, Ganzpflanzengetreide und weiterer haulmgutartiger Biomasse Tautenhain May 2001, 103-113
- [6] Hartmann H; “Die energetische Nutzung von Stroh und strohähnlichen Brennstoffen in Kleinanlagen”, Gülzower Fachgespräche Band 17 Energetische Nutzung von Stroh, Ganzpflanzengetreide und weiterer haulmgutartiger Biomasse Tautenhain May 2001, 62-84
- [7] Williams R; “Project 1.1 – Technology Assessment for Biomass Power Generation – UC Davis”, TASK 1.1.1 Draft Final Report October 2004 http://biomass.ucdavis.edu/pages/reports/UCD_SMUD_DRAFT_FINAL.pdf
- [8] Strömberg B; “Bränslehandboken” Värmeforskrapport 911 March 2005
- [9] Kavalov B & Peteves S D; “Bioheat applications in the European Union: an analysis and perspective for 2010”, European Commission DG JRC Institute for Energy Petten 2004
- [10] Hering T; “Stroh- und Ganzpflanzenverbrennung am Beispiel der Strohheizwerke Schkölen und Jena”, Gülzower Fachgespräche Band 17

Energetische Nutzung von Stroh, Ganzpflanzengetreide und weiterer
haulmgutartiger Biomasse Tautenhain May 2001, 114-126

- [11] Sundberg M, Westlin H; "Hampa som bränsleråvara", JTI-rapport Nr 341 2005

10 Combustion of energy crops

To achieve optimal combustion, it is necessary for each process phase to take place under the right conditions. It is usual to speak of the combustion's T3, Time, Temperature and Turbulence phases, all of which must be fulfilled for satisfactory combustion. Temperature and turbulence requirements are necessary for efficient combustion. Combustion must continue for a sufficiently long time, at sufficiently high temperature and with adequate turbulence (continuous mixing of components). This is achieved by the design of the combustion chamber, different baffles and the location of the air intakes and other features. Other important factors affecting combustion include the fuel's ash content, ash composition, size distribution, calorific value and moisture content. These aspects are dealt with in the following sections.

10.1 Boiler types

Grate boilers, powder boilers and fluidised bed boilers have different requirements for the combustion of energy crops. The fuel's physical form is influential in deciding whether the fuel is suitable for the type of boiler already installed in a plant. Other factors influencing the type of fuel include the ability to handle an increased amount of ash. Different boiler types also vary in combustion atmosphere due to different temperature conditions. Section 10.4 has a more detailed description of the influence of furnace type on combustion temperature.

In order to achieve highly efficient combustion it is important that a new boiler is designed suited to the requirements of the fuel or fuels to be combusted in the boiler.

10.1.1 *Powder firing*

Powder-fired boilers were originally designed for oil or coal dust but since then multi-fuel boilers have been developed which are fully or partly intended for biofuels. Energy crops must be in powder form for efficient combustion. This means that fuel quality and fuel preparation are important parameters leading to high fuel cost. [2]

RCG can be pulverised and used in powder-fired boilers. A nine-hour trial in the Drefviken boiler (30 MW with two 15 MW burners) demonstrated that RCG powder can be efficiently fired without any special plant adjustments. Wood powder has been normally fired in the same plant. Although powder fuel systems are sensitive to variations in fuel quality, it was possible to conclude that it is possible to achieve consistent quality and flow properties with dry spring-harvested RCG. [4] [5] Co-firing of RCG and coal in powder form was satisfactory in a trial at Västhamnsverket (185 MW) without any reported problems. Some loose deposits of ash on the burners were observed, particularly at higher boiler operating conditions, without causing problems. [6]

Willow in milled form has been tested with powder burners. This resulted in significant in-feed problems due to build-up and static electricity which caused a stop in the handling process.[7]

Grain and pellets of various crops (for example straw) can be fired in powder boilers if they have been milled.

10.1.2 Grate boiler firing

Grate boilers can be used to process a relatively wide range of fuel particle size, moisture content and high ash contents. [2] This type of combustion technology is often preferred for biofuels because of its reliability and because of the long experience with grate boilers [5] - in our case in terms of smaller boilers (<20 MW). The grate boiler should be of a suitable size and the fuel needs to be well mixed. Grate boilers are therefore suitable for multi-fuel combustion of different fuels, for example wood and straw fuel. [1]

There are a number of different types of grate boilers. In a boiler with a fixed inclined grate, the fuel moves under its own gravitation along the grate. The fuel is thus gradually dried and volatilised on the grate bed. The fuel moves down the grate with the particles turning over and rolling. This improves fuel mixing, particularly for fuels which are a little larger in size. Another type of grate is the vibrating grate which shakes the fuel ensuring even distribution over the surface. [1]

When a furnace is equipped with a movable grate, the fuel is slowly transported through the boiler. The advantage of a movable grate is that it is easier to control the in-feed speed and thus combustion, as the speed on the grate can be regulated. A combination of both technologies is the inclined movable grate. The supposition is that this type of boiler ensures more complete combustion of the fuel which is continuously mixed as it falls during which the grate be regulated. Another type of movable grate is the “wanderroster”. Here the grate comprises fire bars which form a mat which moves through the boiler. [1]. Figure 13 shows a grate where the different combustion phases take place in different zones on the grating.

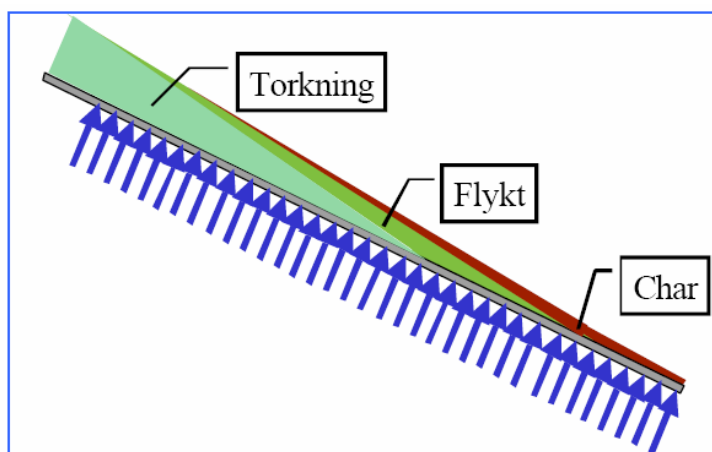


Figure 13. Combustion bed of a grate boiler. The different phases overlap each other since the working force behind drying and gasification is radiation from above.

Grate boiler combustion can be used for straw fuel. Straw fuel in chopped or whole bale form can be fired in a grate boiler. When “cigar” combustion is used, the bales push one another forward and are thus combusted in the boiler.

The biggest challenge in firing straw bales on a grate is ensuring even combustion of the fuel. The density and moisture content of the bales can vary and at the same time the in-feed method can be irregular. This means that steam production, steam temperature, emissions, unburnt residues in ash and slag etc can vary. [6] Firing with whole bales results in intermittent combustion due to the in-feed process. This type of firing should only be used at full load. [7]

RCG has been shown not to work well in whole bale furnaces. The tendency of the ash to form a skeleton gives rise to fuel combustion which is not fully completed. However, combustion plants intended for straw can also usually handle RCG if it is in chopped form. [2] This means that a plant can reduce costs as RCG can be handled using the same equipment as for straw. Moreover the spectrum of fuels that a plant can handle is increased with a reduced dependency on availability of straw. [8]

Combustion trials in Denmark with RCG, partly in whole bales (at the 4.5 MW Ringsted plant) and partly with loose grass (at the 4.0 MW Nykøbing grate boiler facility) gave CO and NO_x emissions which were far over acceptable levels. This is probably explained by the fuel’s low density and moisture content variations in the material giving rise to uneven combustion with high emission levels. [9] Other trials with “cigar”-fired RCG showed no technical problems compared with straw. Even loose RCG straw in a grate boiler gave the same satisfactory result. [9] [10]. The experience of firing RCG is varied in other words. Combustion of RCG briquettes and pellets has been effective in smaller boilers, particularly if the boilers were adapted for high ash content fuels.

In a trial in a “wanderrost” boiler in Arlöv, grain (wheat) was co-fired with varying amounts of coal. The grain lay on the grate and the coal above it. With a 60% energy share grain, a maximum boiler efficiency of 70 – 75% can be achieved of the nominal boiler efficiency (coal-fuelled, nominal efficiency was 28 tonnes of steam per hour). A “wanderrost” trial fuelled with a pre-mixed grain/coal mixture gave coal dust problems if the mixture’s intermediate storage time was too long allowing the grain to absorb surface moisture from the coal. [11]

Willow is commonly used in grate-fired boilers as part of the fuel mixture and gives no problems. However, if the willow has been more coarsely chipped there have been instances of fierce firing and blow-through of air on the grate when the coarser fuel has not adequately covered the fuel bed as well as other fuels which have been used. (Mjölby energi, 14 MW fuel input). [4] [11]

10.1.3 Fluidised bed

Many of the new biomass-fuelled boilers that are built today are fluidised bed boilers, particularly larger boilers over 20 MW. There are no major problems in firing with a range of fuels as long as it is possible to control the bed temperature effectively. [5] A

more compact construction is possible with a circulating fluidised bed boiler than a normal FB boiler. A circulating FB boiler can handle higher ash and dust levels but a higher efficiency level is necessary if it is to operate economically. [13] A circulating bed boiler gives a better mixing of air, fuel and bed material than a BFB (bubbling fluidised bed) boiler resulting in more uniform temperature distribution.

An advantage with FB boilers compared with grate boilers is that fuels with higher moisture content can be used. If straw is burned on its own in a FB boiler, serious problems can result due to the fuel's high alkali content. There is a significant risk that the bed will sinter. See Section 10.2. Straw can however be mixed with other fuels, for example wood pellets, if it is to be burnt in a fluidised boiler. [13]

Willow has been burnt in circulating fluidised bed boilers with relatively satisfactory results. Two large boilers (Örebro with 180 MW fuel input and Eskilstuna with 63 MW fuel input) have co-fired willow at low levels of addition in combination with the main fuel. Experience with bubbling fluidised bed boilers indicates that the fuel transfers itself up on top of the bed. [4] [11] [14]

10.1.4 Suitability of combustion technologies

Table 9 presents in summary form the suitability of different energy crops when fired using different combustion technologies. It is based on current experience with these different crops.

Table 9. The relative suitability for different energy crops for firing with different combustion technologies.

Fuel \ Combustion principle	Straw	Willow	RCG	Grain	Hemp
Fixed grate	+	+	+	+	+
Moving grate	+	+	+	+	+
Powder burner	+	0	+	+	+
Bubbling fluidised bed	-	++	n.a.	n.a.	n.a.
Circulating fluidised bed	-	++	n.a.	n.a.	n.a.

Key: (--) Not possible, (-) Not suitable, (0) Disadvantages compensated to some extent by advantages, (+) Suitable, (++) Very suitable, (n.a.) no available information

A further way of considering combustion technologies is based on the fuel form. Table 10 gives an overview of how straw, in stalk, pellet, briquette, powder and whole bale form can be handled using different combustion techniques.

Table 10. The relative suitability of different combustion technologies in relation to form of the energy crop fuel for heat production

Fuel form \ Combustion principle	Straw	Pellets	Briquettes	Powder	Whole bales
Fixed grate	-	+	+	--	+
Movable grate	+	++	+	--	+
Powder fuel	-	+	+	++	--
Bubbling fluidised bed	0	+	+	-	--
Circulating fluidised bed	0	+	+	-	--

Key: (--) Not possible, (-) Not suitable, (0) Disadvantages compensated to some extent by advantages, (+) Suitable, (++) Very suitable

*pulverised fuel subsequently processed to briquette or powder can be used in powder fuel boilers if milled before firing

10.1.5 General aspects

Efficient combustion requires an optimal balance between the fuel and the combustion technology used. The combustion process must be correctly set and adapted to the fuel to be fired. In particular it is important to ensure that the oxygen content and amount of fuel are compatible for the process. In theory, a plant equipped with advanced control systems should be able to handle fuels of lower quality more easily. Larger plants are generally better equipped in terms of process control. Lower fuel costs can compensate for the higher capital costs necessary to, for example, equip a plant with advanced control systems. [1]

An important difference between the different boiler types is the temperature in the combustion chamber. The temperature in the vicinity of the grate in a grate boiler is approximately 1,100°C, and locally somewhat higher, and mainly with reducing conditions. In a fluidised bed boiler, the bed temperature is relatively constant at 750 - 900°C. The temperature is held down by internal heat exchange surfaces and flue gas circulation. The difference in combustion temperature results in different dust composition, unburnt particles and the aerosols which are lifted up to the heat transfer surfaces. At the lower combustion temperature in fluidised beds, the particles formed increase in size and the proportion of contaminants vaporised is lower. Fuel mixing in the bed is better than in a grate boiler, resulting in combustion proceeding under relatively constant conditions. [2]

10.2 Ash related problems

From a technical point of view, the largest problems in the use of energy crops are the coatings and deposits which form in the boiler and the flue gas system.

10.2.1 *Slag, deposits, sintering and agglomeration formation*

The amount of ash and the composition of ash-forming substances are important parameters in the formation of deposits in boilers. Fouling can be divided into slag and deposits.

Fouling in molten or sluggishly flowing form are termed slag. It is caused by ash particles becoming sticky and adhering to one another or to surfaces in the combustion chamber. Slag is found in the parts of the boiler subject to radiant heat transfer. Deposits comprises fouling which have built up by alkali-containing substances, primarily ash, which has volatilised and then condensed. Deposits are found in the cooler combustion zone where the heat exchangers are positioned. [15] [16]

Fouling formation impairs the efficiency of a boiler. It reduces heat transfer efficiency leading to lower boiler efficiency. Fouling can grow in size and become so large that it reduces the flow in the boiler giving rise to mechanical damage. It can, for example, increase in size on the grate worsening the removal of ash which can lead to plant shut-down. Fouling can also be a source of corrosion. [15] [16]

Sintering and agglomeration are other terms used when discussing combustion. Sintering is defined as a phenomenon where loose composite particles form a tight compact mass. Agglomeration is a term used when particles grouped in clusters have a larger size than the original particles. [15] Agglomeration can, for example, cause problems in fluidised beds. [16]

10.2.2 *Factors determining risk of fouling*

The ash melting process influences the formation of deposits and sinter by a fuel. The ash's melting point is particularly decisive. [17] A low incipient ash melting point is generally the cause of significant problems in terms of formation of slag and deposits on combustion. [18]

The factors associated with the melting point of a fuel's ash are extremely complex and not yet fully researched. However it can be said that the melting point of a fuel's ash is influenced by both the substances making up the ash, the relationship between the different substances, particularly silicon, calcium and potassium. The presence of potassium reduces the ash's melting point while calcium increases it. [16]

Straw and straw ash studies have shown that there is a relationship between the melting point of the ash and the ratio of chlorine concentration to potassium in the fuel. The higher the ratio, the lower the softening temperature. It was also found that both chlorine and potassium are leached out by rain. [17]

In terms of slag overlay, the composition of the ash and sulphur and chlorine levels is significant factors. Deposits can also develop in size through reactions between components in the deposit and flue gases (for example, SO₂, CO₂ and HCl). [16]

The following summarises different ways in which boiler deposits can be reduced.

10.2.2.1 Mechanical factors

Plant design can also influence the extent to which deposits form in a boiler. A vibrating or movable grate prevents slag products sticking with a negative effect on the combustion process. [7] [16] A water-cooled grate also reduces slag formation problems. [6] The grate temperatures are lowered which means that the ash's melting point is less easily reached. [1] Burners are affected by slag formation forming on and around the air holes in burners. This can be avoided by selecting burners with ceramic linings as they give less sintering than cooled burner tubes, for example. [16]

10.2.2.2 Additives

Additives can be used to prevent volatile substances evaporating and travelling with the flue gases up in the boiler and causing deposit formation. Additives must have very effective and fast-working alkali binding properties and form stable products. In addition, they are required to be cheap and have minimum environmental impact. [2]

Additives can be used in a variety of ways:

- Chemical binding of alkalis
- Adsorption of particles
- Sulphating of alkali chlorides
- To reduce formation of alkali silicates in the bed

The different mechanisms can give different synergy effects. In addition to reduced bed agglomeration, deposit formation and corrosion, emissions of other substances such as CO, TOC, dioxins, SO₂ and NO_x are influenced. This is illustrated in Figure 14. [20]

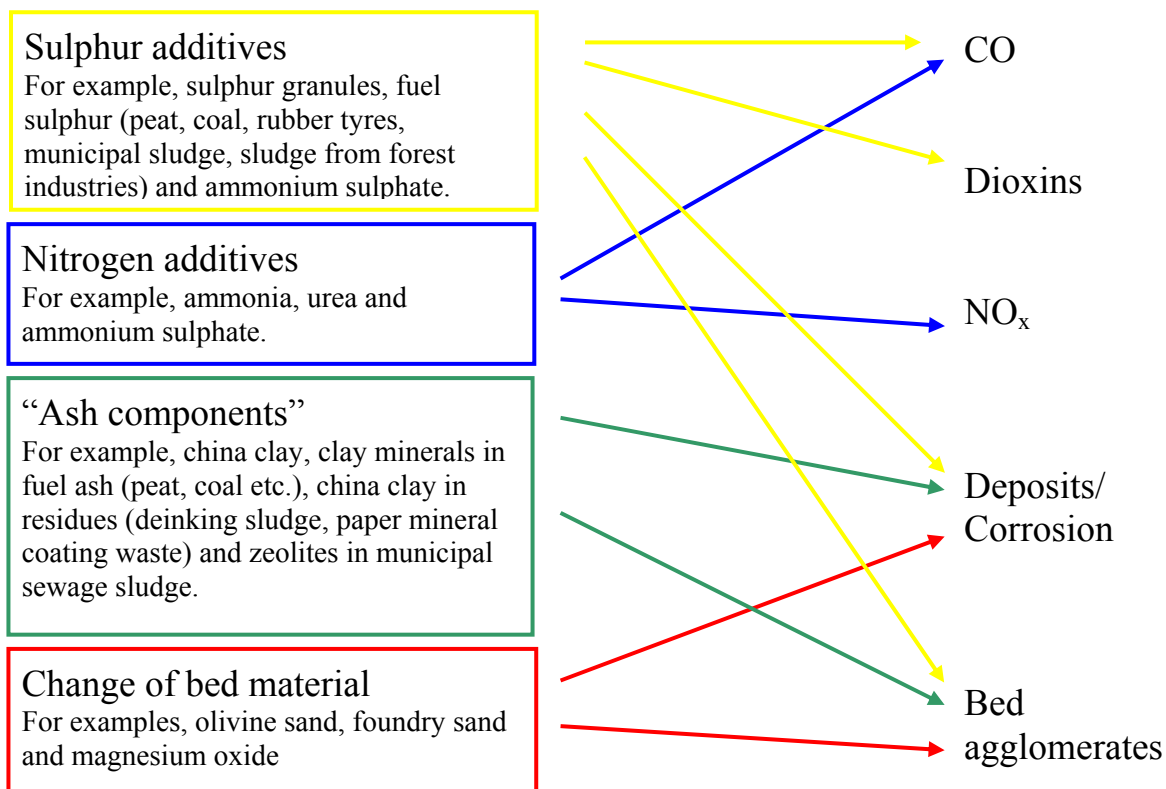


Figure 14. Preventative measures in relation to alkalis and obtainable synergy effects. Adapted from [20]

China clay $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ is a mineral which has been shown to be effective in absorbing alkaline metals in hot flue gases. China clay reacts with potassium and forms compounds with a higher melting point. The deposits then have lower chlorine content and are easier to remove. The amount of deposits however does not reduce if china clay is added as it results in an increase in the number of particles in the flue gases. [2] The china clay does not remain in the combustion chamber but is taken out with the flue gas. [19] At the same time an increase of particles in the flue gas can sometimes result in deposits being abraded away.

Sulphur has also been shown to be able to reduce problems with deposits and is generally used as an additive to reduce corrosion. Sulphur reacts with metal chlorides, for example alkali metal chlorides, and forms sulphates. Sulphates of the same metal generally have a higher melting point compared with the corresponding chlorides and studies have shown that the chlorine level in deposits reduces substantially when sulphur is added. [2] Injection of ammonium sulphate gives significantly less deposit formation, see Figure 15, but also less CO and NO_x. The sulphur can be added in elemental form to the fuel, as $\text{SO}_{2(\text{g})}$ in the combustion atmosphere or by sulphate injection. Ammonium sulphate injection has shown itself to be most effective. [2]



Figure 15. Coating probes exposed to the flue gas at Munksund's CFB-boiler. The picture to the left shows the coating formed when sulphur is not added and the picture to the right shows the situation when sulphur was added.

Other additives which are used to raise the melting point of the ash are limestone (CaCO_3) and dolomite ($\text{CaCO}_3 \cdot \text{MgCO}_3$). These additives bind sulphur to the fuel and can also be used to reduce sulphur emissions. [2]

10.2.2.3 Co-firing

Co-firing using additives can inhibit the risk of deposit formation. Co-firing can also result in chlorine, potassium and other substances which readily promote deposit formation are subject to a dilution effect with a consequent reduction in deposit formation in the boiler. Co-firing with sulphur-rich coal or peat results in a reduction in deposit formation problems, for example. [2] When wood and straw pellets were co-fired in Chalmers' 12 MW CFB boiler, untreated municipal sewage was added. At 13% untreated sewage addition level, the agglomeration temperature was raised from 940°C to 1,067°C. [20]

10.2.2.4 Change of bed material

It is well-known that for normal wood fuels, such as wood pellets, tops, roots and branches, bark etc., if the bed material in FB boilers is changed from quartz-rich natural sand to bed material of low quartz content, such as olivine sand and foundry sand, there is a reduction in the tendency for agglomeration to occur. This has been analysed more closely in co-firing trials at Chalmers' 12 MW CFB boiler with straw and wood pellets (20 % straw pellets and 80 % wood pellets). By changing bed material from silver sand to foundry sand, the tendency to agglomeration reduced significantly for both the bottom bed and the cyclone leg tests. When bottom bed tests were subsequently made it was found that the agglomeration temperature had fallen to approximately 1,000°C, probably due to the ash content in the bed being so high that it was the properties of the fuel's ash which influenced the results. Changing the bed material to olivine sand was not as effective as changing to foundry sand. [20]

When energy crops such as willow and RCG were gasified in a laboratory-scale FB boiler, it was shown that the inorganic substances released from the fuel reacted with the bed material and that was a pre-condition for bed agglomeration to take place. If the

bed material had excess dolomite, then the amount of alkaline substances in the bed reduced as they were volatilised. If the bed contained excess dolomite, this resulted in a reduction in the amount of alkaline materials present in the fuel in the bed. They were volatilised instead. If the bed contained much silicate, the alkalis found in the fuel in the bed were bonded. The risk of a significant increase of agglomeration in the bed thus rose substantially. [21]

10.2.2.5 Pre-treatment (milling and particle size)

Particle size has great significance, not only for the combustion process's physical properties (grate flame pattern, energy yield etc.) but also for chemical properties. Fuel particle size's influence on the fuel's properties has been researched in a study. RCG and elephant grass were milled in a ball mill to give two different particle sizes, < 90 µm and 90-600 µm. The study's results were not clear as to whether particle size has an influence on the tendency to form deposits but the fuel's smaller particle size fraction had an alkali index which indicated a higher ash melting point. The two particle size fractions differ from one another in a range of parameters indicating that some of the substances which the fuel contains do not distribute themselves randomly between the two different particle sizes. The smaller particles had a higher concentration of inorganic material and also higher moisture content compared with the coarser particle size. They also had a higher coal content and lower nitrogen content which gave them a higher calorific value. The volatile fraction was also higher in the coarser particles causing the particles to behave differently. The finer particles had a lower pyrolysis temperature, lower coke combustion temperatures, and a higher proportion of catalytic cracking pyrolysis products. [19]

Particle size can also influence the process temperature (particle temperature) and accordingly, melting characteristics. Studies have shown that a finer particle size results in an increased particle temperature. When a trial was carried out using RCG in briquette and pellet form in a 180 kW grate-fire boiler, it was seen that the particle temperature was relatively similar for both forms. However, it was found that a substantially greater amount of unburnt RCG was found in the ash when pellets were fired. This can be due to a stronger bond between the particles in the pellets and that tar had built up inside the pellets. [22]

10.2.3 Experience with energy crops

10.2.3.1 Straw

Oil plant and wheat straw are regarded as types of straw which are easy to fire in a boiler while oats' straw is not as acceptable. Straw which has been lying after cutting and become thoroughly wet with rain, known as grey straw, is preferred while straw which has been pressed on the same day as it was threshed, yellow straw, should be disregarded. The reason for this is that the potassium level in the straw goes down when it rains, which in turn affects the melting point of the ash. [17] [26] German studies have shown that winter wheat and winter rye are most suitable in terms of combustion. [27]

Straw contains substances (Na, K, Mg) which give a low ash melting point. The temperature in grate boilers should therefore not exceed 800-900°C otherwise the ash may stick together. It is possible to achieve low temperatures like this in a grate boiler by using part load. [13] [28]

I Svalöv, 100 % straw is fired with satisfactory results. The deposits which are formed are easy to remove by soot blowing and the boiler is sooted once a month. The boiler is a 5MW box furnace with a movable grate. [41] Sätenergi also burns 100% straw with satisfactory results. The boiler, a 4 MW movable grate boiler, does not suffer at all from deposit formation due, it is said, to the fact that it was designed as a straw-specific boiler, no other fuel being used. There has even been success in educating the farming community to only deliver straw suitable as a fuel, so avoiding combustion problems. Moisture content is the most important factor on delivery and the straw must be dry with a maximum moisture content of 18 %. [42]

Comparisons between the firing of straw and the whole plant (straw and chaff), has shown that the slag formation reduces when the whole plant is fired. The reason is the lower potassium level in the fuel when the whole plant is fired. Another advantage is that there is reduced chlorine emission. The trials were carried out in two small German plants: Jena (1.75 MW fired with bales which are disintegrated on in-feed) and Schkölen (3.15 MW “cigar firing”). [28]

Newer straw fired plants in Denmark have learned from old mistakes in terms of battling with deposit formation. The Masnedø vibrating grate boiler (8 MW_e and 21 MW_{th}) has the superheater section designed so that the superheater tubes are parallel with the flue gas flow. This reduces build up of deposits but also the heat transfer coefficient. This means that the superheaters need a larger area compared with if they had been positioned transversely in the flue gas channel. The steam temperature is 520°C and the superheaters are positioned as in Figure 16. [29]

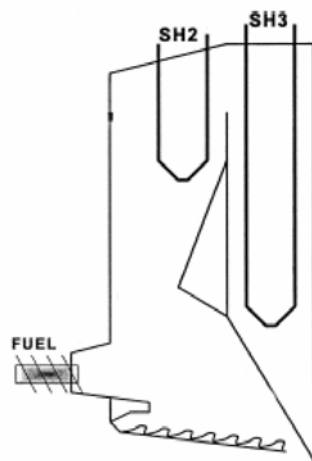


Figure 16. The Masnedø boiler and the position of the superheaters [32]

A small-scale co-firing trial in a 5kW FB boiler using a mixture of peat and straw showed an increase in iron, sulphur and calcium in the ash particles. A “dilution” effect

and/or an actual reduction in potassium level in the ash particles which were formed had a beneficial effect in melting behaviour and consequently in reduced risk of agglomeration also. Mixing peat with straw in small-scale grate boiler reduced the tendency to form slag. This is explained by the fact that straw is rich in potassium and silicon. High calcium to silicon ratio in a fuel is preferred to minimise the formation of slag in grate boilers. A relatively high level of peat addition (close to 40% by weight) is however required to avoid deposit formation and agglomeration. [30]

Coal/straw co-firing trials have been carried out in boilers which are normally coal-fired at the Studstrup powder-fired boilers with a total electricity capacity of 380 MW. The trials showed that deposit formation on the superheater section increased in ratio with the amount of straw in the fuel. The potassium chloride level in the boiler increased resulting in deposit formation. This also had an effect on the susceptibility to corrosion in the boiler. See Section 10.3.2. [2]

A bed agglomeration trial using straw in a small-scale 5 kW BFB boiler showed that the ash particles were large (>5 mm.) like aggregate and porous. The ash particles contain fuel ash, unburnt material and bed material which adhered strongly to the surface. The fuel ash particles were rich in silicon and potassium. Potassium silicates of low melting point were formed during the burn out which were sticky in character and adhered, partly to other fuel particles and partly with colliding bed grains. [24]

10.2.3.2 Grain

In terms of grain, oats have an ash melting temperature similar to wood fuels, approximately 1,150-1,380°C. Other grain types begin to melt earlier, at about 700-800°C. Trials with oats have shown that only a little lightly sintered ash was formed similar in character to that formed when firing with wood pellets. Other types of grain formed hard slag which must be chipped off. [16] Barley however appears to be somewhat better from a sinter formation point of view than autumn wheat and wheat-rye hybrid. [18] The reason for the relatively high ash melting point for oats is probably due to the higher silicon content and higher Si/K ratio. Wheat and rye have the lowest silicon content. [16] The low melting points mean that special technique is necessary to achieve efficient combustion and at the same time prevent the ash from melting. [18]

The addition of limestone to wheat and rye helps to reduce sintering problems. The theoretical explanation for this is that the limestone probably forms calcium phosphates which have a higher initial melting point (approximately 900°C) than potassium phosphates (approximately 700°C). Another effect of limestone addition is that sulphur emissions are partly or totally eliminated. In other words, the sulphur is bound in the ash when limestone is added. In Denmark, where it is commoner to fire with wheat-rye hybrid (*triticale*) which has a lower ash melting point (approximately 700°C), 1-5 % limestone is mixed into the fuel to raise the melting point. Sintering related problems are avoided or significantly reduced if oats are fired as the sole fuel. [16]

Firing trials in a CFB boiler using grain have shown that grain can be used as a CFB fuel if limestone is added simultaneously. During a six-day trial in a 16 MW CFB boiler at Avesta Energiverk, no operational problems were encountered. No sinter lumps were

seen in the bed ash. The cyclone and convector sections were also free from slag overlay. The reactor temperature was 830-860°C and in the cyclone legs 890-910 °C. However, compared with firing with wood chips on their own, there were higher emission levels of nitrogen oxides. [22] Oats differ from other grain fuels in that no limestone addition is necessary. [16]

Grain stalks also have a low ash melting point. This fuel has been used in the in the Jordbro 80 MW powder boiler in which pulverised pellets are fired. The fuel became to a fine powder and gave efficient combustion. In terms of deposit formation, many sintered ash lumps were formed. [38]

In a series of trials at Västhamnsverket with different types of grain (wheat, wheat-rye hybrid and barley) in a 30 MW FB boiler, wheat already produced sintering at a temperature of approximately 550°C. Barley performed reasonably well. The deposit formation results were however rather similar due to the low ash melting point. Both limestone and dolomite were used as additives with dolomite having a beneficial effect. Different bed materials, with varying sand grain size, were also trialled. [39]

10.2.3.3 Willow

Firing with 100 % willow has worked well in some FB plants and without problems while others reported sintering even with a low proportion of willow in the fuel. [43] In a trial in Chalmers' 12 MW CFB boiler it appeared that the potassium level increased somewhat in the quartz bed. At the operational temperatures involved, the potassium reacted with the quartz and silicates were formed. Potassium silicates can cause melting and hence bed agglomeration. This is a problem if the bed material is not changed sufficiently often. [14] [31]

Willow is co-fired at 10% addition together with stem wood chips and leaf chips in the Flintrännan 40 MW fixed grate boiler in Malmö. The deposits which form look like fungal growth and are not hard or glassy. They form on the superheater tubes. If these deposits are not soot-blown, it can be a problem to clean the flue gas channels. If the amount of added willow amounts to as much as 30%, excessive deposit formation occurs in the boiler. [43]

In Eskilstuna, 10 % willow is fired in a 57 MW CFB and a 110 MW FB boiler. The willow is co-fired with wood fuel (tops, roots and branches, bark, sawdust) in chip form. Combustion trials with up to 15 % willow gave problems with deposit formation in the boilers. The deposits are however rather easily removed by soot blowing. [40]

The Grenaa 78 MW CFB boiler is fired with coal and straw. The bed material (sand and fly ash from a nearby grate boiler which is coal-fired) is generally changed every day. The plant has not had any major problems with bed agglomeration. This is probably because the bed material is changed very frequently and the temperature in the boiler is very carefully controlled. When agglomeration problems have occurred, it has generally been due to incorrect operation of the plant. [37]

Co-firing with willow and peat in a small-scale 5 kW FB test boiler has shown that the potassium level decreases while the calcium level increases simultaneously as the proportion of peat increases. At the same time, the sulphur level rises. This results in a rise in the melting point and a reduction in the tendency to agglomerate. Based on the trials in a pellet burning grate boiler, it was on the other hand observed that the addition of peat to a willow fuel with a relatively low silicon level increased the tendency for slag to be formed. Earlier research has shown that the addition of reactive silicon to fuels with a low silicon content level increases the risk of slag formation. Good results for bed agglomeration and deposit formation and corrosion in the boilers' convection sections were already seen at relatively low levels (15-20% by weight) of peat addition. [30]

A study has been carried out on the risk of agglomeration looking at factors such as bed grain size and fluidising speed. A laboratory bench scale agglomeration test showed that increased fluidising speed causes the bed to agglomerate at a higher temperature. It was significant however that this took place at relatively low fluidising speeds. This means that the fluidising speed in a commercial CFB boiler is so high that gas speed has little influence on the risk of agglomeration. Even in BFB boilers the fluidising speed is often sufficiently high for there to be no significant effect on the risk of agglomeration. [31]

10.2.3.4 Reed canary grass (RCG)

RCG which is harvested during the spring has a higher ash melting point in comparison with crop which has been harvested during the autumn. The reason for this is that alkali metals are leached out during the winter and at the same time sulphur and chlorine levels decrease. By delaying harvesting until the spring, the ash melting point increases from 1,070°C to 1,400°C. Section 6.10 has a fuller description of the fuel properties of RCG which has been harvested in spring.

During a series of trials as part of the TPS industry research programme, RCG in the form of briquettes was co-fired in the Eskilstuna 4 MW grate boiler for a number of weeks with good results. The amount of RCG in the fuel amounted to a maximum of 25 %. [40]

When RCG was compared with straw and hemp in a bed agglomeration trials in a small-scale 5 kW BFB boiler, it was shown that RCG has the highest ash level. This is assumed to have significance in terms of the defluidising process when the discrete particles had an element composition with a lower K/Si to Ca ratio which produces a lower melt fraction at the prevailing temperature and thereby probably less stickiness than in the case for straw and hemp. [24]

Co-firing with coal has been trialled. When RCG was added, the melting point of the ash increased compared with that of RCG alone. On the other hand an ash skeleton was formed which was not easily removed and made ash removal difficult. [2]

10.2.3.5 Hemp

According to fuel analyses, hemp has an ash melting point at a level which means that there should be little problem with deposit formation in the boiler. [4]

During controlled bed agglomeration trials with straw, RCG and hemp in a 5 kW BFB reactor, their tendencies to agglomerate with one another was compared as well as the bed material. The bed material varied between natural sand (quartz, plagioclase feldspar and potash feldspar) and alternative bed materials such as olivine. Straw had the highest agglomeration temperature of the three followed by RCG and hemp.

Compared with forest fuels which have been previously analysed in the same boiler, RCG and hemp agglomerated somewhat more than normal forest fuels while straw had a strong tendency to agglomerate. No significant differences were seen among the bed materials in the bed agglomeration trials. [24]

Chopped hemp was fired in a series of trials in the Sätenergi 4 MW grate boiler with satisfactory results. [42]

10.3 Corrosion

10.3.1 What causes corrosion?

Corrosion is mostly caused by potassium and chlorine. At the same time, the material and the combustion environment have a significant role in terms of the tendency for corrosion to take place. The temperature of the flue gas and heat exchanger surfaces and the composition of the flue gases and fly ash contribute to deposit formation. Deposit formation contributes to an increased rate of corrosion through facilitating the transfer of reactants to corrosion processes on the metal surface. They also contain molten salts which are sticky and increase the speed at which these deposits develop. Molten salts also induce a breaking up of the existing oxide layers thereby further contribute to corrosion. [2]

High temperature corrosion occurs primarily on the superheaters which produce steam at a minimum temperature of 400°C. The hot surfaces cause some alkali compounds to melt. Potassium chloride has a decisive role in determining the amount of melt in deposits that are formed. There is a major risk for high temperature corrosion when combustion rises to the superheater region. Uneven flue gas temperature profile, staged combustion and short dwell times are all factors that facilitate corrosion. [16] Dry fuels and fuels with a high volatile content, for example energy crops, bring the risk of uneven flue gas temperature profile, lower oxygen content and hence a different flue gas composition. To counteract this, the air feed can be modified and more fuel in-feed points used. [2]

The corrosion level rises as the temperature on the superheater metal increases. The corrosion level is low around 460°C but increases as the temperature rises. See Figure 17. [2] The temperature at which the corrosion level begins to rise also depends on the fuel and boiler design.

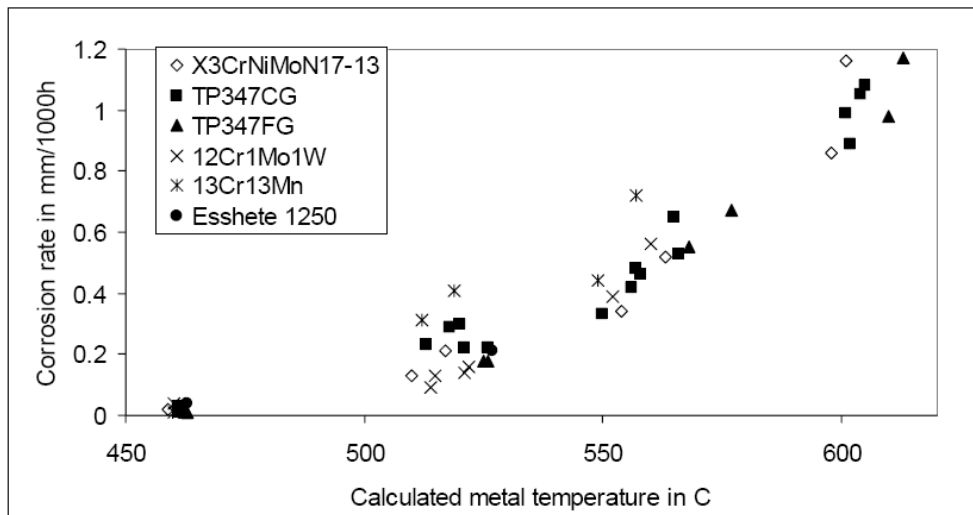


Figure 17. Level of corrosion in comparison with the average temperature for 12 – 18 % Cr steel during an investigation at the Masnedø straw-fired boiler. It should be noted that the temperature of the metal probably is higher than the superheater temperature.

Low temperature corrosion is generally a problem for boilers burning biofuels with a high moisture content and low combustion temperature, particularly if the sulphur content is consistently high. This corrosion can occur in different sections of the plant from the convection section to the chimney. [16]

A third type of corrosion is combustion chamber corrosion. This is also called carbon monoxide corrosion and occurs when high levels of carbon monoxide are caused by insufficient air supply. By designing burners and the air feed in a way that avoids reduced conditions along the walls, the risk of corrosion is decreased. High chlorine levels contribute to combustion chamber corrosion. Staged combustion in particular means an increased risk of combustion chamber corrosion. [16]

10.3.1.1 Additives

In the same way that deposit formation can be prevented or reduced by the use of additives, so can the risk of corrosion. Corrosion can be reduced by preventing the formation of alkali chlorides depositing on heat exchanger surfaces.

Trials have shown that the chloride level in deposited material is substantially lower if sulphur has been introduced. It has been demonstrated that the sulphur/chlorine ratio is the prime determinant of high temperature corrosion. In order to reduce the risk of corrosion, alkali chlorides should be converted to alkali sulphates before the flue gas reach the superheater tubes. Alkali sulphates are more stable and less corrosive at normal superheater temperatures under 600°C. When the total amount of available sulphur rises in the flue gases, there is a corresponding reduction in corrosion caused by alkali chlorides. It was recommended in the studies that the molar ratio of sulphur/chlorine (S/Cl) in the fuel should be at least 4 in order to reduce the chlorine levels in the deposited material to a negligible level and thus eliminate corrosion from this source. See Figure 18. [2]

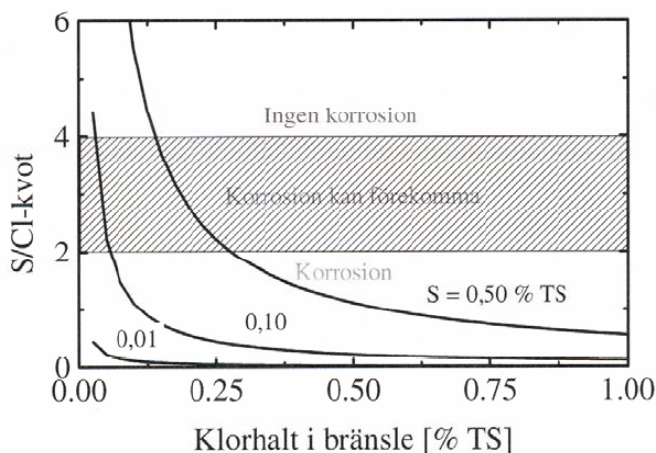


Figure 18. Risk of corrosion at different S/Cl ratios

China clay can also be used to absorb alkali metals and thus reduce corrosion. This additive is relatively expensive and is not currently used in commercial boilers. China clay and other similar minerals are however to be found in some peat qualities. Co-firing with peat can therefore contribute to a reduction in corrosion through both the peat's mineral content and its relatively high sulphur content. [2]

Co-firing with coal has also been shown to give positive results. When wood fuel and coal were co-fired in Chalmers' 12 MW CFB boilers, the reactivity of potassium to chlorine was demonstrated to be lower than when firing with biofuel alone. The use of a mixture with coal substantially reduced the amount of potassium chloride in the fly ash and on the deposit probe. Co-firing with sewage sludge has also been trialled in the same boiler. The trials showed that mixing of sewage sludge with biomass fuel gave a radical reduction in deposits containing potassium chloride on the heat exchanger tubes, even when relatively small amounts of sludge were added. [2]

10.3.1.2 Combustion technology modifications

Combustion technology modifications can be made in order to avoid corrosion. For example, achieving a more effective final combustion and avoiding an uneven distribution of fuel are very important process modifications needed to reduce high temperature corrosion. Improvements in primary and secondary air supply control and fuel in-feed increase combustion efficiency. Effective fuel mixing is vital for multi-fuel operation so that the fuel mixture has uniform quality and moisture content. These measures will avoid excessively high temperatures and/or low acid level which gives rise to CO peaks. In order to achieve even fuel in-feed, it is advantageous if there are several parallel lines. Injecting air using "air curtains" is a process modification aimed at protecting the combustion chamber walls against corrosion. This prevents the formation of zones of low oxygen content near the boiler walls. [2]

Other ways of improving combustion efficiency are increasing the fuel's dwell time in the boiler and so preventing combustion shifting backwards which contributes to corrosion and deposit formation. [44]

10.3.2 Operational experience

Because of the relatively short trial campaigns that have been carried out with energy crops, it can be difficult to determine a fuel's propensity to corrosion. In addition, it is difficult with co-firing to determine the direct influence which the energy crop had on any corrosion that may have occurred.

10.3.2.1 Straw

The weather at the time of harvesting plays a part in straw's propensity to corrosion. During a year in which there has been little rain in the weeks preceding harvesting, chlorine and potassium levels will be particularly high. This gives problem in terms of corrosion. [33]

KCl and K_2SO_4 condense on sensitive components in the plant, for example the superheaters, when straw is fired. Experience from Danish plants indicates that the degree of corrosion is low at 460°C when protective chrome-rich iron oxide is formed. When the temperature reaches 525°C the degree of corrosion against temperature curve is more linear. See also Figure 17. A high flue gas temperature gives higher heat transfer. This also affects the thickness of deposits and their morphology and chemical composition. These factors affect the risk of molten deposits will be formed which can lead to more rapid corrosion. [2]

The higher the steam temperatures that a plant operates at, the higher the corrosion level. To keep corrosion at an acceptable level, the steam temperatures must be under 490-500°C when firing 100% straw. At the same time it is advantageous if the combustion chamber walls are cooled so that the wall temperature does not exceed 510-520°C. [29] [33]

Co-firing coal with different amounts of straw at the Studstrup powder-fired plant (at 10% and 20% addition levels) for 300 hours, changed the composition of the ash's main components. See Figure 19. [2]

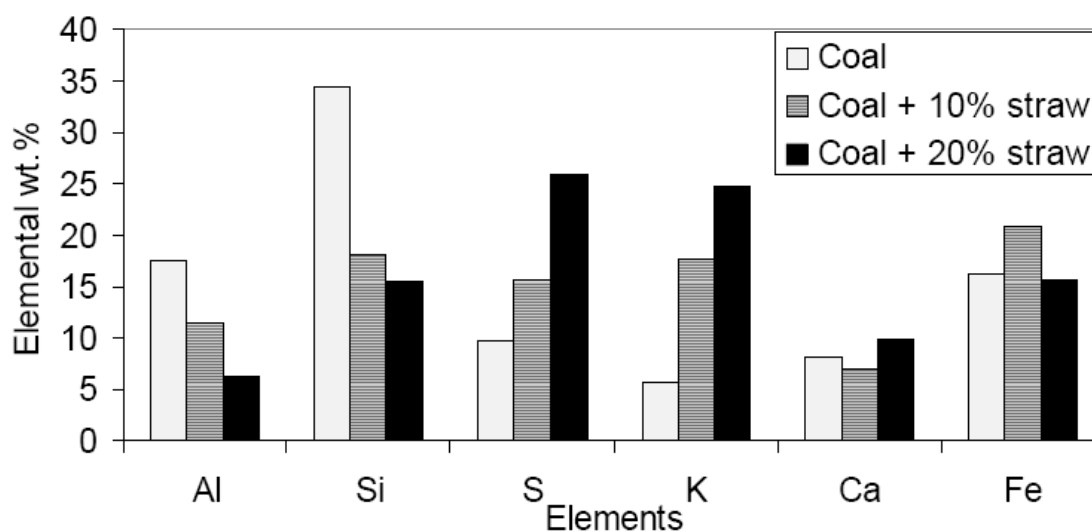


Figure 19. Average composition of the main substances in ash. The ash formed layers on corrosion probes during an investigation with SEM-EDS analysis

The main components detected in the ash were aluminium, silicon, sulphur, potassium, calcium and iron. While aluminium and silicon decrease when the amount of straw in the fuel increases, sulphur and potassium levels increase. No chlorine was detected in the deposits. The study shows that at 10 % or 20 % addition of straw, the corrosion level reduces compared with a boiler using straw as the sole fuel and are close to the levels in a coal-fired power plant. [2]

Changing the boiler walls one metre up from the bed to acid-resistant steel has significantly reduced the risk of combustion chamber corrosion at the 4 MW Sätenergi grate boiler which is fired 100 % straw. The chimney has also been lined with the same steel to prevent low temperature corrosion. [42]

10.3.2.2 Grain

With grain, low temperature corrosion was primarily observed, particularly in the form of point corrosion. That indicates that chlorine is an important factor. Sulphur can also be involved as a source of corrosion. Grain cuttings contain more sulphur and chlorine than, for example, wood pellets. The sulphur is released mostly as sulphur dioxide, SO_2 which partly converts to SO_3 in the convection zone. This can in turn at lower temperatures convert to sulphuric acid. The chlorine in the fuel converts to hydrochloric acid, HCl , which is found in subsequent point corrosion. [16]

Corrosion takes place very rapidly and can be very extensive. Certainly plants are quickly affected by corrosion on the inlet tubes, ash bins or chimney end sections while others can be operational for a number of years without any problem at all. [16]

10.3.2.3 Willow

When newly-harvested willow of high moisture content is fired in a grate boiler, ignition of the fuel can be delayed. This means that degasification is displaced further down on a grate and gas combustion shifts to the combustion chamber. [4] Typical willow fuel contains a relatively high level of potassium and phosphorus compared with

wood. [2] Sulphur and chlorine have also been found in deposits on tube surfaces. Sulphur and chlorine can in conjunction with potassium form a discernible fused mass at 550-600°C indicating a risk of corrosion in heater exchanger tubes and other surfaces on the flue gas side of a CFB plant. [14] [31]

10.3.2.4 RCG

There are no documented results on corrosion related to the combustion of RCG.

10.3.2.5 Hemp

There are no documented results on corrosion related to the combustion of hemp.

10.4 Ash quality dependent on combustion method and fuel

Energy crops generally have higher ash content than wood fuel. This is detrimental to the process and plant efficiency. The fuel's calorific value is lower, efficient ash removal equipment is necessary and there are higher costs resulting from handling large amounts of ash.

Combustion results partly in bottom ash (ash which falls to the bottom of the boiler) and partly fly ash, which separates out from the flue gases. On combustion, the lighter particles are transported by the flue gases while the heavier particles fall and are collected in the bottom ash. Fly ash also comprises to some extent of components found in the gas phase and which subsequently condense when the temperature falls. [34] The higher volatile content of energy crops compared with coal means that less coke is formed on combustion in comparison with coal. [1] [7]

The distribution of chemical substances between the bottom ash and fly ash depends on factors such as boiler type, combustion temperature, local atmosphere (oxidising or reducing conditions), dwell time in the boiler and additive addition. [2]

The amount of dust in the flue gases is particularly high on combustion in CFB boilers. Even if the main parts of the bed material is separated in the cyclone nevertheless many particles which are less than approximately 10 µm are transported by the flue gases. [2] Combustion of biofuels in a fluidised bed gives ash which is predominantly bed sand.

A bed agglomeration trial in a small-scale 5 kW BFB boiler demonstrated that there are differences between ash particles from straw, RCG and hemp. Ash particles produced during straw trials were like aggregate, large (> 5 mm) and porous. The particles contained fuel ash, unburnt material and bed material firmly adhering to the surface. The fuels particles were rich in silicon and potassium and on burn out, low melting point and sticky potassium sulphates were formed which partly stuck to other fuel particles or partly to colliding bed sand. On the other hand, RCG and hemp ash particles comprised a fine fraction of thin splinters. These ashes were found in the bed.[25]

A more detailed description of the ash's composition from different energy crops see Chapter 13.

10.5 Current research

A number of Värmeforsk projects are related to the combustion of energy crops. The “Process Control” programme, for example, evaluates the current use of in-boiler flame cameras in grate boilers. In trials carried out in a biomass-fired plant, the flame front was detected using a camera and adjusted by means of increasing/decreasing the frequency of the fuel in-feed system. The overall purpose of the project is partly to quantify to what extent flame front management and a stable flame front influence different process parameters and partly to show what possibilities there are of using fuel of more varied quality, with an overriding need to maintain or improve emission levels and ash qualities.

A Värmeforsk project in the “Moisture Content” programme studies the use of IR sensors to measure flame characteristics. The purpose is to find a low cost technique which can replace more expensive systems for bulk flow measurement. The IR sensor will provide the same information as bulk flow measurement systems enabling it to be integrated in the regulation of the combustion process.

In Värmeforsk’s Base Programme “Plant and Combustion Technology”, research is undertaken to minimise alkali-related problems. Stage 1 is found under the reference Davidsson K, Eskilsson D, Gyllenhammar M, Herstad Svärd S, Kassman H, Steenari B-M, Åmand L-E; “Åtgärder för samtidig minimering av alkalirelaterade driftproblem; Ramprogram”, Värmeforskrapport 997 December 2006 and Stage 2 is currently ongoing. Stage 2 studies methods for minimising alkali-related problems. Digested sludge, ammonium sulphate, china clay, zeolites, peat, de-inking sludge and coal ash are added to the process with subsequent analysis. Fuels used include straw and PVC is added to the fuel to raise the chlorine level further,

Within TPS industry research work, current research includes trials on firing RCG briquettes in a 4 MW grate boiler in Eskilstuna. The purpose of the trials is to develop a method enabling new fuels to be combusted in a grate boiler. Parameters being measured are emissions, deposit overlay, boiler data and ash composition. A report is expected in the autumn.

The possibility is being currently being investigated of using Vattenfall’s patented “ChlorOut” concept in a powder-fired boiler when using straw as fuel. “ChlorOut” involves injecting an ammonium sulphate solution into the boiler and the alkali chlorides are converted to alkali sulphate. The purpose is to minimise the amount of alkali chloride in the flue gases causing the boiler to be stopped every other week for cleaning to remove heavy deposit formation. Using IACM (In-situ Alkali Chloride Monitor) it has been possible to show that the KCl level reduces after dosing. The results are now being evaluated. [45]

Mälardalen University is carrying out a project where combustion of rape seed oil from Ecoil is investigated in the Kungsör 5 MW boiler and a small-scale boiler (30-70 kW) in Västerås. Normally LPG and diesel oil are fired in the boilers. The emissions and heat energy output when firing with rape seed oil will be evaluated compared with combustion of fossil fuels.

Production of the motor fuel RME (rape methyl ester) is expected to grow. A major industrial facility for the production of RME is currently underway in Norrköping by Swedish Bioenergy AB, a subsidiary of Scanoil. The plant is planned to start during 2007 and is expected to produce 325,000 tonnes biodiesel and 450,000 tonnes pelleted rape cake per annum. A project is being financed by Värmeforsk, "Combustion characteristics of rape cake and recommendations for optimal use in various boiler operations" in order to determine the combustion characteristics of rape cake. This is now underway and the project report is expected in October 2007. The project work covers fuel characterisation and firing trials on bench and pilot plant scale, together with recommendations for optimal mixes of rape cake and traditional biofuels. A number of thermal power stations in the regions have expressed interest in future full scale combustion trials.

10.6 References

- [1] Kavalov B & Peteves S D; "Bioheat applications in the European Union: an analysis and perspective for 2010", European Commission DG JRC Institute for Energy Petten 2004
- [2] Henderson P, Ifwer K, Stålenheim A, Montgomery M, Högborg J & Hjörnhede A; "Kunskapsläget beträffande högttemperaturkorrosion i ångpannor för biobränsle och avfall", Värmeforskrapport 992 May 1997
- [3] Stridsberg S & Segerud K; "Pulvereldning kol/rörflen/mald bränslekärna", Värmeforskrapport 566 March 1996
- [4] Strömberg B; "Bränslehandboken" Värmeforskrapport 911 March 2005
- [5] Maniatis K; "R&D Needs for Bioenergy" IEA Bioenergy REWP seminar 3 March 2005
- [6] Sørensen L H; "Straw-fired Combined Heat and Power Plant", Gülzower Fachgespräche Band 17 Energetische Nutzung von Stroh, Ganzpflanzengetreide und weiterer halmgutartiger Biomasse Tautenhain May 2001, 103-113
- [7] Hartmann H; "Die energetische Nutzung von Stroh und strohähnlichen Brennstoffen in Kleinanlagen", Gülzower Fachgespräche Band 17 Energetische Nutzung von Stroh, Ganzpflanzengetreide und weiterer halmgutartiger Biomasse Tautenhain May 2001, 62-84
- [8] Nilsson D & Hansson P-A; "Influence of various machinery combinations, fuel properties and storage capacities on costs for co-handling of straw and reed to district heating plants", Biomass and Bioenergy 20 2001, 247-260
- [9] Geber U, Tuvevsson M; "Vallväxters egenskaper som producenter av energi- och fiberråvara och som biologiska renare av näringsrika vatten", SLU Serie Växtodling 1993
- [10] Burvall J; "Provförbränning av energigräset rörflen vid två kommersiella halmeldade anläggningar i Danmark", Värmeforskrapport 440 July 1992
- [11] Rudling L; "Spannmålsförbränning på wanderrost", Värmeforskrapport 414 December 1991

-
- [12] Hjalmarsson A-K, Ingman R; "Erfarenheter från förbränning av salix", Värmeforskrapport 631 March 1998
 - [13] "Energie aus Biomasse", Fachagentur Nachwachsende Rohstoffe E.V. Gülzow April 2002
 - [14] Sifris G, Gärdenäs S, Skrifvars B-J & Backman R; "Förbränning av salix i CFB", SLF rapport nr 23, 1995
 - [15] Paulrud S; "Upgraded Biofuels – Effects of Quality on Processing, Handling Characteristics, Combustion and Ash melting", Doctoral thesis Swedish University of Agricultural Sciences Umeå 2004
 - [16] Rönnbäck M & Arkelöv O; "Tekniska och miljömässiga problem vid eldning av spannmål – en förstudie", SLF January 2006
 - [17] Hadders G; "Förändringar under skördeperioden av bränsleegenskaper hos halm", JTI-rapport Jordbrukstekniska institutet Nr 186 1994
 - [18] Hadders G, Arshadi M, Nilsson C & Burvall J; "Bränsleegenskaper hos spannmålskärna, betydelsen av jordart, sädesslag och sort", JTI-rapport Lantbruk & Industri Nr 289 2001
 - [19] Bridgeman T G et al; "Influence of particle size on the analytical and chemical properties of two energy crops", Fuel 86 2007, 60-72
 - [20] Davidsson K, Eskilsson D, Gyllenhammar M, Herstad Svärd S, Kassman H, Steenari B-M, Åmand L-E; "Åtgärder för samtidig minimering av alkalirelaterade driftproblem; Ramprogram", Värmeforskrapport 997 December 2006
 - [21] Zevenhoven-Ondwater M et al; "The ash chemistry in fluidised bed gasification of biomass fuels. Part I: predicting the chemistry of melting ashes and ash-bed material interaction", Fuel 80 2001, 1489-1502
 - [22] Paulrud S, Nilsson C, Öhman M; "Reed canary-grass ash composition and its melting behaviour during combustion", Fuel 80 2001, 1391-1398
 - [23] Rudling L; "Spannmålsförbränning I en cirkulerande fluidiserad bädd", Värmeforskrapport 415 December 1991
 - [24] Burvall J; "Influence of harvest time and soil type on fuel quality in reed reed canary grass", Biomass and Bioenergy Vol 12 No 3 1997, 149-154
 - [25] Erhardsson T, Öhman M, de Geyter S, Öhrström A; "Bäddagglomereringsrisk vid förbränning av odlade bränslen (hampa, rörflen, halm) i kommersiella bäddmaterial", Värmeforskrapport 998 December 2006
 - [26] Hadders G & Nilsson D; "Storskalig hantering av stråbränslen från jordbruket", JTI-rapport Jordbrukstekniska institutet Nr 160 1993
 - [27] Vetter A; "Qualitätsanforderungen an halmutartige Bioenergieträger hinsichtlich der energetischen Verwertung", Gülzower Fachgespräche Band 17 Energetische Nutzung von Stroh, Ganzpflanzengetreide und weiterer halmgutartiger Biomasse Tautenhain May 2001, 36-49
 - [28] Hering T; "Stroh- und Ganzpflanzenverbrennung am Beispiel der Strohheizwerke Schkölen und Jena", Gülzower Fachgespräche Band 17 Energetische Nutzung von Stroh, Ganzpflanzengetreide und weiterer halmgutartiger Biomasse Tautenhain May 2001, 114-126

- [29] Williams R; "Project 1.1 – Technology Assessment for Biomass Power Generation – UC Davis", TASK 1.1.1 Draft Final Report October 2004 http://biomass.ucdavis.edu/pages/reports/UCD_SMUD_DRAFT_FINAL.pdf
- [30] Öhman M, Boman C, Erhardsson T, Gilbe R, Pommer L, Boström D, Nordin A, Samuelsson R, Burvall J; "Minskade askrelaterade driftsproblem (beläggning, slaggning, högttemperaturkorrosion, bäddagglomerering) genom inblandning av torv i biobränslen", Värmeforskrapport 999 January 2006 http://rapporter.varmeforsk.se/publish/show_report.phtml?id=4622
- [31] Nilsson K; "Sammanställning av bränsledata för Salix och skogsbränslen", Vattenfall Utveckling AB, U-V 96:Ö1 June 1996
- [32] Eriksson M, Wikman K, Berg M, Öhman M; "Effekten av fluidiseringshastighet och kornstorlek på agglomereringsrisk vid biobränsleeldning i FB-pannor", Värmeforskrapport 890 November 2004
- [33] Clausen J C & Sørensen M; "Plant and Operating Experience in Straw-Fired Boilers in CHP Plants", VGB Krafwerkstechnik 77 1997, s 724-728
- [34] Mahmoudkhani M & Theliander H; "Långsamupplösande askpellets", Värmeforskrapport 880 October 2004
- [35] Hadders G & Flodén S; "Spridning av aska från stråbränslen på åkermark, Förutsättningar och rekommendationer", JTI-rapport Lantbruk & Industri Nr 234 1997
- [36] Höglund C, Lundborg R, Myringer Å; "Tillförsel av skogsindustriellt slam till eldstäder - etapp 1", Värmeforskrapport 757 December 2001
- [37] van der Drift A & Olsen A; "Conversion of Biomass, Prediction and Solution Methods for Ash Agglomeration and Related Problems", ECN report ECN-C-99-090 November 1999

10.6.1 Personal communications

- [38] Baldefors, Jan, Vattenfall
- [39] Jönsson, Bengt, Öresundskraft
- [40] Björklund, Ulf, Eskilstuna Energi & Miljö
- [41] Leire, Rolf, SEFAB
- [42] Green, Sven-Göran, Lantmännen Agrovärme AB
- [43] Resmark, Martin, E.ON
- [44] Berglund Tommy, Öresundskraft
- [45] Kassman, Håkan, Vattenfall Power Consultant

11 Production of electricity with energy crops

One method of producing electricity is heat up steam and run it through a turbine. The steam must have a high temperature. There are also other possibilities of producing electricity, e.g. combined heat and power and gasification. The different methods for electricity production are presented in this chapter.

11.1 Electricity production from steam turbine

In the case of electricity, the steam is superheated and, in simple terms, it could be said that the higher the superheating temperature the more electricity is produced. The superheaters may, for example, hang vertically in coils from the ceiling or be placed as vertical pipes in superheater passages after the boiler. After the steam has passed through the superheater passages it reaches the economizer and air preheater. Here the feed water, condenser water and combustion air is heated up. See Figure 20 for a description of the process. The electrical efficiency level for a straw-fired plant is most frequently of the magnitude of 20-30 %. [2]

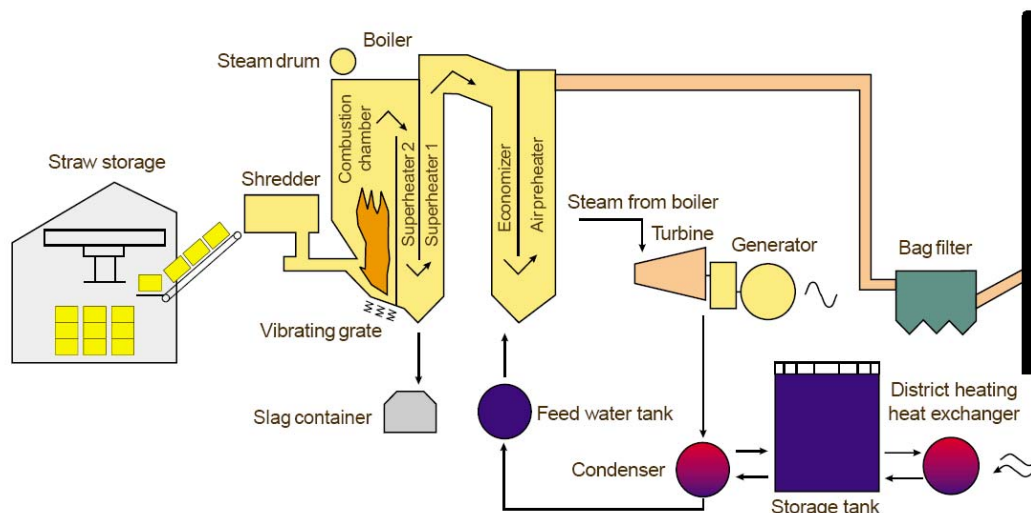


Figure 20. Schematic view of electricity production at a straw-fired power plant [2]

Owing to the relatively low ash melting point of the energy crops it is more difficult than for other biofuels to retain a high superheating temperature. Thereby, there is a risk that the electrical efficiency declines. In simultaneous production of electricity and heating the ratio between electricity produced and heat produced declines. Most experience in relation to the production of combined heat and power from energy crops has been concentrated around the burning of straw which is largely associated with the demand of Danish energy policy that the plants must use a high proportion of straw in electricity production. See for example [1].

11.2 High steam temperatures

When energy crops such as straw is used for electricity production there often arise problems with slag and corrosion. Owing to the high content of alkali metals and

chlorine in straw ash the flue gas is corrosive, particularly in the case of temperatures above 450°C. Since the ash particles have a low temperature they may also easily cause slag problems in the boiler. [2] Different methods to achieve high steam temperatures and at the same time to avoid corrosion or deposits are presented below.

11.2.1 Design

In order to avoid problems with corrosion and coatings some of the Danish plants have attempted to limit the superheater temperature to 450°C. This has been combined with placing the superheater section further back in the boiler system so that the flue gas temperature is around 650-700°C when it comes in contact with the first superheater section. This however leads to lower electrical efficiency. Another method has been to maintain the steam temperature at 550°C but to make it possible to easily replace any superheater tubes that have suffered corrosion. [2] [4]

Other plants have chosen to invest in the selection of resistant materials or greater space between the superheaters which means that deposits are managed better. [2]

11.2.2 Separate combustion

Another way of using energy crops such as straw in energy production is to have the energy crop burned separately. High-temperature corrosion is avoided since the temperature of the steam in the biomass boiler is kept under the critical level. [2]

Unit 2 at the combined heat and power plant Avedøre uses a series of different fuels that are burned in different boilers. Straw is one of these and is burned in a separate boiler at 100 MW steam capacity. The steam produced in the boilers is brought together and drives a highly efficient steam turbine. [5]

If the combustion of biofuels and e.g. coal takes place in parallel instead of through co-firing in the same boiler the possible fuel spectrum is increased. Another advantage is that a plant using its coal ash for cement or other processing will still have an ash clean from biofuel.

11.3 Energy combines

Energy combines is a technology that brings together production of transport fuels and energy production (e.g. electricity or district heating). The starting material is biofuel which is converted to liquid biofuel that is normally intended for transport purposes e.g. ethanol, methanol, synthetic diesel or DME (dimethyl ether). The production of the liquid biofuel is integrated in the power plant which utilises the surplus energy that arises in the production process. Energy crops are an interesting starting substance in which grains and straw is discussed together with crops such as sugar cane, maize and wood fuels. [5] [7] [15]

11.4 Other methods

Owing to the tendency of energy crops to form slag and give rise to corrosion it is interesting to use its energy content in other ways. Gasification and ORC (Organic Rankine Cycle) offers different methods for use of energy crops. The methods have in

common the principle that the fuel is not directly burned in the boiler. Thereby the problem with sintering and corrosion is reduced.

The following methods are not used to a large extent on an industrial scale. They are however interesting in a future perspective in respect of exploiting energy crops.

11.4.1 Gasification

Gasification may either be used as a co-firing technology that makes use of existing combustion and electricity generation equipment at the plant or in more advanced cycles, e.g. IGCC (Integrated Gasification Combined Cycle). The introduction of a new biofuel therefore does not bring with it high production conversion costs. If, on the other hand, one chooses more advanced cycles the investment costs increase but on the other hand the conversion efficiency to electricity for the biofuel increases, e.g. it is possible to achieve approx. 40-50 % electrical efficiency with IGCC. [1] [8]

In the case of gasification of solid biomass at high temperatures gaseous energy carriers are formed (fuel gas, synthetic gas). The biomass is separated into solid and gaseous compounds and the coal that remains is fired partly during formation of high CO contents. [1]

The fuel gas that is produced may, directly or after various levels of cleaning, be used in burners for producing heat. In this way, after a degree of gas purification, a biofuel is burned in an existing boiler without all substances found in the fuel coming into the boiler. Another method is to use the fuel gas in gas turbines to generate power. The latter is an attractive way to use biomass since it yields a higher efficiency in comparison with direct biomass firing. [1] [9] In this case it involves IGCC technology. The process gas that is produced, however, contains a whole series of undesired pollutants, e.g. alkali and tar, which must be kept at relatively low levels. Tar must be kept at such a low level that it does not condense out when the gas is cooled and alkali at a level that is not damaging for the turbine. The gas must therefore undergo purification before it may be used in an effective way. One of the problems in gasification has until now been to find an effective method of removing the tar that is formed. [1] [10]

Gasification of pelletised straw and willow has been carried out in Värnamo's IGCC facility with good results. The high alkali content in willow did not cause any problems at the plant and the volume of sintered material in the bottom ash was very small. Trials with up to 100 % straw have been undertaken without any problems with sintering. The gas produced had a somewhat higher water content than in the case of normal production, which is first-rate for gas turbine operation. Figure 21 shows the process diagram for Värnamo's IGCC [11]

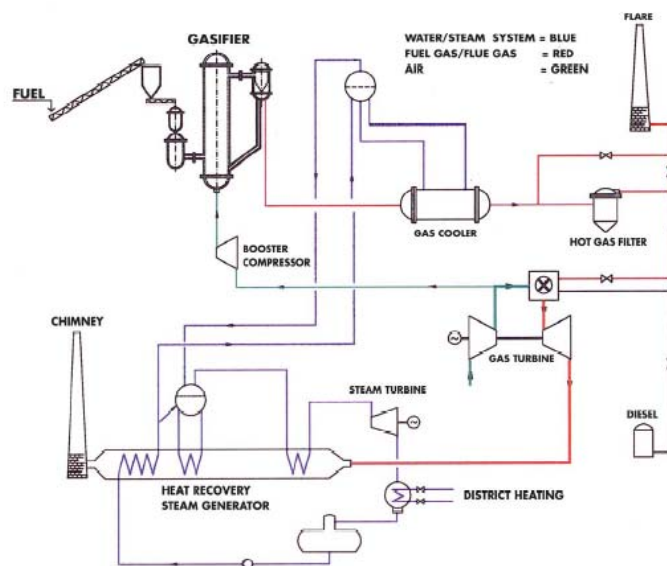


Figure 21. Process diagram of the Värnamo IGCC facility

11.4.2 ORC

Organic Rankine Cycle (ORC) is a kind of power and heat coupling. Compared with the steam turbine process an organic work fluid is used instead of water. These may be hydrocarbons in the form of isopentane, isooctane, toluene or silicon oil. This enables large energy volumes to be transferred at low temperatures and pressures. It is a separate cycle that offers higher accessibility to the system and the lower working temperature yields less pollution of heat exchanger surfaces. [9] [12]

The ORC functions in such a way that the flue gas that is formed on combustion of biomass emits heat to the organic work fluid, more or less as in the case of a normal steam cycle. The temperature for vaporisation and condensation is however lower compared with ordinary boilers where water is the work fluid. [9]

The degree of efficiency of an ORC plant may attain more than 12 %. There are few practical examples of the combustion of biomass with ORC technology. In Europe only a few attempts and demonstrations been carried out and these are limited to combustion of wood. [12] [13]

11.5 Current research

An international project on the use of straw in ethanol production is currently in progress under the title of IBUS (Integrated Biomass Utilisation System). The principal goal is to investigate how the costs may be reduced on production of electricity and ethanol based on biomass. The by-product that arises in ethanol production are fibres that are pressed and dried before undergoing combustion together with coal or natural gas in combustion plants. For more information please refer to www.bioethanol.info [14].

Several other projects relating to production of liquid propellants are also in progress, both in respect of production of ethanol and production of methanol, synthetic diesel or DME via thermal gasification. The latter projects focus, however, primarily on the use of biofuels from forestry although as previous trials at the Värnamo plant demonstrated the use of fuels from arable land may also be an option.

Together with ENA Energi and Sala Heby Energi, the Technical University of Mälardalen is undertaking a project in which ethanol production and gasification take place in existing thermal power plants and in this way also give rise to heating and electricity. The project operates under the designation 'Polygeneration – Bioenergy Combination' with willow and the fuels studied are wood fuels, energy crops and waste fractions.

The Chrisgas project (Clean Hydrogen-rich Synthesis Gas) is currently in progress. Its goal is to demonstrate production of clean hydrogen-rich gas from the biofuel. The gas will then be converted to liquid fuel, e.g. DME, methanol or FT diesel. The project is carried out at Värnamo's IGCC plant and production is expected to be under way during 2008.

The IVL is currently conducting a project that is looking at energy combines in respect of technology trends, systems and means of control. This project is carried out within the framework of Värmeforsk's Tvärteknikprogram [cross-technology programme].

Carl Bro is investigating the ORC for electricity production in thermal power stations within the framework of Värmeforsk's programme for power plant and combustion technology.

11.6 References

- [1] Williams R; "Project 1.1 – Technology Assessment for Biomass Power Generation – UC Davis", TASK 1.1.1 Draft Final Report October 2004 http://biomass.ucdavis.edu/pages/reports/UCD_SMUD_DRAFT_FINAL.pdf
- [2] Nikolaisen L (ed); "Straw for Energy Production – Technology - Environment - Economy", andra upplagan The Centre for Biomass Technology Köpenhamn 1998
- [3] Kavalov B & Peteves S D; "Bioheat applications in the European Union: an analysis and perspective for 2010", European Commission DG JRC Institute for Energy Petten 2004
- [4] Clausen J C & Sørensen M; "Plant and Operating Experience in Straw-Fired Boilers in CHP Plants", VGB Krafwerkstechnik 77 1997, s 724-728
- [5] Ottosen P, Gullev L; "Avedøre unit 2 – the world's largest biomass-fuelled CHP plant", News from DBDH 3/2005
- [6] Värmeforskrapport 904
- [7] Global insight http://www.globalinsight.com/gcpath/BioFuels_WEB_11-2006.pdf
- [8] Sims R, Hastings A, Schlamadinger B, Taylors G & Smith P; "Energy crops: current status and future prospects", Global Change Biology, Nr 12 2006 s. 2054-2076

- [9] "Energie aus Biomasse", Fachagentur Nachwachsende Rohstoffe E.V. Gülzow april 2002
- [10] Maniatis K; "R&D Needs for Bioenergy" IEA Bioenergy REWP seminar 3 mars 2005
- [11] Ståhl K, Waldheim L, Morris M, Johnsson U, Gårdmark L; Biomass IGCC at Värnamo – past and future", GCEP Energy Workshop 27 april 2004
- [12] Wenig B; "Bioenergie – Pflanzen, Rohstoffe, Produkte", Fachagentur Nachwachsende Rohstoffe e.V.Gülzow 2005
- [13] "Biomass fired CHP plant based on an ORC cycle – Project: ORC-STIA-Admont", Thermie-A-project BM/120/98/AT/IT mars 2001
- [14] IBUS, www.bioethanol.info
- [15] "Värnamoverket – En demonstrationsanläggning för el- och värmeproduktion ur biobränsle, baserad på trycksatt förgasning", Demonstrationsprogrammet 1996-2000 Sydskraft 2000

12 Flue gas cleaning and emissions

Fast growing energy crops are characterised by higher nitrogen and ash contents than stemwood. Levels of sulphur, chlorine and the alkali metals sodium and potassium are also generally higher than stemwood, although here there are large variations between different crops and within a crop. Please see tables 11 and 12 for fuel parameters.

Table 11. Chlorine, nitrogen, ash, calorific value and moisture content in a number of fuels [1].

	Chlorine, Cl (weight% ds)	Sulphur, S (weight% ds)	Nitrogen, N (weight% ds)	Ash (weight% ds)	Calorific value (MJ/kg dry ash free)	Moisture content (weight- %)
Wood	0-0.05	0-0.3	0.04	0.4-0.8	16-21	8-60
willow	0.01-0.1	0.005-0.03	0.4	1-5	18-20	25-50
Straw	0.05-1.5	0.05-0.2	0.7	4-10	18-20	10-20
Grain	0.02-2.3	0-0.5	1.7	2-4	17-22	14
Reed canary grass	0.1-0.2	0.05-0.2	1.0	3-7	17-20	10-15
Hemp	0.04 -0.1	0.03-0.07	1.4	2-4	19	15-75

Table 12. Content of potassium and sodium in a number of fuels [1].

	(mg/kg ash)	
	Potassium, K	Sodium, Na
	min - max	min - max
Wood	67 491 - 89 656	2 533 - 7 307
willow	38 104 - 158 558	1 484 - 7 752
Straw	9 132 - 152 747	5 564 - 7 419
Grain	116 596 - 219 989	334 - 78 125
Reed canary grass	57 447 - 189 274	2 077 - 8 902
Hemp	14 500 - 263 222	3 463 - 4 222

12.1 Emissions originating from complete combustion of fuel

Emissions on combustion can be divided into emissions that come from incomplete combustion and emissions from complete combustion. Emissions from incomplete combustion depend on the combustion technology and combustion strategy and are, in principle, not fuel dependent. These include: carbon monoxide (CO), methane (CH₄) and Non-Methane Volatile Organic Compounds (NMVOC), Polycyclic aromatic hydrocarbon (PAH), particles in the form of soot, coke and tar, dioxins (PCDD), polychlorinated dibenzofuran (PCDF), ammonia (NH₃) and ozone (O₃).

In the case of agrifuel combustion it is mainly emissions generated from the content of the fuel on complete combustion that differ from emissions from wood fuels and are therefore addressed in this initial study. The exceptions are dioxins and furans that are also covered here. Attendant uncombusted material can be affected by the size spread of the fuel and is also therefore addressed. Emissions from complete combustion include nitrogen oxides (NO_x), laughing gas or nitrous oxide (N_2O), sulphur dioxide (SO_2), hydrogen chloride or hydrochloric acid (HCl), heavy metals and dust in the form of aerosols that are formed from elements with low melting points, especially salts such as potassium chloride (KCl) and sodium chloride (NaCl). Carbon dioxide (CO_2) and steam (H_2O) also come from complete combustion but are not addressed here. Examples of emission values from different fuels are given in tables 13 and 14.

*Table 13. Emissions that are mainly influenced by fuel properties. Comparison between various fuel types (examples of values). Altholz = urban waste wood and demolition wood
Chipboard = spånskiva [2].*

Emissions at 11% O_2	Fuel type	Typical data
NO_x ($\text{mg}/\text{m}^3_{\text{O}}$)	Native wood (soft wood) Native wood (hard wood) Straw, grass, miscanthus, chipboard Altholz	100 – 200 150 – 250 300 – 800 400 – 600
HCl ($\text{mg}/\text{m}^3_{\text{O}}$)	Native wood Altholz, straw, grass, miscanthus, chipboard (NH_4Cl)	< 5 raw gas: 100 - 1000 with HCl absorption: < 20
Particles ($\text{mg}/\text{m}^3_{\text{O}}$)	Native wood Straw, grass, miscanthus, chipboard Altholz	after cyclone: 50 - 150 after cyclone: 150 - 1000 after bag- or electrostatic filter: < 10
$\Sigma \text{Pb, Zn, Cd, Cu}$ ($\text{mg}/\text{m}^3_{\text{O}}$)	Native wood Altholz	< 1 raw gas: 20 - 100 after bag- or electrostatic filter: < 5
PCDD/F ($\text{ng TE}/\text{m}^3_{\text{O}}$)	Native wood Altholz	typical: < 0.1 range: 0.01-0.5 typical: 2 range: 0.1 – 20

Table 14. Emissions from 13 different straw-fired district heat-only boiler stations measured between 1987 and 1993. Values in brackets show their distribution [4].

Straw-fired district heat-only boiler stations		
Parameter	mg/Nm ³ wood 10% O ₂	mg/MJ el. mg/kWh
Particles (installations with filters)	80 (5-200)	40 (3-100) el. 144 (11-360)
CO	1200 (240-2300)	600 (120-1150) el. 2160 (432-4140)
NO _x	180 (80-300)	90 (40-150) el. 324 (144-540)
SO ₂	150 (140-170)	75 (60-100) el. 270 (216-360)
HCl	80 (30-150)	40 (15-80) el. 144 (54-288)
PAH	0,35 (0,20-0,60)	0,18 (0,10-0,30) el. 0,65 (0,36-1,08)
Dioxin (Nordic tox.eqv.)	(0,01·10 ⁻⁶ – 0,4·10 ⁻⁶)	(0,005·10 ⁻⁶ – 0,2·10 ⁻⁶) el. (0,018·10 ⁻⁶ – 0,72·10 ⁻⁶)
Dioxin (PFDD+PCDF)	(0,8·10 ⁻⁶ – 8·10 ⁻⁶)	(0,4·10 ⁻⁶ – 4·10 ⁻⁶) el. (1,44·10 ⁻⁶ – 14,4·10 ⁻⁶)

12.1.1 Nitrogen oxides(NO_x)

Nitrogen oxides cause nutrient overload and acid rain. Via secondary reactions in the atmosphere fine particles are also formed. Emissions of nitrogen oxides on combustion of biofuels are mainly due to oxidation of nitrogen in the fuel. Temperatures on combustion of biofuels are normally less than 1300°C, and so thermally formed NO_x is considered to be negligible. The formation of NO_x via reaction with CH (prompt NO_x) is also considered negligible on combustion of biomass.

Nitrogen oxide (NO) is formed at both gas phase combustion and coke combustion. NO is then transformed into NO₂, although most of this transformation takes place in the atmosphere. The level of nitrogen oxide formed increases the higher the nitrogen content in the fuel, with increased excess air and increased combustion temperature. However the amount of NO_x formed from the fuel nitrogen goes down with the level of nitrogen in the fuel. Typical values for emissions of nitrogen dioxide for different fuels are shown in Table 13.

Emissions of nitrogen oxides can be reduced via primary methods, i.e. combustion technology and secondary purification methods, i.e. flue gas cleaning.

12.1.2 Laughing gas (N₂O)

Laughing gas has a high GWP factor¹ and also depletes the protective ozone layer in the stratosphere. Laughing gas is formed to a greater degree from burning combustion fossil

¹ GWP = Global Warming Potential in relation to carbon dioxide. Carbon dioxide has a factor of 1, methane 21 and laughing gas 310.

fuels and measured levels of laughing gas on combustion of biomass are usually very low. In the 1980s, laughing gas formation was noted on FB combustion of coal as the low temperature in the fluid bed resulted in the laughing gas formed not being combusted. Such problems can be addressed by e.g. support combustion in the outlet. Laughing gas can also be formed with the use of urea for NO_x reduction, however improved technology for urea addition has meant this problem has been reduced.

12.1.3 Sulphur dioxide (SO_2)

Sulphur dioxide causes acidification and gives rise to fine particles via secondary gas phase reactions in the atmosphere. Some of the sulphur dioxide forms sulphur trioxide, SO_3 , which can condense and form sulphuric acid and cause low temperature corrosion, if the temperature of the emission gases is lower than the acid dew point, and a material is not corrosion resistant. The sulphur in the fuel is converted on combustion to gaseous SO_2 , remains in the bottom ash or forms aerosols in the form of salts, e.g. potassium sulphate (K_2SO_4). The proportion of sulphur that forms sulphur dioxide depends on the other substances present in the ash. On combustion of straw, it has been reported [4] that around 40% remained in the bottom ash and similar results in [5], in which straw, wood chips and pellets are compared. On combustion of sawdust [36] shows that the majority of the sulphur is converted to SO_2 . The addition of 2% limestone flour to the fuel reduced emissions of sulphur dioxide by up to 40% [35].

Emissions of sulphur dioxide can be reduced by the addition of limestone to the fuel, or by flue gas cleaning with scrubbers or the addition of slaked limestone ($\text{Ca}(\text{OH})_2$) to the flue gases. These technologies are well known and standard within e.g. waste combustion [34].

12.1.4 Hydrogen chloride (HCl)

Hydrogen chloride causes acidification, and can also cause chloride corrosion if the flue gas temperature falls below the water dew point, and a material is not corrosion resistant. The chlorine in the fuel is converted on combustion to gaseous HCl or to aerosols in the form of salts, e.g. potassium chloride (KCl) or sodium chloride (NaCl). The proportion of chlorine that forms hydrogen chloride depends on the other substances present in the ash. Chlorine is also required for the formation of dioxins and furans, see below.

Emissions of hydrogen chloride can be reduced by washing the fuel, which is applied when straw burning, or harvesting the fuel in spring, see those sections. Spring harvested hemp has a lower chlorine content, due to the fact that hemp sheds its leaves for winter and the stems are cleaned by rain during the winter. Hydrogen chloride can also be reduced from flue gases in the same way as sulphur dioxide by flue gas cleaning with scrubbers or the addition of slaked lime.

12.1.5 Dust

Dust from combustion are a health hazard. The substances of interest when combusting agrifuels are primarily those in the ash with low melting points that form fly ash, such as KCl and NaCl . In recent years, special attention has been drawn to ultra fine particles

(less than 1 μm) as a cause of increasing human fatalities [24], and scientific studies are being made that are looking at particulate characteristics from different sources and the impact of dust on health. These substances can also cause problems in the form of coating and high temperature corrosion on heat transferring surfaces and flue gas paths.

Emissions of dust from wood fuels or cyclone cleaning are often around 100 mg/Nm^3 . Cyclone cleaning detaches dust larger than 1 μm . Good separation requires flue gas cleaning in the form of electrostatic or textile filters. Flue gas condensation also delivers particulate separation but not as well, plus flue gas condensation is often mainly used for energy recovery and if so, preceded by a particulate separator.

12.1.6 Heavy metals

Various metals are harmful to plants, animals and people if present in too high levels. Above all, this applies to mercury, cadmium and lead. Several of these metals can be stored in living tissues and remain there for a very long time. On combustion certain heavy metals remain in the bottom ash, while others form aerosols and these are separated along with dust. Mercury is given off in gaseous form and can be separated in a wet scrubber or with active charcoal in dry cleaning, but the levels are normally very low in biofuels. It is firstly fly ash that can contain raised levels of heavy metals. Ash handling is addressed in a separate chapter in this report.

12.1.7 Dioxins and furans (PCDD and PCDF)

Dioxin formation (for the sake of simplicity, both dioxins and furans are included here under dioxins) is affected by the combustion conditions (presence of hydrocarbons), chlorine content, catalytic activity (Cu, Fe, Al), sulphur content and how long it spends in the convection passage (450 - 250 $^{\circ}\text{C}$). For instance, a short time spent by flue gases in this temperature area is of major significance.

Emissions of PCDD/F are reduced via good combustion conditions, and via flue gas cleaning by placing active charcoal in front of the particulate filter. Hitherto, specific efforts to restrict dioxin emissions have been done with waste combustion rather than biofuel combustion.

12.2 Emission standards, recommendations and practice with reference to the size and location of an energy plant

12.2.1 Emission standards in Sweden

Emission standards are normally set by a supervisory body. This is the case for e.g. carbon monoxide, where no specific standards exist.

Plants between 300 kW and 50 MW

There are no general emission standards for **nitrogen oxides** for plants smaller than 50 MW. In practice, emissions are restricted by standards developed for licence approval and by the nitrogen oxide charging system. Examples of limits are given in [28] of 80 mg/MJ (ca 170 mg/Nm^3), but for new plants these can be around 50 – 60 mg/MJ (ca

105-130 mg/Nm³). The nitrogen oxide charging system includes plants that produce over 25 GWh per annum (equivalent to around 5 MW and above). Preliminary average emissions in 2006 were 51 mg NO_x/MJ_{fuel} (ca 108 mg/Nm³).

For plants from 0.5 till 10 MW the Swedish Environmental Protection Agency general advice (AR 87:2) applies for **particulate emissions** in built up areas of 100 mg/m_n³ at 13% CO₂, and 350 mg/m_n³ outside built up areas. In practice, the limit is far below 100 mg/m_n³ today even outside built up areas [6], with the exception of very small plants.

Emissions of **sulphur** into the atmosphere are limited to 100 mg/MJ by regulations on sulphur rich fuels (1998:946). If annual emissions from an plant exceed 400 tons of sulphur, a maximum 50 mg/MJ may be emitted, based on the annual average. Only really large plants > 200 MW, reach emission levels above 400 ton/year. Individual limits can be placed on individual plants. In practice, sulphur emissions are limited by the sulphur levy imposed on the fuel with a sulphur content higher than 0.05 by % weight.

Plants above 50 MW

In the case of plants above 50 MW, emissions of SO₂, NO_x and dust are limited by Swedish Environmental Protection Agency directive (NSF 2002:26). In practice, licence approvals require lower levels than this today.

For solid biofuels in *existing* plants larger than 50 MW the limit for SO₂ is:

Maximum permitted emissions of sulphur dioxide(SO ₂) [mg SO ₂ per m _n ³ at 6% O ₂]		
50–350 MW	>350–500 MW	>500 MW
Combustion is only permitted if emissions to the atmosphere are lower than 0.19 g sulphur per MJ of fuel	1000–400 (linear reduction)	400

For solid biofuels in *new* plants larger than 50 MW (excluding gas turbines) the limit for SO₂ 200 mg SO₂ per m_n³ at 6% O₂ is

For solid biofuels in *existing* plants larger than 50 MW the limits for NO_x are:

Maximum permitted emissions of nitrogen oxides(NO _x) [mg NO _x per m _n ³ at 6% O ₂]	
50–500 MW	>500 MW
600	500

For solid biofuels in *new* plants larger than 50 MW (excluding gas turbines) the limits for **NO_x** are:

Maximum permitted emissions of nitrogen oxides(NO _x) [mg NO _x per m _n ³ at 6% O ₂]		
50–100 MW	>100–300 MW	>300 MW
400	300	200

For solid biofuels in *existing* plants larger than 50 MW the limits for **dust** are:

Maximum permitted emissions of dust [mg per m _n ³ at 6% O ₂]	
<500 MW	>500 MW
100	50

For solid biofuels in *new* plants larger than 50 MW the limits for **dust** are:

Maximum permitted emissions of dust [mg per m _n ³ at 6% O ₂]	
50-100 MW	>100 MW
50	30

Emission standards at waste to energy plants

As several energy crops contain more chlorine and sulphur than clean wood fuels, it can be of interest to compare emission limits that apply for waste to energy combustion (NSF 2002:28).

Maximum permitted emissions from waste combustion [at 11% O ₂]	
Dust	10 mg/Nm ³
SO ₂	50 mg/Nm ³
HCl	10 mg/Nm ³
Dioxins and furans	0.1 ng/m ³
NO _x	200 mg/Nm ³ 400 mg/Nm ³ , for existing plant with capacity < 6 ton/hour

12.2.2 Emission standards in other countries

Below are several examples of emission standards in other countries. A more complete picture is provided in e.g. [2]. By way of summary, standards in Sweden and neighbouring countries are very similar. The charging system for NO_x has, however, resulted in NO_x emissions being lower in Sweden.

Denmark

Recommended emission limits are provided in the national guidelines but the ultimate limits are set in a plant's environment licence issued by the local authority [2].

Fuel input [MW]	CO [ppm]	Particles [mg/m ³ ₀]	NO _x [mg/m ³ ₀]
Wood fuels, like wood pellets, sawdust, wood chips, grain (ref. 10% O₂)			
> 1,0	Usually 500	40 or 100*	-
> 5,0	Usually 500	40 or 100*	300
Straw (ref, 10% O₂)			
> 1,0	500	40	-
> 5,0	500	40	300

* Depending on the applied flue gas cleaning method.

Finland

General emission limits for domestic fuels (wood, peat, straw) are shown in the table – local authorities can set stricter limits [2].

Heat output [MW]	NO _x [mg/MJ]	SO ₂ [mg/MJ]	Particles [mg/MJ]
1 – 5	-	-	200
5 – 50	-	-	85 – 4/3 (P-5) *
	NO ₂ [mg/m ³ _n at 6% O ₂]	SO ₂ [mg/m ³ _n at 6% O ₂]	Particles [mg/m ³ _n at 6% O ₂]
50 – 300	400	Biomass: 200 Peat: 400	50
100 - 300	300	Biomass: 200 Peat: 200	30
> 300	150	Biomass: 200 Peat: 200	30

* P is the capacity in MW. For grate combustion the limit is 200 mg/MJ in power range 1 - 10 MW.

Germany

The table summarises current German legislation.

Fuel input [MW]	CO [mg/m ³ ₀]	NO _x [mg/m ³ ₀]	SO ₂ [mg/m ³ ₀]	Particles [mg/m ³ ₀]
Peat (ref. 11% O₂) (TA-Air 5.4.1.2.1)				
1 – 5	150	fluidised bed: 300 others: 500		50
5 – 50	150	fluidised bed: 300 others <10 MW: 500 others >10 MW: 400		20
Straw and similar (ref. 13% O₂) (1.BImSchV)				
1 – 50	250	400	350*	20
Clean wood (ref. 11% O₂) (TA-Air 5.4.1.2.1)				
1 – 2.5	150	250	350*	100
2.5 – 5	150	250	350*	50

Fuel input [MW]	CO [mg/m ³ ₀]	NO _x [mg/m ³ ₀]	SO ₂ [mg/m ³ ₀]	Particles [mg/m ³ ₀]
5 – 50	150	250	350*	20

* applies above a total mass flow of 1.8 kg SO₂/h

12.3 Anticipated consequences of flue gas cleaning on the combustion of agrifuels

12.3.1 Nitrogen oxides

Emissions of nitrogen oxides from agrifuels will be restricted on licence assessment and by the system for nitrogen charging. As nitrogen rich fuels can give off nitrogen oxide levels of up to several hundred mg/MJ, there will be a need for both combustion technology measures and flue gas cleaning in order to reduce emissions. The introduction of recovered waste products from fuel production is one example of potential fuels with a high nitrogen content. Combustion technology measures are well known and established (flue gas recovery, boiler reconfiguration, air control, low NOX burners etc). There is also the risk of carbon monoxide levels increasing as a consequence of trimming to reduce the level of nitrogen oxide. Even secondary reduction of NO_x formed using SCR (selected catalytic reduction) and SNCR (selected non-catalytic reduction), are well known established technologies for charcoal and biofuel, but there are problems and knowledge gaps, especially in the case of SCR, with the use of these technologies on combustion of nitrogen rich wood fuels that also contain alkalis and acids. In the longer term, additional research into how nitrogen oxides are formed from fuel nitrogen when burning biofuels can contribute to keeping emissions in check. Sound knowledge is available on how fuel nitrogen is formed from fossil charcoal, but equivalent knowledge related to biofuels is less well documented [38].

The government targets set for the reduction of nitrogen oxide emissions by 2010 do not look like being met, which is why every ton of emissions that can be prevented is important [13]. In the case of smaller plants that fall outside the system for nitrogen charging (< 25 GWh), there are no set limits today, and there are no indications to suggest that any will be set during the course of this programme. SNV has submitted a proposal to the government that NO_x charging be raised from 40 to 50 SEK/kg. The aim of this increase would be to persuade more plants to invest in flue gas cleaning. As yet, the government has not responded to the proposal. Today plants that exceed the mean value have to pay from SEK 10,000 to several million. The plant that got the most back from the system received SEK 11 million. Most biofuel-fired boilers today do not have secondary nitrogen reduction, see Table 15. Of the 20 boilers with the lowest emissions, 15 have SNCR or SNCR+SCR, although secondary cleaning occurs throughout the register. Several boilers that received refunds in the system only have combustion technology measures. Please note however that almost half the boilers have not provided details of any measures installed.

Table 15. Data from Swedish Environmental Protection Agency from 134 boilers for heat- and power generation with > 80% biofuel[7].

	SNCR	SCR	SNCR +SCR	Combustion technology measure	No information	Total no of plants
Pay to NO _x -system	17	1		22 flue gas recovery 5 low NO _x burners 2 rotating over-fire air (ROFA) 2 over-fire air (OFA) 2 Ecotube 1 combination	39	83
Get back from NO _x system	11		3	10 flue gas recovery 1 rotating over-fire air (ROFA) 2 combination	21	51

12.3.2 Experiences of straw burning in Denmark

The limit for NO_x emissions in Denmark is 300 mg/Nm³, which is why secondary equipment for reducing them is not installed for straw burning.

12.3.3 SNCR

SNCR (Selective Non Catalytic Reduction) entails ammonia injection directly into the boiler at 900-1050°C. This reduction is usually 40 – 60%. Urea is also used, but to an ever decreasing extent due to risk of corrosion and laughing gas formation. The investment costs for SNCR are around 2 – 3 MSEK[8]. Operating costs are low. At an ammonium cost of around SEK 1 per kg 25% ammonium solution it would cost SEK 4-5 per kilo of NO reduced. As a rule of thumb, the stoichiometric relationship for the dosage of reduction agent is 2, i.e. one needs 2X more ammonia than that utilised for nitrogen oxide reduction.

SNCR is a simple technology, requires the boiler to be designed such that injection can be done at a suitable temperature range, and that there is enough exposure time and mixing is good. Non reacted ammonia (slip) is separated in solid waste products (fly ash) and/or released with the flue gases. If the boiler is fitted with a flue gas condenser a large proportion of the ammonia can be washed out and reused in the process. The more acid components there are such as sulphuric acid and chloride containing in the flue gases, the more ammonia is bound as salts and captured by particulate separation. Ammonia slip in flue gases is restricted by current environment regulations in the magnitude of 2-20 mg/MJ [31].

More reducing agent must be used when burning nitrogen rich fuels. An increase in reducing agent does not usually face any obstacles in an existing SNCR installation. When the NO_x content in the raw gas increases, the degree of reduction also increases,

(closer between molecules) but there is little experience of by how much. Increased quantities of reducing agent can lead to problems with ammonium salt coating and increased ammonia slip.

12.3.4 Corrosion with ammonia injection

The use of SNCR and even SCR has the associated risk of corrosion from the SNCR or SCR material. This occurs when unreacted ammonia (or urea) forms ammonium salts with elements liberated from the fuel on combustion. As there is more slip with SNCR the risk is greater there. Common to all salts is an increase in the dew point for the flue gas, and quite low levels of ammonium salts in coating that can make the coating damp and corrosive [17].

12.3.5 SCR

In the case of catalytic cleaning, a catalyser is positioned after the boiler - SCR (Selective Catalytic Reduction). The temperature of the catalyser is usually 300 - 400°C, although an SCR can be used at a lower temperature. The location is largely dictated by the fuel as pollutants from the fuel require different degrees of cleaning before reaching the catalyser. Reduction of 90 – 95% is achieved with a new catalyser. An SCR costs around 10 times more than an SNCR. The cost for installation in an existing boiler largely depends on how much reconstruction work is involved. Operating costs are low and as a rule of thumb, the stoichiometric relationship for dosages is 1, i.e. there is no ammoniac slip in principle. In some cases an SCR is installed after an SNCR, which results in very low NO_x emissions and negligible ammonia slip. Catalysers are dimensioned in accordance with the flue gas flow, which means an increase in the NO_x content would not require redimensioning. On the other hand, combustion of a damper fuel in the fuel mix increases flue gas flow.

SCR is rarely used with biofuel burning, as alkali salts in the flue gas deactivate (pollute) the catalyser 2-4 times faster than in charcoal burning. A number of Värmeforsk reports address SCRs with biofuel combustion, the most recent being: [22][10][32][9][12]. There are also findings from a completed EU project [42]. There are still several question marks surrounding how particles in particular affect catalysers. For instance, the phosphorus content in many agrifuels can be significant [44].

SCR is more commonly used for waste combustion, where the catalyser is positioned after particulate reduction (low-dust installation). In order to reach working temperature, a heated electric filter can be used, which is less common, or via flue gas heat recovery after particulate purification. If steam is available, this is a cost effective alternative. Reheating with LPG is expensive.

Charcoal contains as much potassium as biofuels, but the potassium remains in the bottom ash in the former. One possible solution would be to find an additive, that captures the potassium and keeps it in the bottom ash. Other European countries are more oriented in the direction of cocombusting biofuels with charcoal where alkali are then better bound in the bottom ash and therefore less of a pollution problem.

Research on catalysers and biofuel combustion has been done by several research groups in recent times. See for instance [22] who investigated deactivation in a 100 MW boiler where the cat was positioned before particulate cleaning (high-dust). The fuel was forest chips and peat. They found a linear connection between deactivation and the alkali concentration (mainly potassium) in the flue gas. The addition of sulphur had no effect, as the additive did not affect the amount of aerosols containing potassium.

Deactivation on straw burning was investigated by [41], that found that deactivation caused by potassium salts was quick, and while reactivation with H_2SO_4 was possible, it had to be done so often it was deemed not feasible in practice.

Ann-Charlott Larsson of Alstom Power has recently completed a PhD in a method of producing emissions in a lab environment [44]. The aim was to simulate what happens in a catalyser and obtain rapid results, as taking measurements in a genuine environment is both expensive and time consuming. Her recommendation is that the catalyser be placed after particulate cleaning (tail-end or low-dust) on combustion of agrifuels. This solution has been chosen in a plant being built in Amager in Denmark, which intends to use a broad fuel mix.

12.3.6 Example of Örtofta

Before Lunds Energi planned to construct a 45 MW_{th} straw-fired boiler in Örtofta NO_x-reduction has been studied in a thesis [14]. Technological and economic comparisons were made between SNCR and SCR. The separation of pollutants in the hose filter potentially hazardous for the catalyser was also studied. The calculations were based on an assumed 300 mg/Nm³ NO_x in the flue gases, the same value as published by the straw-fired 90 MW boiler in Avdöre. SEK ? /kg NO_x was used for the NO_x charge. The economics analysis showed that both technologies are profitable. SNCR is more profitable for lower NO_x levels (250 mg/Nm³, saving MSEK per annum), and SCR for higher NO_x levels (350 mg/Nm³, saving MSEK 3.5 per annum).

However SCR installations are very sensitive to pollutants in flue gases, especially sodium and potassium pollutants. A hose filter with excellent separation qualities is considered a necessity in front of the catalyser. The installation and maintenance costs for flue gas heat exchange between the particulate filter and catalyser are not included in the cost calculation. Co-combustion with sulphur containing fuels is recommended, as straw contains a low sulphur content that activates the catalyser. On installation of an SNCR the ammonia slip must be kept as low as possible to avoid corrosion by ammonia salts. The flue gas temperature must also be kept at up to 140 °C to avoid low temperature corrosion.

12.3.7 Nitrogen oxides - knowledge gaps and research needs

There are three measures for limiting NO_x emissions:

- limit the amount of nitrogen rich fuel in the fuel mix,
- reduce emissions by additional combustion technology measures,
- introduce/improve NO_x reduction in flue gases.

Table 16. Compilation of knowledge gap, nitrogen oxides.

Knowledge gap	Nature of measure	Time required	Prioritisation within the programme
NO _x levels when burning different crops and fuel mixes	Measurements in lab and/or full scale. Experience gathering and exchange	< 3 years	High
	To increase fundamental knowledge requires long term research projects	> 3 years	Low
Potential to restrict NO _x formation via combustion technology measures without increasing CO	Experience gathering and exchange	< 3 years	High
SNCR technology			
Possible separation with ammonia injection. If plant has emission limits for ammonia slip, can this be included? Economic effects? Risk of salt coating and low temperature corrosion?	Full scale trials and measurements Experience gathering and exchange	< 3 years	High
SCR technology			
Characteristics of flue gas emissions from different fuels and fuel mixes, in both the gas and particle phases.	Trials in lab and/or full scale.	< 3 years	High
High-dust-application: Increased knowledge on deactivation: effect of emissions at gas and particle phases, how fast deactivation occurs, possible regeneration etc	Trials in lab and/or full scale	> 3 years	Low
Low-dust (tail-end)-application: Increased knowledge on deactivation: effect of emissions at gas and particle phases, how fast deactivation occurs, possible regeneration etc	Trials in lab and/or full scale Evaluation of existing installations	< 3 years	High
What is required of particulate cleaning for SCR to be feasible? (How well are alkali pollutants and other catalyser pollutants separated?)	Evaluation of existing installations	< 3 years	High
Economics – installation and operation, can NO _x charges be recouped?	Can be done at project planning stage	< 3 years	High
Is there the potential for additives to reduce the concentration of alkali pollutants in the flue gases? How can co-combustion be utilised?	Trials in lab and/or full scale Evaluation of existing installations	< 3 years	Low
	Long term research projects required to acquire fundamental knowledge	> 3 years	

12.3.8 Sulphur dioxide

If the sulphur is converted into sulphur dioxide on combustion, certain agrifuels can exceed the 100 mg/MJ limit set for sulphur rich rules. Consultation with the Swedish Environmental Protection Agency[13] has given no indication that any measures related to sulphur emission from biofuels will be introduced in the next few years.

12.3.9 Hydrogen chloride

There are currently no limits for emissions of hydrogen chloride from biofuel-fired plants, and no indications that any such measures will be introduced in the immediate future [13]. The problematic with chlorine is more to do with problems arising from coating and high temperature corrosion. Low temperature corrosion risk should also be taken into consideration.

12.3.10 Sulphur dioxide and hydrogen chloride knowledge gaps

Low temperature corrosion risks should be taken into consideration.

The problematic related to coating and high temperature corrosion is dealt with elsewhere in this report.

12.3.11 Dioxins/furans (PCDD/F)

In signing the Stockholm Convention, Sweden has undertaken to determine the sources of emissions and then prioritise measures for their reduction and develop plans of action. Mapping has been done previously, [29], that revealed that there are gaps in current knowledge on the sources of dioxin emissions, and also that burning biofuels, in the first instance on a small scale, can be a significant source. It was also noted that over 10% of the Swedish population exceeded the TDI (tolerable daily intake) for dioxins.

The latest report to the Stockholm Convention [30] says that “there is a need for the operational ventures concerned to further clarify the amount of emissions produced by their operations. Data showing how emissions vary during the various different phases of the entire process would provide a better platform for more accurately determining total emissions. Such data would also contribute to knowledge on how the formation of dioxins in particular could be reduced. At the same rate emissions from industry are being reduced, secondary sources such as polluted areas and sediment plus diffuse sources including small scale combustion, illegal combustion and acid rain from emissions in other countries have increased in importance.”

According to [33] better knowledge on where and when in operating cycles dioxins are formed from different fuels is vital. The Swedish Environmental Protection Agency is hoping that the industry will drive forward technology development, produce information and recommendations on correct procedures, right choice of fuel etc such that it will not be necessary for authorities to introduce regulation.

Very limited, low levels of dioxins are emitted to the atmosphere on the combustion of waste. Instead, the dioxin formed during the process is found in the fly ash, which is disposed of as hazardous waste.

12.3.12 Dioxins on combustion of biofuels

A comprehensive summary of measurements obtained for the combustion of wood fuels (pure and processed) can be found in [23]. The summary includes several straw and grass examples. The following conclusions have been drawn:

- Dioxins and furans can be formed in all combustion processes where organic charcoal, oxygen and chlorine are present.
- Formation occurs at both the solid phase and gaseous phase, and there are several paths to formation.
- Formation can be prevented by the addition of additives such as sulphur and nitrogen combinations.
- Good combustion conditions in combination with secondary cleaning offers good control over dioxin levels in flue gases.
- Non contaminated wood produces low emissions.
- Even though e.g. grass and straw contain chlorine, the measured levels of dioxins formed are usually low. This is thought to be due to the presence of alkali that leads to chlorine binding into salts, and so minimising gaseous chlorine.
- High combustion efficiency, i.e. good combustion in the gaseous phase is very important for emission levels.
- Combustion can be optimised for low emissions. Important parameters for this are combustion temperature, mixing, interval time and oxygen surplus.
- Other important combustion parameters include avoiding soot building, and the presence of charcoal particles in the gas phase.

Projects published by Värmeforsk:

- Two methods for reducing the cost of dioxin reduction on co-combustion of biofuels and waste were investigated by [12]. One method was based on reducing dioxins together with NO_x reduction. A commercial SCR catalyser for biofuel combustion was tested on a pilot scale. 70% of the dioxins formed were reduced at the same time as NO_x reduction in the catalyser. The second method was based on reducing dioxins in association with the addition of additives. A review of research published revealed that additives, primarily urea and sulphur combinations can restrict dioxin formation by up to 80%. Sulphur is added to reduce corrosion in heat transfer surfaces. The authors feel that the study indicates a potential to achieve dioxin reduction via a deNox catalyser. To ascertain whether the technology is viable on a full scale, it ought to be further evaluated and verified. The use of additives as reducing agents for dioxins is an interesting avenue that could benefit from further investigation.
- Readings in two boilers for co-combustion showed up to 70% reductions in dioxins with SCR [22].
- The additives ammonium sulphate, sulphur dioxide and ammonia were added in a study to restrict the formation of dioxins and chlorobenzenes [11]. The biggest effect came from the addition of SO₂ with the primary air that reduced dioxin formation by 58% and that of chlorobenzenes by 73%. The addition of ammonium sulphate reduced dioxin formation by 41% and that of chlorobenzenes by 77%. Nitrogen containing additives delivered no inhibiting

effect. Due to the limited amount of experimentation and the uncertainties surrounding the experiment, no conclusions can be drawn on the recommended amounts of additives or the highest possible inhibition. The conclusion is rather that the study should be complemented by additional experiments.

Dioxin emissions on burning sawdust have been measured in a 20 kW burner [16]. The results revealed low dioxin content on normal operation but relatively high levels during maintenance operation with glow beds.

In the case of co-combustion of reed canary grass and sorted dry combustible household waste emissions were below the limit set for waste combustion [18]. Trials with small scale combustion of wood pellets and wood showed low emissions from modern burners but higher emissions from an old burner [19].

12.3.13 Dioxins - knowledge gaps and research needs

There are big gaps in current knowledge on dioxin formation and emissions on combustion of agrifuels, which is natural as combustion of these fuels has yet to take off on any real scale. However based on experience of wood fuels and straw, the indications are that dioxin formation can be kept at a low level with the right combustion technology. Costly secondary reduction is best avoided through a greater understanding of what conditions produce the lowest dioxin formation.

Table 17. Summary of knowledge gaps.

Knowledge gap	Nature of the measures	Time required	Prioritisation within the programme
Formation and levels of PCDD/F on combustion of different crops and fuel mixes	Review of published research Measurements in lab and/or full scale Can be done via both practical experiments and long-term research projects	< 3 years and > 3 years	Average and Low
Significance of combustion technology and operation for dioxin emissions	Review of published research Measurements in lab and/or full scale Can be done via both practical experiments and long-term research projects	< 3 years and > 3 years	Average and Low
Significance of co-combustion and additives for dioxin formation	Review of published research Measurements in lab and/or full scale Can be done via both practical experiments and long-term research projects	< 3 years and > 3 years	Average and Low

12.3.14 Dust

More fly ash is generated on combustion of ash rich agrifuels. How much, and the size distribution of particles, mainly depends on what the ash contains, and what remains in the bottom ash and what is gasified and joins the flue gas flow. Here, co-combustion with other fuels and possible additives is significant. There is no proper picture of how much the particulate content increases for different agrifuels. If the fuel contains a lot of small fractions that can be easily swept into the flue gases, such as husks and peelings, the interval time for combustion of the coke can be of importance as short interval times then generate high levels of uncombusted dust.

The dominant technologies for particulate separation are cyclones, electrostatic filters, textile filters (also called particulate or hose filters) and flue gas condensation. The physics behind the various separation mechanisms are described in e.g. [37]. In the case of wood fuels, emission levels of around 100 mg/Nm³ are common following cyclone technology.

There have been no mention from supervisory authorities on requirements as to measurements or any reduction of particles in term of size breakdown.

12.3.15 Cyclones

On smaller biofuel-fired plants cyclones (or multicyclones) can be the only form of separation, and in larger plants they can be positioned as separators before electrostatic or particulate filters. As cyclones utilise the movement of dust, they can separate particles greater than ca 1 µm (aerodynamic diameter) well, but particles smaller than ca 1 µm pass straight through a cyclone. One example is small-scale sawdust combustion, where particulate content lies between 150 and 350 mg/Nm³, and most of the dust are submicron size, i.e. they are not separated by a cyclone [36]. In other words, it can be a problem for a plant that only has cyclones to stay within given particulate standards, if the amount of agrifuels in the fuel mix is increased.

12.3.16 Electrostatic filters

In an electrostatic filter dust particles are first charged electronically, and then trapped in an electric field. The electrical resistivity of the particles is of major significance for electrostatic filter efficiency. If resistivity is low, typically in the case of fossil fuels, the particles will not “stick” and therefore easily pass into the gas flow. On high resistivity, typically in the case of straw, high potential is required in the electrical field to charge the particles, which can lead to overcharge. An el filter is dimensioned for a certain level of separation and if the particulate content in the raw gas increases, particulate emissions will also rise. A common limit for el-filters is 20 - 40 mg/Nm³, but 10 mg/Nm³ can be achieved. However a certain margin is normally allowed for increased particle content.

Burning biofuels with fossil charcoal offers several favourable benefits [25]. Particles from the biofuel usually have higher resistivity, which is an advantage as charcoal particles often have a resistivity that is too low to work well. Biofuels are often damper

than charcoal, which means gas flow increases, but as increased moisture content in flue gas is better for separation, while at the same time, the biofuel generally has a lower ash content than the charcoal, the combined effect of burning them together is usually beneficial for particulate separation.

The clean wood fuels that are mainly combusted today, are easier fuels for electrostatic filters and these are installed at plant down to 1 MW. The market for electrostatic filters modified for smaller plants is increasing today [40]. Sulphur in the fuel does not cause problems in this respect, as the sulphur forms sulphates. Willow is pretty similar to wood fuels, and in principle, should not cause problems for electrostatic filters. Experience from straw burning has shown that chlorine content causes problems with high resistivity, and electrostatic filters are therefore not suitable for straw combustion. In Denmark, hose filters are mainly used when burning straw.

There are many question marks concerning the composition of dust from different fuels, and how different fuels affect electrostatic filters. For instance silicon content is an issue. Reed canary grass contains high levels of silicon. Rice husks also contain silicon, although electrostatic filters work well with them [25]. Silicon is found in fossil charcoal as mineral deposits, while in biofuel, silicates occur, which can be of significance.

12.3.17 Textile filters

Textile filters deliver the best separation of dust in a wood-fired boiler, down to mg/Nm^3 . Hose filters are more common at smaller plants as the installation costs are lower than for electrostatic filters. Operating experiences from Swedish biofuel-fired plants down to 2 MW have been compiled in a Värmeforsk report [26], where the total costs for hose filters are compared with the total costs for electrostatic filters, and this shows that for plants smaller than 10 MW, hose filters come out on top. There is a debate about the fire risks associated with hose filters. There are claims that one in two hose filters has suffered a fire, while others argue that fires are caused by the design of the particulate outfeed (there are pockets where glowing coke particles can accumulate), and that the risk of fire has been designed away in principle today.

With hose filters, the degree of separation is not proportional to the particulate content entering in the same way as with electrostatic filters, and other factors dictate more, such as pressure drop, cleaning frequency and particle size breakdown. Which means, in principle, that an existing hose filter can be used even when particulate content increases, although the lifespan of the filter can then be truncated due to more wear and tear.

Experiences are limited of hose filters used for agrifuel combustion apart from straw. Hose filters are used exclusively for straw burning as the particulate resistivity is high and therefore electrostatic filters work poorly. In the case of straw combustion, the fly ash mainly consists of submicron particles, which means filters are dimensioned for a relatively low filter load, (filter load = gas flow/hose filter area). Hose filters for straw combustion are set for a 10% lower load than for wood chip fuel, and nearly 50% lower when fossil charcoal is the fuel.

Filters for straw combustion are usually made from polyacrilnitrile (PAN) or aramid. PAN filters are usually changed each year, while aramid is changed every two or three years [43]. These filters utilise the filter cake built up to separate the dust.

One alternative to filters that use filter cakes is a membrane filter, i.e. a type of gortex material where the bearing material has a Teflon coating. Membranes are very tight so the pressure drop (and separation) is done via the filter itself. Membrane filters have a longer lifespan in a straw boiler than conventional filters [39]. However gortex filters require close supervision of the combustion conditions to avoid becoming clogged by hydrocarbons in the flue gas. For instance, smaller plants without an accumulator tank that go down to maintenance load, have a tendency to clog the filters. Sulphur dioxide that is converted into sulphuric acid can have an adverse effect on the filter material. In the case of a conventional hose filter the sulphuric acid does not usually reach the filter as it is trapped by the filter cake. In a membrane filter, the sulphuric acid reaches the filter material and can then affect the bearing material (Teflon is not sensitive).

12.3.18 Other technologies for particulate reduction

Other technologies for particulate reduction worth mentioning include flue gas condensation, gravel beds and wet electrostatic filters. There are other technologies not currently used for particulate separation of biofuels, but in terms of pure technology, have great potential [46]. One example of a technology that has been growing on the market in recent years is a combination of flue gas condensation and wet electrostatic filters from 1.5 MW and above [45].

12.3.19 Example of grain combustion, 2 MW

Sala-Heby Energi has a 2 MW boiler where they burn grain kernels. The aim is to reduce particulate content to 100 mg/Nm³, which could not be achieved with a multicyclone. They now wish to test a new product adapted for smaller plants; a vertical electrostatic filter with ultrasound purification [15]. If everything goes to plan, the electrostatic filter will be installed this autumn. They have also had problems with sticky coatings in the boiler. These coatings contain high levels of potassium. The problems have been reduced since crushed dolomite was added to the fuel. The dolomite additive also seems to be having a positive effect on the dust such that the proportion of bottom ash has gone up, although this effect has yet to be evaluated.

12.4 Current research

No research is currently being done in the area of reducing nitrogen oxides from agrifuels.

No research is currently being done in the area of reducing dioxins from agrifuels, but various project proposals have been made for the forthcoming STEM programme on Small Scale heating supply (< 10 MW).

A project for measuring, characterising and reducing dust on grain combustion has been approved for SLF funding in 2007.

Research into the reduction of dust can be of interest in the area of small scale combustion, if licences for particulate emissions cannot be obtained. Several project applications concerning product development for particulate reduction have been made for the coming STEM programme on Small scale heating supply (< 10 MW).

12.4.1 Dust - knowledge gaps and research needs

Table 18. Summary of knowledge gaps.

Knowledge gap	Nature of actions	Time required	Prioritisation within the programme
A) Formation and characterisation of particles in flue gases from different fuels and fuel mixes: chemically (what they contain) physically (particle size breakdown)	Fundamental research in ash chemistry, formation of aerosols, modelling (?) etc	> 3 years	Lower
B) Formation and characterisation of particles in flue gases from different fuels and fuel mixes: chemically (what they contain) physically (particle size breakdown)	Measuring in lab and/or full scale. Experience gathering and exchange	< 3 years	High
Consequences of handling large quantities on increased particulate separation: capacity for particulate output, storage, transport and costs of disposal	Evaluation on full scale Experience gathering and exchange	< 3 years	Low
Risk of attendant uncombusted particles (fuel particle sizes and stop times in boiler areas)	Evaluation on full scale Experience gathering and exchange	< 3 years	Low
Electrostatic filters			
Resistivity of particles from different fuels	Review of published work Measurements in lab and/or full scale evaluation	< 3 years	Average
Flue gas flows and moisture content in flue gases on combustion/co-combustion with agrifuels	Review of published work Measurements in lab and/or full scale evaluation	< 3 years	Average
Textile filters			
Suitable filter loads for different agrifuels, particulate density, pressure drop through filter cake, temperature in filter to avoid acid dew point, hygroscopic effects	Measurements in lab and/or full scale Experience exchange	< 3 years	High
Hose material:	Evaluation (lab analysis) in	< 3 years	High

Evaluate materials under load (sustainable at different loads, affect of sulphur etc) New materials	association with burning of different fuels Experience exchange		
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12.5 References

- [1] Strömberg, B., *Fuel handbook*, Värmeforsk report no 911, 2005
- [2] IEA, *Biomass Combustion and Co-firing*, 2007
- [3] Videncenter for Halm- og Flisfyring, Videnblad no 61, 1988
- [4] Centre for biomass Technology, *Straw for Energy production, Technology – Environment – Economy*, Second Edition 1998 www.videncenter.dk
- [5] Houmøller, S., Evald, A., *Sulphur Balances for Biofuel Combustion Systems*, 4th Biomass Conference of the Americas, 1999
- [6] Swedish Environmental Protection Agency, *Combustion plants for energy production including flue gas condensation*, Branschfakta, issue 2, March 2005
- [7] Oral communication, Anders Melin Swedish Environmental Protection Agency
- [8] Oral communication, Reidar Värner Petrokraft Miljö
- [9] Andersson, Christer, Bodin, Henrik, Khodayari, Raziye, Odenbrand, Ingemar, Sahlqvist, Åsa (2000). "SCR with biofuel combustion - stage 2; Measures for extending catalyser lifespan." Värmeforsk report no 705.
- [10] Andersson, Christer, Kling, Åsa, Odenbrand, Ingemar, Khodayari, Raziye (2002). "SCR with biofuel combustion - stage 3 Regeneration on full scale." Värmeforsk report 787.
- [11] Aurell, Johanna, Marklund, Stellan, Kling, Åsa, Myringer, Åse (2005). "Reduced dioxin formation with the aid of additives on co-combustion of forest fuel and recovered fuel" Värmeforsk report no 928.
- [12] Aurell, Johanna, Kling, Åsa, Liljelund, Per, Andersson, Christer, Marklund, Stellan (2003). "SCR as a method for combined dioxin and nitrogen reduction on cocombustion of biofuel and waste." Värmeforsk report no 823.
- [13] Ejner, Björn (2007). Swedish Environmental Protection Agency, Oral communication.
- [14] Elwin, Erland (2007). "Reducing nitrogen oxides from a straw-fired biofuel boiler". Faculty of Chemical Engineering, Lund University Faculty of Engineering.
- [15] Eriksson, Benny (2007). Sala-Heby Energi.
- [16] Eskilsson, David (2006). "Dioxins/furans and hexachlorobenzene from small scale grain combustion (oats)" The Swedish Farmers' Foundation for Agricultural Research.
- [17] Goldschmidt, Barbara (2004). "Low temperature corrosion in boilers with SNCR." Värmeforsk report no 847.
- [18] Hedman, B, Burvall, J, Nilsson, C, Marklund, S (2005). "Emissions from small-scale energy production using co-combustion of biofuel and the dry fraction of household waste." Waste Management 25 (): 311-321

-
- [19] Hedman, B, M, Näslund, Marklund, S (2006). *"Emission of PCDD/F, PCB and HCB from combustion of firewood and pellets in residential stoves and boilers."* Environmental Science & Technology 40(16): 4968-4975.
- [20] Karlsson, Hanna L, Ljungman, Anders G , Lindbom, John, Möller, Lennart (2006). *"Comparison of genotoxic and inflammatory effects of particles generated by wood combustion, a road simulator and collected from street and subway."*
- [21] Kling, Åsa, Andersson, Christer, Myringer, Åse, Eskilsson, David, Järås, Sven G (2007). *"Alkali deactivation on high-dust SCR catalysts used for NO_x reduction exposed to flue gas from 100 MW-scale biofuel and peat fired boilers: Influence on flue gas composition."* Applied Catalysis B: Environment 69: 240-251.
- [22] Kling, Åsa, Myringer, Åse, Eskilsson, David, Aurell, Johanna, Marklund, Stellan (2005). *"SCR with cocombustion of biofuels and recovered waste fuels."* Värmeforsk report no 932.
- [23] Lavric, Elena Daniela, Alexander , A, Konnov, Jacques De Ruyck (2004). *"Dioxin levels in wood combustion - a review."* Biomass and Bioenergy 26: 115-145.
- [24] Lighty, J., Veranth, J.M., Sarofim, A.F. (2000). *"Combustion Aerosols: Factors Governing Their Size and Composition and Implications to Human Health."* Journal of the Air and Waste Management Association 50: 1565-1618.
- [25] Liljedal, Lena (2007). Alstom Power.
- [26] Lindau, Leif (2002). *"Hose filters with biofuel-fired plants. Reliability and operation economics."* Värmeforsk report 771.
- [27] Marklund, Stellan (2007). Umeå University, Faculty of Chemistry, Environment Chemistry
- [28] The Swedish Environmental Protection Agency(1987). *"Solid fuel-fired plants 500 kW - 10 MW, Swedish Environmental Protection Agency General Advice 87:2."*
- [29] The Swedish Environmental Protection Agency (2005). *"Survey of unintentionally formed substances, Report to government 2005-03-31."*
- [30] The Swedish Environmental Protection Agency (2006). *"National Implementation Plan for the Stockholm Convention on Persistent Organic Pollutants for Sweden."* www.pops.int/documents/implementation/nips/.
- [31] The Swedish Environmental Protection Agency (2002). *"Emissions of ammonia and laughing gas from combustion plants that use SNCR/SCR "*. Fakta October 2002.
- [32] Niemann, Therese, Henningsson, Claes, Andersson, Christer (2000). *"Systems study on combined NO_x reduction with SNCR/SCR."* Värmeforsk report no 699.
- [33] Nyholm, Maria (2007). The Swedish Environmental Protection Agency, Oral communication.
- [34] RVF (2004). *"Reduction of sulphur dioxide emissions on waste combustion with dry flue gas systems"* RVF - Svenska Renhållningsföreningen, Report no 2 2004.

-
- [35] Rönnbäck, Mariekk, Arkelöv, Olof , Johansson, Mathias (2006). *"Additives for preventing corrosion and acid emissions on grain combustion."* SP-report 2006:55.
- [36] Rönnbäck, Marie, Arkelöv, Olof (2005). *"Technical and environmental problems on burning grain – an initial study"* SP Technical Research Institute and Äfab.
- [37] Rönnbäck, Marie, Gustavsson, Lennart, Martinsson, Lars, Tullin, Claes, Johansson, Linda (2002). *"Particulate cleansing technology for biofuel plants smaller than 10 MW – technology situation and development potential."* Värmeforsk 786.
- [38] Samuelsson, Jessica (2006). *"Conversion of nitrogen in a fixed burning biofuel bed"*. Department of Energy and Environment, Chalmers University of Technology, Göteborg.
- [39] Wieslander, Peter (2007). Alstom Power.
- [40] Wollblad, Hans, Bravida.
- [41] Zheng, Yuanjing, Jensen, Anker Degn, Johnsson, Jan Erik (2005). *"Deactivation of V2O5-WO3-TiO2 SCR catalyst at a biomass-fired combined heat and power plant."* Applied Catalysis B: Environmental 60: 253-264.
- [42] Catdeact, www.eu-projects.de
- [43] Feldt, Klas-Göran (2007). Simatec.
- [44] Larsson, Ann-Charlotte (2007). *"Study of Catalyst Deactivation in Three Different Industrial Processes"*. Växjö University.
- [45] Svensk Flue gas energi, www.sre.se
- [46] Rönnbäck, M, Gustavsson, L, *"Separation of submicron particles on biofuel combustion with flue gas condensation or condensing wet electrostatic filters - Analysis of the possibilities"* Värmeforsk report 2006

13 Ash handling and returning ash to the field

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The large amounts of ash given by energy crops provides motivation to investigate whether opportunities exist to return it to the field, taking account of the fact that landfilling of ash is relatively expensive. Ash from biofuel cultivated on arable land can be an important plant nutrient resource if the quality is satisfactory. Return of ash to arable land is a step in further completing the ecological cycle.

Other waste products from the community are already returned to the farming industry currently as fertiliser and additional products can be of interest. Biogas plants return all biofertiliser using organic waste sorted at source from the food industry, the retail food trade, the catering industry and households. A certain amount of municipal sewage sludge is also returned to the land even if this is strongly questioned by the food industry. The key issues regarding the return of communal waste, for example biofuel ash, to the agricultural industry are purity, quality assurance and arable land origin. The farming industry warns that it is unacceptable for there to be a rise in the metal content of the land when fertilising with waste.

13.1 Chemical composition

Ash is far from being a uniform product. The chemical composition varies depending on the plant involved, fertilisation and harvest weather conditions. [22] The composition is also influenced by the combustion technology used, flue gas cleaning and boiler operational conditions. [16] An ash contains almost every mineral and nutrient, nitrogen excepted, that has been in the fuel that has been used. [20] The amount of unburnt fuel in the ash has a significant influence on the nutrient content of the ash. [27] Ash has many beneficial properties which contribute to it being a good fertiliser from a nutrient point of view. [27]

13.1.1 Straw

Straw has a higher ash content than wood. The ash level also varies depending on the type of straw. At one extreme, rape straw can have an ash content of up to 15 % although the normal level for straw is about 5-8 %. [2]

The phosphorus level in straw ash is naturally lower than grain ash, at about 1 % of total solids. [15][16]. According to the results of a study carried out in Denmark in 2004, the potassium level in bottom ash was about 10 % of total solids. The potassium level in straw ash varies a lot, for example depending upon whether the straw has been subjected to rain or not before cutting and the soil's available potassium for plant use. [17] Fly ash often contains higher levels of volatile heavy metals, for example cadmium, compared with bottom ash. Table 19 shows an example of the composition of bottom ash, fly ash and mixed ash derived from straw combustion. [1] [3] The level of polycyclic aromatic hydrocarbons (PAH) is eight times lower with straw ash compared with wood. PAH's are formed when there is incomplete combustion and are

carcinogenic substances. Dioxins are however present at exceptionally high levels in chlorine rich fuels like wheat straw and hay. [14]

Table 19. Composition in bottom, fly and mixed ash from combustion of straw. The mean values for wheat (V), barley (K) rye (R) and rape (Ra) are given. Dry substance is measured in per cent per tonne and grammes per tonne (ppm).

	Bottom ash	Fly ash	Mixed ash
P, %	1.4	1.9	1.8
K, %	13.1	22.4	12.6
CaO*, %	21.1	19.2	20.5
Cr, ppm	42.5	28.6	33.6
Ni, ppm	17.7	16.5	16.4
Cu, ppm	41.4	97.1	62.3
Zn, ppm	52.7	872.3	139.8
Pb, ppm	3,4	139,2	20,9
Cd, ppm	0.10	9.0	1.5
Cd/P, mg/kg	29	593	79
Unburnt, %	9.7	12.0	12.9
No. of samples V/K/R/Ra	21/11/6/8	10/3/3/3	6/1/4/3
No. of plants	7	3	3

*The ash's liming effect is given as the corresponding amount of CaO

13.1.2 Grain

Grain is noted for its high mineral and ash levels. [5] The ash level of different types of grain chaff varies, probably depending on varying silicon uptake. Oats and barley have an ash content of about 2.5-3 % of total solids while wheat and wheat-rye hybrid have an ash content of just under 2 % of total solids. [6]

In an analysis of primarily ash from oats, the ash contains 10% phosphorus while the corresponding figures for potassium and magnesium were 10% and 4% on total solids respectively. The heavy metal content was very low, for example, only approximately 5 mg. cadmium per kg. phosphorus, on a par with the best mineral fertilisers. The amount of citrate soluble phosphorus was about 70 % of total phosphorus content, indicating that the phosphorus fertiliser effect of ash from oats should be good. A very low liming effect was given by ash from oats. [15].

13.1.3 RCG

The ash content of RCG varies, primarily depending on where it was grown. If the RCG was grown in a light soil, it has approximately the same ash content as wood fuel, about 2 %, while RCG from heavy clay soil has had up to 16 % ash content. This probably depends on the fact that RCG takes up more silicon from a clay soil. The low ash

content from RCG grown in light soil means that no ash feed adjustment is required, as is generally the case with other energy crops. Compared with straw ash, RCG contains more silicon and less potassium. The chlorine level is also significantly higher in straw compared with spring-harvested RCG. [8] [9]

The particles in RCG ash are larger and more irregular than in wood fuel ash. This means it is easy for the particles to entangle with one another and form small lumps. This phenomenon is probably caused by the high silicon level in RCG.

13.1.4 Willow

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13.1.4.1 Ash level

In an unpublished study by Ledin and Vigré (1993), sample willow shoots were taken from 28 commercial willow nurseries through Sweden. The ash level in these samples varied somewhat but had an average value of 1.6% with a scatter between 1.3% and 2.1%. (Figure 22, Ledin & Vigré, unpublished data). Some trend is seen in the data in terms of a decreasing ash level with increasing shoot age (Figure 22). The ash content correlated well with the calcium level in wood (Figure 23). The ash content in the study largely correlated with findings presented by Strömberg [25] from analysis of a relatively small number of chip samples.

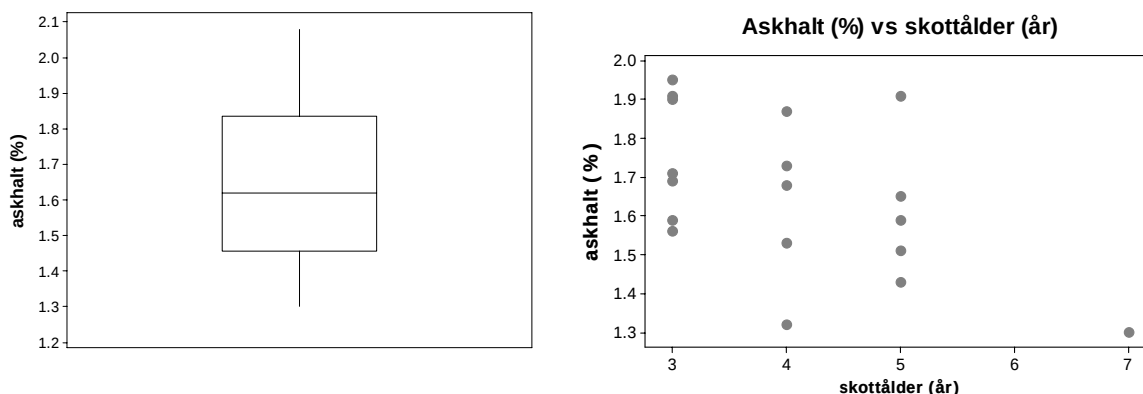


Figure 22. Ash content in 28 test samples of willow presented as median values with 25% quartiles (left) and ash content in the same samples plotted (right) against age of shoots (from Ledin & Vigré, unpublished data).

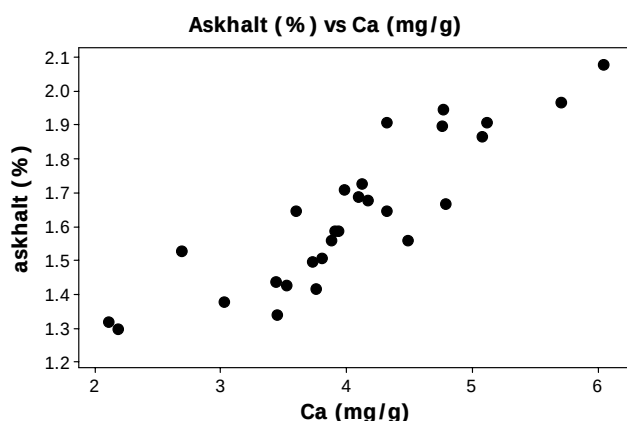


Figure 23. Correlation between calcium content in the wood and ash content in 28 test samples of willow (from Ledin & Vigré, unpublished data).

13.1.4.2 Ash composition

There are few studies of the chemical composition of ash from willow alone. Strömberg [24] presents data from a small number of willow analyses. This data shows that calcium and potassium are the predominating substances in the ash followed by silicon and phosphorus (Table 20). The presence of heavy metals was also found, primarily zinc and manganese but also copper and cadmium. If the ash is to be offered for sale as fertiliser, the cadmium level would present a problem since the cadmium level limit is 100 mg Cd/kg P, which is exceeded by a factor of 22 in Table 20 below.

Table 12. Chemical composition of ash from willow and the phosphorus ratio for each substance respectively

Element	P/X ratio	Level (mg/kg)
Al	17	2,170
Ca	0.15	243,000
Cd	450	82
Cr	1,850	20
Cu	315	120
K	0.30	123,000
Mg	1.6	23,300
Mn	18	2,030
Na	15	2,500
Ni	684	54
P	1	37,000
Pb	3,520	10
Si	0.40	93,200
Zn	12	3,140

In some studies the use of biofuel ash and/or digested sludge as a fertiliser substitute in willow nurseries has been looked at. However, it is not known whether any study has been made of the use of willow ash alone in willow nurseries or for any other crop

cultivation. In one study biofuel ash from the district heating plant in Enköping, undigested sludge and blends of these waste products were supplied to freshly harvested willow in central Sweden. [25] The purpose was to study both the fertilising effect and the balance of metals in the system. The use of large amounts of sludge/ash mixture resulted in a significant increase in pH in the upper soil layers probably caused by the ash's alkaline character but the use of the material did not affect the uptake of various metals in the willow. The raised pH was still seen after three years. The use of ash was consequently considered not to affect the wood or its ash in terms of the content of different substances. On the other hand the soil's content of all metals was considered to have increased somewhat with the exception of cadmium which is taken up by willow relatively effectively.

There are a number of international studies relating to the use of sludge as a fertiliser for willow. These are of limited value in terms of Swedish conditions as the amount of sludge used, and thus the amount of metals present, in the majority of the studies by far exceeds the limit values which have been applied in Sweden for many years now. When willow is used to actively extract heavy metals from soil, high metal levels can be demonstrated in the wood [27], which then affects the composition of its subsequent ash. This is however a very unusual situation and cannot be regarded as constituting a practical problem.

13.1.5 Hemp

Apart from the information that is given in Värmeforsk's "Fuel Handbook" ("Bränslehandboken") [25], there are no published results concerning the composition of hemp ash.

13.2 Ash handling

13.2.1 Ash out-feed

Ash-rich fuels like energy crops require feed ash out-feed equipment capable of handling the volumes involved. Large boilers always have automatic ash out-feed equipment but small boilers require frequent ash removal. The combustion of biofuels from energy crops in small boilers is best suited to boilers with automatic ash out-feed or a movable grate. [10]

When bottom ash falls out of a grate boiler, it is normally collected in a water bed. Wet transport of the ash from the boiler prevents the ingress of air to the combustion chamber and extinguishes any ash which is still glowing. The risk of the ash powdering on handling is also reduced through the use of a water bed. A scraper conveyor is normally used to transport the material to a screw which takes it further to a container. [1] [3] [11]

Handling of dry bottom ash is carried out using an ash screw which de-ashes the boiler via load cells to an ash holder. A screw conveyor then takes the ash to a container. [12]

Subsequent storage dries out the ash somewhat when the water evaporates and runs off. Leachate should be kept separate as it contains a very high concentration of salts and other pollutants from the ash. The ash should be also protected from rain while it is stored. [1] [12]

Both dry and wet systems perform satisfactorily from a technical point of view. Wet ash out-feed has, as referred to above, its advantages but it is also a source of problems due to the high level of pollutants in the water. Dry ash out-feed is more problematical in terms of operational disruption due to the de-ashing screw or load cells stopping. The risk is greatest when straw is being fired which has led to wet ash out-feed being predominating for straw firing. [12]

Fly ash is separated out using a cyclone or filter and sent via a screw conveyor to a chain scraper. For those plants which currently have experience of firing straw, fly ash and bottom ash are mixed. Analytical results from 23 district heating plants primarily firing grain, but also straw and oats' chaff, have shown that the increase in the levels of heavy metals is not such that separate handling of fly ash is necessary, as it can be mixed with bottom ash without any changes in quality. If fly ash contains levels of heavy metals which are too high, it should be landfilled. Methods for the extraction of heavy metals from ash have been researched in previous studies. [3] [11] [13] [28]

13.2.2 Ash hardening

A number of chemical reactions take place in ash when it is stored. In the presence of water, fast-reacting oxides convert to hydroxides. These form carbonates on contact with air and the ash hardens. The ash's liming effect increases with time and the risk of a pH shock effect when spread onto soil decreases. [1]

Hardening which takes place in wet ash directly after ash out-feed from the boiler has been observed to be relatively extensive. Ash which has hardened considerably can cause problems on spreading due to the presence of hard lumps. The ash should therefore be crushed before use to ensure it can be evenly spread. [1]

It can be difficult to harden ash which contains a large amount of unburnt material. This type of ash is water repellent. Spreading dry ash is not suitable because it is difficult to spread evenly on the land and it also contains reactive oxides which constitute a health risk on inhalation. The ash should therefore be humidified and a similar technique can be used similar to that used with wet out-feed from boilers. [1]

13.2.3 Pelletizing and granulation

No ash granulation or pelletizing of agricultural crops is currently carried out in Sweden. However, trials have been carried out in the forest industries with both the granulation and pelletizing of ash. Stora Enso and AssiDomän ran a full scale project on roll pelletizing of ash during 1999-2003 [19][21]. The study showed that full-scale roll pelletizing worked well and there was no need for further development work on the roll pelletizing principle. Research workers at the Engineering Faculty of Lund University together with Kemira carried out trial on the granulation of ash. Reasons for granulating ash

include facilitating ash handling and improving the uniformity of the product. [29]. Ash in powder form soon shows a beneficial effect on forest land while hardened and granulated ash are generally less water soluble and easy to handle. [20]

The fertiliser substitute efficiency of straw and sludge was studied in a basic research trial in Denmark in 1994. [17]. The straw ash and sludge were spread in different forms: unmodified and after drying, both in a powdered and a granulated form. The trial showed that there was less available phosphorus in the modified material compared with the unmodified ash and sludge.

Pelleting or granulation is essential to enable a farmer to be able to spread fertiliser in an amount representing the crop's annual fertiliser requirement.

It is difficult to avoid multi-year fertilisation when spreading unmodified ash. Pelleting or granulation are essential when spreading amounts representing the annual requirement.

13.3 Spreading technique

The majority of grain ash currently comes from smaller farmyard waste treatment plants where the ash is spread as part of the overall fertilisation programme. [15]. The spreading of ash from energy crops is not covered by environmental protection legislation. In the absence of specific guidelines for ash from energy crops, the limit values applicable to fertilisers and sewage sludge can be used as a starting point. Ash from biofuels may not be used in admixture with permitted fertilisers for farm production intended to comply with the Swedish Seal of Quality, Svenskt Sigill. [23]

Spreading tests with ash from energy crop fuels has mostly been carried out using traditional farm machinery used for spreading manure and lime. Examples of machinery which has been used both in the spreading tests and on the farms include different types of manure spreaders and lime spreaders. Spreaders designed for spreading with commercial fertilisers require the ash to be in granular form.

The spreading tests have shown that the field application pattern is strongly influenced by the ash's characteristics. [14]. Ash containing sintered lumps, for example, gives a variation in the spreading pattern. This uneven pattern is emphasised by the fact that the sintered lumps release nutrients slower compared with finely divided ash powder. Ash storage also influences spreading characteristics and with dry ash in dust form, for example, wide spreading can be difficult. [15] Ash handling can be made easier by mixing with liquid fertiliser, for example.[16]

The need for even spreading has to take account of the purpose for which the ash is being used. If the ash is being applied as multi-year fertilisation or for liming, the effect of uneven spreading is less than when the purpose is just to apply the annual requirement.

13.4 Crops which can be grown after ash spreading

As part of a study in 1989, crop trials were carried out with spring grain, potatoes, peas, oil crops and lettuce using wheat straw ash as fertiliser. [13] The ash was applied in pot

trials and the amount added corresponded to 2, 4 and 10 tonnes per hectare together with a control where no ash was applied. The results from the trial showed that the pH rose with an increasing amount of ash in the pots. None of the crops showed evidence of deleterious effects due to the use of ash as a fertiliser.

It would be interesting to carry out more field trials with energy crops and to investigate how they react when fertilised with different ashes from bioenergy crops from arable farming.

13.5 Emissions and environmental impact from handling and use

Since ashes generally have a high pH, they have to be ploughed in on land which is not under cultivation or, if perennial crops are involved, immediately after harvesting. [16] In this way, effects damaging to the plants and shoots are avoided. To avoid plant nutrient levels which are too high and to use plant nutrient substances optimally, not more than 1-2 tonnes ash should be spread per fertilisation, according to a report from Energigården, the Centre for Bioenergy in Norway, (2007) [15]. This dosage is estimated to be sufficient for four to eight years.

A rise in the soil pH results in increased nitrification which in turn can lead to increased nitrogen elution. When lime is applied to soil to raise the pH, it is done on uncultivated land in the autumn, which is considered to be an acceptable risk as regards nitrogen elution. The same should be applicable to ash from straw fuel. [16]

According to Hadders & Flodén (1997) spreading dry ash is unsuitable because it contains reactive oxides which constitute a health risk if inhaled. [16]

13.6 Economics

Ash from field crops is handled as a waste product and is not at the moment sold in Sweden as a fertiliser. It would be interesting to investigate the opportunities which may exist for producers of ash from field crops to be able to sell ash as a fertiliser. Physical processing of ash would make it more competitive as a fertiliser.

13.7 Current research

The Department for Biometry and Engineering (BT) at the Swedish University of Agricultural Science and the Swedish Institute of Agricultural and Environmental Engineering (JTI) have a project entitled “Addition of ash to anaerobic rotted waste”. The purpose of the work is to study techniques and systems for adding ash to anaerobic rotted waste. The work covers laboratory measurements and spreading trials in the field. The laboratory measurements have been carried out with the following conclusions: adding ash to the rotted waste did not increase the release of ammonia, the ashes contain a lot of abrasive material with a consequent risk of increased wear in the spreading equipment, that there is a considerable risk of troublesome sediment forming in the spreader tank and that only a small proportion of straw and oats’ ashes are water soluble. The project will be concluded in March 2008.

13.8 References

- [1] Hadders G & Flodén S; "Spridning av aska från stråbränslen på åkermark, Förutsättningar och rekommendationer", JTI-rapport Lantbruk & Industri Nr 234 1997
- [2] Vetter A; "Qualitätsanforderungen an halmgutartige Bioenergieträger hinsichtlich der energetischen Verwertung", Gülzower Fachgespräche Band 17 Energetische Nutzung von Stroh, Ganzpflanzengetreide und weiterer halmgutartiger Biomasse Tautenhain May 2001, 36-49
- [3] Bernesson S & Nilsson D; "Halm som energikälla", Rapport – miljö, teknik och lantbruk 2005:07 Uppsala 2005
- [4] Hartmann H; "Die energetische Nutzung von Stroh und strohähnlichen Brennstoffen in Kleinanlagen", Gülzower Fachgespräche Band 17 Energetische Nutzung von Stroh, Ganzpflanzengetreide und weiterer halmgutartiger Biomasse Tautenhain May 2001, 62-84
- [5] Brökeland R, Bühl R & Hiendlmeier S; "Heizen mit Energiekorn" C.A.R.M.E.N. August 2006
- [6] Hadders G, Arshadi M, Nilsson C & Burvall J; "Bränsleegenskaper hos spannmålskärna, betydelsen av jordart, sädesslag och sort", JTI-rapport Lantbruk & Industri Nr 289 2001
- [7] Rönnbäck M & Arkelöv O; "Tekniska och miljömässiga problem vid eldning av spannmål – en förstudie", SLF January 2006
- [8] Johansson H; "Resultat av forskningsprogrammet Stråbränsle" Stockholm May 1997
- [9] Paulrud S, Nilsson C; "Briquetting and combustion of spring-harvested reed canary-grass: effect of fuel composition", Biomass and Bioenergy 20 2001, 25-35
- [10] Burvall J; "Rörflen som bränsleråvara", Fakta Teknik, Nr 1 1997
- [11] Nikolaisen L (ed); "Straw for Energy Production – Technology - Environment - Economy", andra upplagan The Centre for Biomass Technology Köpenhamn 1998
- [12] Hansen M T; "Separation og genanvendelse af aske fra biobrændselanlæg" Miljøministeriet Miljøprojekt Nr. 962 2004
- [13] Marmolin C, Gruvaeus I, Ugander J, Lundin G; "Återföring av aska från bioenergigrödor odlade på åkermark", Energigården 2006
- [14] Carlfelt, M.; *Halmaska som gödselmedel: Effekt på tungmetallupptag vid odling av jordbruksgrödor*, Sveriges Lantbruksuniversitet, Institutionen för ekologi och miljövard, rapport 36, Uppsala, 1989
- [15] Flodén, S.; Spridning av aska från stråbränsle med spridare från stallgödsel, JTI-rapport 211, Uppsala, 1995
- [16] Gruvaeus, I., Lundin, G., Marmolin, C. & Ugander J.; *Återföring av aska från bioenergigrödor odlade på åkermark*, Energigården Slutrapport, Hushållningssällskapet och JTI, 2006

-
- [17] Hadders, G. & Flodén, S.; Spridning av aska från stråbränslen på åkermark – Förutsättningar och rekommendationer, JTI-rapport 234, Uppsala, 1997
 - [18] Hansen, J.F. & Kjellerup, V.; Gødningsevirkning af fosfor og kalium i slam og i halmáske. Rammeforsøg. SP-rapport nr 14, Landbrugsministeriet Statens Planteavlsforsøg, 1994
 - [19] Hansen, M.; *Separation og genanvendelse af aske fra biobrændselanlæg*, Miljøministeriet, Miljøprojekt nr 962, 2004
 - [20] Högbom, L., Lövgren, L. & Nordlund, S.; *Rapport Etapp 2 – Miljöeffekter i skogen vid spridning av valspelleterade askprodukter*, Statens energimyndighet, projekt P11647-1, Stora Enso Environment och SkogForsk, Uppsala, 2003
 - [21] Lundborg, A.; Retur av aska från skogsbränslen. Bioenergi 6/1997, s.35-37
 - [22] Lövgren, L., Lundmark, J-E. & Jansson, C.; *Rapport Etapp 1 - Kretsloppsanpassning av bioaskor. Utvärdering av ny teknik för pelletering av bioaska med avseende på dels driftsegenskaper, dels miljöeffekter i skogen av askåterföring*, Statens energimyndighet, projekt P11647-1, Stora Enso Environment och AssiDomän AB, Falun, 2000
 - [23] Sander, M.L. & Andrén, O.; Ash from grain and rape straw used for heat production: Liming effect and contents of plant nutrients and heavy metals. Water, Air and Soil Pollution, vol 93, issue 1-4, s. 93-108, Dordrecht, 1997
 - [24] Svenskt Sigill; Handbok för IP SIGILL Gård 2007, s. 19-20, Stockholm, 2007
 - [25] Strömberg, B. Bränslehandboken. Värmeforsk. F-324. ISSN 0282-3772. Stockholm, 2004.
 - [26] Dimitriou, I., J. Eriksson, A. Adler, P. Aronsson T. Verwijst, 2006. Fate of heavy metals after application of sewage sludge and wood-ash mixtures to short-rotation willow coppice. Environmental pollution 142 (1) 160-169.
 - [27] Aronsson, P. & Perttu, K. 1994. Willow vegetation filters for municipal wastewaters and sludges - a biological purification system. Swed. Univ. Agric. Sci., Department of Ecology and Environmental Research, Report 50. ISBN 91-576-4916-2. Uppsala, Sweden.
 - [28] Wikman, K., Berg M., Bjurström H., Nordin A; ”Termisk rening av askor”

13.8.1 Personal communications

- [29] Marmolin, C.; Miljörådgivare vid HS Skaraborg, 2006

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