A two-stage pyrolysis/gasification process for herbaceous waste biomass from agriculture

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ABSTRACT: Cereal straw and strawlike residues from agriculture can contribute a small but significant share of about 5% to the world primary energy supply. Straw is among the cheapest renewables, because it is reliably available as a by-product of food-production without additional cultivation and harvest expenses. But straw is far more difficult to manage technically than wood and therefore hardly used for energy generation. As all fast growing biomass, straw contains more ash, potassium, chlorine and other heteroatoms; the low ash sintering temperature can cause reactor slagging due to baking and sticking of the reaction material. Gasification technologies are expected to be superior to combustion in view to flexibility, efficiency and environmental compatibility. Wood gasifiers are not suited for straw. Straw gasifiers are not available on the market, but the large amounts of residual straw justify a special development.

On the basis of a systematic analysis of various gasifier types and experience on straw gasification reported in the literature, we have selected a two-stage pyrolysis/gasification process for further development, which especially takes care of the particular straw properties. The first step is an allothermal pyrolysis of straw chops in a fluidised bed of sand, followed by a second autothermal gasification step with oxygen or air at higher temperature. Various chemical and engineering aspects of the process and its many variants are being studied in a number of test facilities. The final aim of these experiments is the collection of design data for a pilot plant.

1. ENERGY FROM AGRICULTURAL BIOMASS RESIDUES

The consumption of fossil fuels is not sustainable. With business as usual, the proven and economically recoverable fossil reserves will be exhausted in little more than 100 years. Substitution of fossil fuels is therefore required anyway on the long term. If CO₂ emission from fossil fuel combustion is responsible for adverse climate changes like global warming, substitution is desirable on the short term. The share of the renewable energy sources like wind, hydropower and biomass may be increased in a relatively short time. Each of these traditionally well known sources can contribute a significant part to our primary energy supply. A crude estimate of the energy potential of biomass, especially for the agricultural biomass residuals like straw and strawlike materials is given in the following sections.
1.1 PRESENT AND FUTURE ENERGY CONSUMPTION

An estimate of the world primary energy consumption can be obtained by multiplication of the world population with the energy consumption per capita (see Fig. 1). The present world population of 6 billion consumes an energy of 12 Gt of carbon equivalent\(^1\) (not coal) per year; this corresponds to an average of 2 tonnes of carbon per capita and year. The per capita consumption in most industrialised countries is usually 2 to 3 times higher than the average. The rapidly growing world population is predicted to arrive at about 9 billion in 2050 and to stabilise at around 10 billion towards the end of the new century. If the average energy consumption per capita and year increases only slightly from 2 to 2.4 t/y carbon equivalent – this is about half the present level in Europe – the world energy consumption will be doubled to 24 Gt carbon equivalent per year.

Almost 80% of our present energy mix comes from fossil fuels; the rest is renewable and nuclear energy. In fig. 2, the biomass contribution is summarised among the solid fuel share, together with coal. Today, biomass still contributes about 10% to the world primary energy supply; commercially traded firewood amounts to almost half of this share.

\[\text{Energy conversion factors: } 1 \text{tC (tonne carbon equivalent)} \approx 1.12 \text{tce (coal equivalent)} \approx 0.77 \text{toe (oil equivalent)} \approx 2 \text{t biomass (daf = dry and ash free)}\]

The Kyoto conference agreement in 1997 imposes legally binding obligations on its international signatories to reduce the greenhouse gas emissions. For the European Union (EU) this implies an 8% reduction until 2010 in comparison with 1990 levels. Emission of fossil CO\(_2\) is responsible for about half of the greenhouse effect. If we gradually consume all proven and economically recoverable fossil coal, oil and gas reserves (with ca. 1400 Gt carbon content) as usual, the present CO\(_2\)-level of 367 ppmv in the atmosphere will be about doubled. If we continue to consume also some less economic ultimate reserves, a CO\(_2\)-level of 0.1 %vol. will be quickly approached.

\(^1\) Energy conversion factors: 1 tC (tonne carbon equivalent) corresponds to \(\approx 1.12 \text{tce (coal equivalent)} \approx 0.77 \text{toe (oil equivalent)} \approx 2 \text{t biomass (daf = dry and ash free)}\)
It has been proposed as a transitional solution, to recover CO₂ from the flue gas of large fossil fired power stations and to dispose it of in the deep sea or empty gas or oil fields [6]. But the development and implementation of such transitional technologies takes much time and money and the real application consumes a considerable fraction of the energy produced. There is some doubt, if such measures are really useful. The only sustainable solution to the CO₂-problem, is the development and use of all reasonable renewable energy sources. The EU for example intends to double the share of renewables from 6% (3% biomass, 90% from forestry (Ph.C.P Chartier et al. in Ref. 1 p. 62)) today to 12% until 2010, as an essential contribution to achieving the Kyoto objectives. The major part of this increase is expected to come from biomass.

## 1.2 ENERGY POTENTIAL OF BIOMASS

The global biomass production in the various ecosystems of the earth is summarised in fig. 3, based on data given in [7]. The total harvestable biomass production amounts to about 65 Gt C-equivalent per year. About 38% (ca. 25 Gt C/y) is produced in the oceans and not considered for energy generation for various reasons. About 62% of all biomass (ca. 40 Gt C/y) is produced on land. Since about 34% of the land area are deserts, the average productivity of the fertile land area is about 1 kg air-dry biomass (0.4 kg carbon equivalent) per m² land area and year, with a large scatter of factor 3. This corresponds to a low photosynthetic efficiency between 0.1 and 1%. Though photovoltaic cells are 10 to 100 times more efficient per m², harvest, combustion or gasification of biomass is still a more cost-effective power generation possibility.

Almost 70% of the land biomass is produced in forests (ca. 27 Gt C/y). The major part of the production are falling and rotting leaves etc.; the valuable wood and woody parts make up only about a quarter or less. With a world forestry management including afforestation, a sustainable wood harvest of about half of the up-growth can be expected. This corresponds to an about three-fold increase compared to the present production of timber plus commercial firewood (ca. 2 Gt/y).
Fig. 3: Global biomass production in the various ecosystems

Agriculture comprises arable land and grasslands with 10% and 15% of the land area respectively; the percentage contribution to the land biomass production corresponds to 11% to each part (ca. 4.2 Gt/y C-equivalent). The main products are human and animal food. In the course of the next 50 to 100 years, food production has to increase in proportion to the population from 4.2 Gt/y C for 6 billion today to about 7 Gt/y C for an almost 10 billion population. This aim can be achieved by a combination of (1) an increase of the arable land area and (2) a productivity increase with the help of fertilisers etc.

1.3 ENERGY POTENTIAL OF CEREAL STRAW

One part of the agricultural harvest are crops and the other part are by-products. By-products are only partly used and a substantial fraction will be available for energy generation without additional cultivation and harvesting expenses. Specially grown energy crops are more expensive than the agricultural by-products.

A rather simplified breakdown of the total agricultural harvest of 4.2 Gt C-equivalent is outlined in fig. 4. Half of the arable land (total 14 million km²) is cultivated for cereals: wheat, rice, maize and barley make up about 90% of all grain. The known world grain harvest in 1998 amounts to 2.1 Gt. From the average grain/straw ratio of ca. 1, the world straw harvest can be estimated to be about the same. From present practice it is known, that about half of the straw harvest is not required as litter, coarse fodder or humus for soil improvement. The long stubble and the roots left in the field are usually sufficient for humus formation. In a number of Danish district heating plants, about 20% or 1 Mt of the Danish straw harvest is already used for space heating. An extension to 50% is thought to be possible [M.G.Larsen in Ref. 1, p.1196]. Therefore, about 1+ Gt/y of air-dry (15% water) cereal straw and unused residues will be available for energy generation. The energy content (LHV 4 kWh/kg) is equivalent to 0.44 Gt C or about 3.7% of the present world primary energy consumption.
The harvest on the other half of the arable land comprises a large diversification of different food crops and also some raw materials like cotton. For a crude first estimate, the energy potential of the total biomass harvest as well as the product/by-product-ratio are assumed to be similar to the grain/straw harvest. Examples for by-products are leguminous and rapeseed straw, sunflower and cotton stalks, sugar cane bagasse and many others. Many of these agricultural residuals are also suited for energy generation and some of them have a considerable local importance like sugar-cane bagasse in Brazil. Due to the large diversification of these herbaceous biomass by-products, we assume, that an energetic utilisation of only 16% of the total amount is justified for practical reasons. This is equivalent to 0.14 Gt C/y or 1.2% of the present primary energy consumption.

A small additional contribution may be expected in form of dry grass, roadside and spoiled hay, which is unsuited as animal food. A small contribution from 3% of the grassland area results in 0.12 Gt/y C (3% from 4.2 Gt C total grass up-growth per year) or 1% of our present primary energy consumption.

### Table 1: Estimate of the potential energy contribution from agricultural by-products

<table>
<thead>
<tr>
<th>World population</th>
<th>cereal straw</th>
<th>herbaceous biomass</th>
<th>unsuited hay</th>
<th>total contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 billion</td>
<td>0.44</td>
<td>+ 0.14</td>
<td>+ 0.12</td>
<td>0.70 Gt C/y</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>this is equivalent to 5.8% from 12 Gt/y primary energy consumption</td>
</tr>
<tr>
<td>10 billion</td>
<td>0.74</td>
<td>+ 0.28</td>
<td>+ 0.12</td>
<td>1.14 Gt C/y</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>this is equivalent to 4.8% from 24 Gt/y primary energy consumption</td>
</tr>
</tbody>
</table>

The crude estimate for the energy potential of all agricultural by-products can be summarised as follows (see also fig. 4): They can contribute a small but significant share of about 5% to the world primary energy supply. Different to the potential biomass energy from forestry, the contribution grows about in proportion to the population. Half of the cereal straw harvest makes up almost two third of this contribution. The potential energy contribution of wood from forestry is expected to be 2 to 3 times higher than the contribution from agriculture. In view to the energy potential of the CO₂-neutral biofuels, straw ranges in a second position behind wood. The large amount and the uniformity of straw justify a special technology development for an optimum energetic utilisation.
2. SELECTION OF A STRAW GASIFICATION PROCESS

2.1 SPECIAL PROPERTIES OF STRAW

In the following sections, “straw” is used as a synonym for all herbaceous, thin-walled and rapidly drying biomass with a low water content. Only dry biomass is storable without biological degradation. Compared to firewood, straw and herbaceous by-products from agriculture have some unpleasant properties. Straw bales have a low storage density of about 0.1 t per m³ (straw chops ca. 0.05 t/m³), transport and storage become more expensive. The composition is a more serious and general aspect. The large organic lignocellulosic CHO-fraction of straw or wood is almost the same. This dry, ash- and heteroatom-free (dahf) biomass part can be represented by a simplified stoichiometric formula \( C_3(H_2O)_2 \) (MW 72); formally an equal weight mixture of carbon and water with a slightly higher gross heating value (5 kWh/kg).

But all rapidly growing biomass, such as grass, cereals, leaves etc. contains more ashes and heteroatoms such as N, S, Cl, alkali and others, than wood. Ash constituents and volatile heteroatoms are needed in larger concentrations for a fast growth. Especially the ash-, K- and Cl-contents in herbaceous biomass can be higher up to one order of magnitude than in wood without bark. A typical composition of wood and straw is compared in table 2 [9, 10].

Table 2: Typical percentage composition of straw and hay compared to willow wood.

<table>
<thead>
<tr>
<th>dry biomass heating val.</th>
<th>CHO-fraction</th>
<th>heteroatoms</th>
<th>ash constituents</th>
</tr>
</thead>
<tbody>
<tr>
<td>MJ/kg</td>
<td>C   H   O   N   S   Cl   K₂O  P₂O₅  CaO  ash</td>
<td></td>
<td></td>
</tr>
<tr>
<td>willow wood</td>
<td>18.4</td>
<td>49.8</td>
<td>6.5</td>
</tr>
<tr>
<td>dahf** (calculated)</td>
<td>50.8</td>
<td>6.6</td>
<td>42.6</td>
</tr>
<tr>
<td>wheat straw</td>
<td>17.5</td>
<td>46.7</td>
<td>6.3</td>
</tr>
<tr>
<td>dahf (calculated)</td>
<td>49.6</td>
<td>6.8</td>
<td>43.6</td>
</tr>
<tr>
<td>hay</td>
<td>16.4</td>
<td>45.0</td>
<td>6.2</td>
</tr>
<tr>
<td>dahf (calculated)</td>
<td>49.6</td>
<td>6.8</td>
<td>43.6</td>
</tr>
<tr>
<td>( C_3(H_2O)_2 )</td>
<td>~18.2</td>
<td>50</td>
<td>5.6</td>
</tr>
</tbody>
</table>

*< 1% without bark, **dahf: dry, ash- and heteroatom-free

In particular, technical difficulties of straw combustion or gasification are caused by the higher ash and heteroatom contents, especially chlorine and potassium:

- The high HCl- concentration in the fuel gas is the cause of (1) corrosion problems,
  (2) catalyst poisoning in the gas cleaning system and (3) PCDD/F-formation on the
  surface of entrained dust particles during fuel gas combustion.
- K lowers the ash sintering temperature, eventually down to 700°C. This creates the
  risk of reactor slagging by sticky and glueing ash particles.
- Volatilisation of alkali compounds like KOH or KCl at temperatures above 600 to
  700°C causes deposition, plugging and corrosion problems by desublimation during
  cooling down in the piping downstream.

Thermal treatment technologies for wood are usually not designed to control these special effects.
2.2 GASIFICATION VERSUS COMBUSTION

A thermochemical conversion of a solid biofuel into a fuel gas is an additional operation prior to application, which can be justified by a more efficient and flexible use of the cleaner gas. The pollution and flue gas cleaning problems from direct combustion of dirty coal are expected to be reduced by more efficient and environmentally compatible integrated gasification combined cycle (IGCC) processes. This strategy for an advanced utilisation of fossil fuels is also suited for solid biofuels like the relatively clean wood, as it is even more suited for the dirtier cereal straw and related herbaceous bio-materials.

Compared to a simple high temperature heat generation via combustion, a combustible fuel gas is suited for many different applications. The required fuel gas cleaning efforts depend on the final utilisation. Moderate purity requirements are connected to a special application such as a

- **reduction gas** e.g. for ore reduction
- **fuel gas for high temperature process heat** generation in cement kilns; lime- or brick furnaces or during glass production.

Higher fuel gas purities in view to dust, tar, HCl, SO₂, alkali etc. are needed for

- **power and electricity generation** in turbines or diesel and otto internal combustion engines

The highest fuel gas purities are required for catalysed processes, since many catalysts are sensitive to a number of trace impurities in the gas

- **syngas or hydrogen** for the production of methanol, hydrocarbon fuels, ammonia or H₂ for electricity generation in low temperature fuel cells (PEMFC) at ~ 80°C and phosphoric acid fuel cell (PAFC) at ~ 200°C. High temperature fuel cells like the solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC), operating at 1000°C and 600°C respectively, tolerate CO and hydrocarbon vapours, but are sensitive to various trace impurities like HCl, H₂S, alkali etc.

2.3 EVALUATION OF STRAW GASIFICATION TECHNOLOGY

Wood gasifiers are state of the art. In view to a reliable long term operation of turbines or internal combustion engines with a fuel gas, there are still some remaining problems with the high tar content in the gas. Technology for straw gasification is not well developed. Straw gasifiers are not yet available on the market. In gasifiers originally designed for wood or waste, straw has been used occasionally and in most cases in a mixture together with other solid fuels. Further details and references are found in [1-5, 18, 19]. The suitability of the basic gasifier types for straw gasification has been evaluated in a FZK-study [11]. The basic gasifier types considered are fixed-bed, fluidised-bed and entrained flow gasifiers.

**Fixed bed gasifiers** are simple and easy to operate with larger wood pieces but not with chopped straw. This will block the gas flow. The production of larger straw pellets or briquettes is a available technology, but pelletisation costs of 25 to 50 Euro per ton are too high. A sufficiently fast gasification requires temperatures ≥ 800°C and even for straw pellets, the risk of ash sintering and reactor slagging can not be completely eliminated. The high thermal efficiency of an updraft gasifier (counter-current flow) is connected with a low fuel gas temperature and a high tar content >10 g per m³.
A downdraft gasifier (co-current flow) has a lower tar content < 0.5 g per m³ fuel gas, but is thermally less efficient.

Gasification in the flame of an *entrained flow gasifier* proceeds in ≤ 1s at high temperatures of ≥ 1300°C. Precondition for an efficient conversion is, that the fuel can be milled to a fine ≤ 0.1 mm powder. This is easy for brittle coal, but complex and expensive for biomass with cellulose fibres, like straw. In the very hot fuel gas the tar content is rather low and a molten slag is obtained. The large amount of sensible heat must be recovered and recycled afterwards to achieve a good cold gas efficiency > 70% (LHV of cold fuel gas/LHV of initial fuel). Cooling-down of the fuel gas may also become necessary for efficient gas cleaning, since efficient hot gas cleaning procedures are not yet available.

Gasification in a *bubbling or circulating fluidised bed* of sand must be conducted at ≥ 800°C in order to achieve a sufficiently fast gasification. At such temperatures, the low melting potassium salts in the straw ash were found to cause bed agglomeration and breakdown of fluidisation [12].

None of the common gasifier types is really suited for straw chops. The main reasons are either the expensive straw preparations steps (pelleting, briquetting, milling) or the high risk of reactor slagging, due to the low ash sintering temperature in the presence of much K.

### 2.4 TWO-STEP STRAW GASIFICATION CONCEPT

![Fig. 5: Two-stage process concept for straw gasification](image)

In response to the considerations of the previous section, a FZK study group has selected the two-step straw gasification concept in fig. 5 as a good basis for the further development of straw gasification [11]. Only cheap straw chops are considered as feed, whereas reactor slagging by sintering ash is avoided with a two-stage concept. In general, gasification and combustion are always preceded by a pyrolysis step. There is a number of newly developed gasification processes for municipal and hazardous wastes [13, 14] and solid biofuels [15, 16], which also make use of a separate pyrolysis reactor prior to gasification.

The **first step** of the straw gasification concept, is an *allothermal pyrolysis* of chopped straw in a fluidised bed of sand at temperatures below the ash softening temperature of about 700°C. Steam can be added to sustain bed fluidisation and to reduce...
tar formation. The allothermal reaction mode in combination with the excellent heat transfer in a fluidised bed, permits the recycle of heat to improve the process efficiency and simultaneously reduces the O₂-consumption during fuel combustion in the following gasification step. Allothermal gasifiers are less common, but have been studied extensively within the framework for the use of nuclear process heat for gasification [17].

The second step is an autothermal gasification of the pyrolysis gas and the solid pyrolysis char at temperatures above 800°C after partial combustion with air or oxygen. The pyrolysis char carries the whole ash and must be separated from the bed material prior to gasification. Straw char is a rather brittle material and is easily crushed to a fine powder, which gasifies faster. After a relatively fast pyrolysis step the pyrolysis gas contains > 50% of the energy.

3 CHEMICAL AND ENGINEERING ASPECTS

3.1 MASS AND ENERGY BALANCES

Mass and energy balances are obtained from stoichiometric reaction equations. For the preparation of the pyrolysis equation, the product spectrum must be known experimentally. The same is true for gasification, except for very high temperatures, where thermodynamic equilibrium is attained.

Pyrolysis in inert atmosphere between 400 and 700°C produces water vapour, CO₂, combustible gases CO, H₂, CH₄ and a multitude of organic vapours from the biopolymers cellulose (C₆(H₂O)₅), hemicellulose (C₅(H₂O)₄) and lignin. An impression of the complex product spectrum especially of the condensable organic vapours is given in fig. 6. The remainder is a black char, mainly consisting of carbon and inorganic ash oxides.

Fig. 6: Condensable organic CHO-vapours

The following examples of pyrolysis equations are oversimplified, but show the essentials. The simplified formula C₅(H₂O)₂ (MW 72) represents the dahf-composition of the organic part in wood, straw or any other lignocellulosic biomass.

CHO-intermediate:  
C₅(H₂O)₂ → C + HOCH₂-CHO \[ \Delta H = +102 \text{ kJ/mol} \]

biomass (dahf) char tars, oils  
Gas production can be exothermal with CO₂ and CH₄ as products or endothermal with CO and H₂ as products. Since both reactions proceed simultaneously, pyrolysis can be almost thermoneutral. Most of the energy is then required to heat up the feed material to the pyrolysis temperature.
3.2 KINETICS OF STRAW PYROLYSIS AND GASIFICATION

Heterogeneous kinetics of straw pyrolysis and straw gasification are essential data for reactor design. Pyrolysis is a relatively fast process. In view of the poor heat conduction of straw and straw char, the pyrolysis time is the time which is required to heat the center of the particle to the decomposition temperature. This is a rather simplified model, but allows a reasonable time estimate in view of the order of magnitude.

For an experimental determination of the pyrolysis time, a fluidised bed of sand and a large volume hot vessel have been used [20]. The method for reaction rate measurements in the fluidised bed is partly explained in fig. 7. The pyrolysis gases in the fluidising nitrogen gas stream are combusted after O_2-addition downstream from the vessel and the CO_2 plus some CO are monitored with NDIR-analysers. Thus, the course of a slow pyrolysis has been followed with a time resolution of several seconds. After pyrolysis, the O_2 is added upstream from the fluidised bed and the combustion of the pyrolysis char can be followed in the same way. The equipment is calibrated by injection of a known CO_2-volume to the bed. Area and time response of the resulting calibration signal are needed for data analysis.

Pyrolysis kinetics for cylindric 12 mm diameter straw pellets in a fluidised bed of sand at different temperatures are shown in fig. 8. The long pyrolysis times around 100 s are a consequence of the large particle dimension. This demonstrates, that pellettisation is not an advantage: it is expensive and destroys the high reactivity of untreated straw with thin ca. 0.5 mm thick walls.

Fig. 7: Concept for pyrolysis and combustion rate measurement in a fluidised bed of sand [20]
Fig. 8: Pyrolysis kinetics for cylindric 12 mm straw pellets in a fluidised bed [20]

At comparable temperatures, the pyrolysis of straw chops proceeds more than 10 times faster than straw pellet pyrolysis. This is demonstrated in fig. 9. Small cm-sized single walled straw chops have been added to a large preheated steel vessel with a sand layer at the bottom. The pyrolysis gases quickly displace a certain amount of inert gas in the thermostated vessel. The released inert gas is collected in a burette, whose level

Fig. 9: Generation of pyrolysis gases during straw chop pyrolysis
is observed with a TV-camera. A time resolution of \(< 0.1 \text{ s}\) has been obtained in this way. Fig. 9 shows, that the pyrolysis times at \(\geq 600^\circ\text{C}\) are less than 10 s. Nodes in the straw stem halm must be squeezed to maintain short reaction times.

![Arrhenius diagram for combustion and CO\(_2\)-gasification of straw char in comparison to other chars (thermobalance data for a char particle size of 50 \(\pm\) 10\(\mu\text{m}\)][20]](image)

In the Arrhenius diagram in fig. 10 the straw char reactivity is compared to some other chars. Compared to the other chars the combustion reactivity of the straw char is relatively high, but this fact is not reproduced during gasification in CO\(_2\). This is astonishing. The straw char contains the intrinsic ash with much potassium, which is reported to be a very efficient gasification catalyst.

### 3.3 BEHAVIOUR OF POTASSIUM AND CHLORINE

Most of the particular difficulties of straw gasification are caused by the high K and Cl-content. The behaviour of these impurities in the successive process steps is therefore of special importance. The selection of a method for their removal is a major process decision. Chlorine volatilisation starts at relatively low pyrolysis temperatures of about 200\(^\circ\text{C}\). About half of the chlorine can be removed into the pyrolysis gas up to about 500\(^\circ\text{C}\). The rest of the HCl is volatilised together with the potassium at higher temperatures. At lower pyrolysis temperature, K can be kept completely within the char particles together with the residual ash, but the chlorine distributes between char and gas.

K and Cl can be completely leached from the straw with hot water in an additional pre-treatment step [8]. We have found that the straw soaks somewhat more than its own weight of water; about 2 m\(^3\) of waste water per ton of straw with ca. 1\% KCl will be generated even in an optimum countercurrent washing process. Concentration or distribution of the lean salt solution and drying of the soaked wet straw chops are expensive additional operations.
If the fresh yellow straw is left in swaths on the field after harvest for about two months, ≥ 150 mm of rain will wash out most of the K and Cl. There are logistic problems connected with this method and also the reduction of the K and Cl content is not reliable enough.

The K and the residual half of the chlorine can also be leached from the straw char with hot water in the same way. If K and Cl are not completely removed prior to the high temperature gasification step, they are routed into the hot fuel gas in the form of volatile KCl and other volatile alkali salts. These salt vapours can be removed in a specially designed desublimation step in combination with the recovery of the sensible heat from the fuel gas.

3.4 FLOWSHEET OPTIONS

Based on the two-stage concept with allothermal pyrolysis and autothermal secondary gasification, a large number of process variants can be generated. The selection of a simple and reliable process variant with regard to the type and design of the major components, suitable operating conditions and a good cold gas efficiency requires the accumulation of sufficient specific experimental experience with straw. The simplified process flowsheet in fig. 11 represents just one of the favourite flowsheet options, which are still under investigation.

Some options are summarised in the following. The basic two stage concept can be realised in two separate reactors or in a single reactor vessel with pyrolysis and gasification proceeding at two different sites. Pyrolysis gas and pyrolysis char may be gasified together, in two separate steps or the char may be separated and utilised for other purposes. Pyrolysis can be performed in a bubbling, circulating or a mechanically fluidised bed either with or without additional steam. Air or oxygen can be used for gasification. Cl and K can be removed prior to gasification by straw or char leaching.
with hot water in an additional pre-treatment step. Recuperators or regenerators can be used to recover the sensible heat from the syngas. The pyrolysis bed can be heated internally or externally in a recycle loop. The possible flowsheet options are certainly not limited to the above examples.

One central step considered in all flowsheet options, is an entrained flow gasifier operating at a flame temperature up to 1500°C. The hot tar-free syngas generated in the gasifier flame should be quenched with crushed char powder (not shown in the flow-sheet) to increase the cold gas efficiency by chemical quenching [16].

4 CONCLUSION AND OUTLOOK

Cereal straw, (wheat, maize, rice, barley) is among the cheapest renewables. The energy potential of straw and some related herbaceous biomass residuals from agriculture can contribute about 5% to our primary energy supply. This is a significant biomass contribution and straw holds a second place behind wood. Straw contains more ash, K and Cl than wood, therefore it is more difficult to manage technically. Compared to combustion, gasification is expected to be more flexible, efficient and environmentally compatible. Gasification technologies for straw are not well developed. Yet, the large amount of unused residual justifies the development of a special technology for optimum energetic utilisation.

A gasification concept, which considers the particular properties of straw, has been selected as a suitable starting basis for further development. At present, this concept is being investigated in the laboratory and on the bench scale. The work will be accompanied by systems analyses regarding technology, economy and market situation. The final aim are flow charts and design data for the components of a larger pilot plant. It is intended to construct and operate this pilot plant in co-operation with potential industrial users.

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