1 INTRODUCTION

The chemical energy amount stored in terrestrial biomass has been estimated to 25,000EJ. Given the respective 2002 annual world primary energy consumption of 450EJ, it becomes obvious that biomass is an interesting option to supply future energy demands [1]. Although not all biomass can and will ever be used to produce energy, only a small fraction of it can provide a substantial supply of energy to the world. In addition to being renewable and carbon-dioxide-neutral, biomass is comparably easy to convert and to handle and therefore not only UK and European long-term goals see biomass as one of the main factors of future renewable energy generation [2].

Due to its dispersed location and comparably low energy density, biomass should best be converted locally. It is thus of high interest to design micro- or small-scale plants, to be installed directly in locations with high amounts of biomass feedstock. Ideally, those plants can be used to supply remote customers with energy independent of the grid, which can result in substantial savings when taking transmission losses and grid infrastructure costs into the calculation. However, the issue of supplying highly transient and fluctuating load levels is critical, especially when no or only weak grid connections are available.

In this paper, current biomass conversion and generation technology have been discussed with an emphasis on the applicability to micro-scale plants. Finally, a combined plant design which is able to cope with the issues mentioned is suggested.

2 CONVERSION TECHNOLOGIES

Conversion technologies are employed to produce intermediate energy carriers in both liquid and gaseous form from raw biomass feedstock. The fuel's chemically stored energy can then be released and transformed into heat and/or electrical power using generation technologies. Depending on the moisture content of biomass feedstock, either thermochemical or biochemical conversion technologies can be employed, the first being more suitable for dry feedstock, whereas the latter is better for wet feedstock.

2.1 Thermochemical Conversion

Main thermochemical conversion technologies include the high-temperature partial oxidation of feedstock, a process called gasification, as well as the lower-temperature breaking of biomass macromolecules into smaller molecules in the absence of air, called pyrolysis. Additionally, liquefaction as a low-temperature high-pressure process to convert biomass is included in this category.

2.1.1 Gasification

Gasification is the partial oxidation of solid biomass particles into a producer gas mainly consisting of CO, H2, CH4 and CO2 [3]. Due to the substochiometrical amount of oxygen used in gasification, it can be compared to incomplete combustion. Depending on the oxidation agent, different producer gas calorific value (cv) ranges can be achieved: using air as a gasification agent results in the lowest cv of around 5MJ/Nm3, whereas the use of pure oxygen or steam result in higher cv levels of 10-12MJ/Nm3 and 15-20MJ/Nm3, respectively [3, 5]. Temperature ranges for gasification vary, but are rather high with around 700-1000°C [6-10]. In general, three main gasification steps are involved: First the particle drying process where all water is evaporated from the biomass material. This is followed by the pyrolysis process where the material is broken up into volatiles and a char residue. Finally, in the oxidation zone of the reactor, the volatiles, a mixture of different organic and anorganic compounds, are oxidised by the gasification agent and part of the char is reduced from carbon dioxide and water into hydrogen and carbon monoxide [11].

1 Compared to those values, the cv of natural gas is still significantly higher: around 44MJ/Nm3 [4].
Biomass particle size ranges vary, but in general are from around 5 cm down to a few mm; the feedstock should preferably be dry due to the heat needed to vaporise the water within the particle, however maximum moisture contents of up to 30-50% were mentioned as suitable [11]. Most gasifiers, especially for larger scale units, are designed and set up for steady state production and, although the feedstock input flow can be varied, will result in a rather steady throughput and hence producer gas output. Startup times for smaller plants of around 10-20 min were reported [12, 13], so gasification technology seems to be well-suited for base load applications and a continuous gas output. Also, by using gas storage facilities, a very flexible energy supply system can be designed. Due to producing a comparably low-calorific gas, pressurised storage of the producer gas seems to be a promising alternative to storing large amounts of uncompressed gas. Thus a producer gas compression unit preceding the gas storage is necessary. An alternative is to employ a pressurised reactor. Pressure ranges of 3-10 bar have been reported [14, 15], and the advantage of the latter design is that only the gasification agent needs to be compressed, whereas in the original design a far higher volume of producer gas must be compressed and thus a significant amount of energy input is needed [2, 5, 16]. However, the cost impacts of using pressurised reactor equipment strongly limit the utilisability of such designs.

A broad range of gasification reactor designs has been discussed in literature, and three main categories can be divided, differentiated by the velocity of the gasification agent in relation to the biomass particles: fixed-bed reactors, fluidised bed reactors and entrained flow reactors (e.g. [3, 5, 11]).

In Fixed-bed Reactors, the gasification agent velocity is rather low, thus it steadily flows through the biomass particles. This reactor design is comparatively simple and cost-competitive and thus is the preferred option for small scale applications. Varying particle sizes as well as varying feedstock quality can be handled so this design is a very interesting option for small scale applications. Two options exist: the design which employs the same flow direction for biomass particles and the gasification agent (co-current or downdraft), whereas the alternative employs the counter-current or updraft flow principle, i.e. biomass particles flowing from top to bottom whereas the gasification agent flows from bottom to top.

The advantages and disadvantages of the co-current design include:

- relatively clean producer gas due to exiting at the reactor bottom directly after conversion of biomass
- high temperature of exiting gas (around 700°C)
- lower mixing intensity resulting in the problem of clogging of biomass particles due to co-current flow, thus higher requirements regarding equal feeding of the particles

The advantages and disadvantages of the counter-current design include:

- intensive mixing of particles and agent due to counter-current flow, resulting in higher conversion rates
- high heat transmission levels from the hot producer gas to the entering biomass particles, thus drying the effect of the entering biomass
- relatively cold exiting gas due to the heat transmission
- high amounts of tar in exiting gas due to contact with biomass material entering the system

In general, the co-current design is more interesting for micro-scale applications, and sophisticated gas cleaning equipment can be avoided. Compared to fixed-bed reactors, Fluidised-bed Reactors employ a higher gasification agent velocity and a bed consisting of particles and inert bed material such as sand. The advantages are higher conversion rates due to the better mixing of agent and biomass and better heat transmission from the bed material to the biomass feedstock. However, this design necessitates cyclones to separate bed material and unconverted particles from the exiting producer gas system and loops to re-cycle the bed material into the reactor and thus is only viable for large scale units of greater than 1 MW.

Entrained flow Reactors employ an even higher gasification agent velocity and result in an evenly distributed particle/gasification agent stream within the reactor. They result in the highest mixing rates of particles and agent and therefore in very high conversion rates. However, their need to have a high velocity results in rather large designs to ensure long retention times to convert the biomass. The need to accelerate the gasification agent results in higher energy inputs when compared to fixed-bed reactors.

When considering plant sizes, it has been mentioned in numerous reports that a throughput of around 1 kg/hr of biomass feedstock can be converted into a gas volume suitable to generate 1 kW, output [7, 15, 17-20].

2.1.2 Pyrolysis

Pyrolysis is the conversion of solid or liquid biomass into a mixture of liquid, gaseous and solid intermediate fuels in the absence of air [10]. Therefore, pyrolysis can be seen as either incomplete gasification or one step of the gasification process described above. When biomass particles are pyrolysed, the water amount is vaporised and then the particle is broken up into char and a volatile compound. This volatile portion is then partly cracked into gaseous side-products. The main product of pyrolysis is the liquid phase, called bio-oil, a mixture of a complex range of organic and inorganic compounds diluted in a high amount of water.

Temperature levels for pyrolysis are significantly lower than gasification temperatures and vary around 300-500°C [5, 21-24]. The heat necessary to pyrolyse the feedstock needs to be supplied without introducing oxygen into the reactor, so most pyrolysis processes burn the char residue externally and employ heat exchangers to heat the reactor [25-28]. Alternative designs include a combustion area within the pyrolyser where combustion air is introduced and the char is combusted [29, 30].

One of the main advantages of pyrolysis is the possibility of varying the ratio of the three product categories by varying process parameters. The gaseous phase yield can be increased by high temperatures and long residence times to intensify cracking processes, whereas moderate temperatures and short residence times result in a higher amount of bio-oil by preventing oil cracking. Low temperatures and long residence times predominantly result in char residues. Given those variations, three different pyrolysis processes are classified in literature (e.g. [5, 24, 31, 32]): conventional pyrolysis or carbonisation with low heating rates and temperatures, resulting in higher particle retention times of up to several minutes and char as the main product;
rapid and fast pyrolysis with medium to high temperatures and high heating rates resulting in shorter retention times of several seconds; and finally flash pyrolysis with very high temperatures and heating rates resulting in very short retention times. However, high heating rates correspond with the need for smaller and very uniform feedstock particles to facilitate rapid heating, an effect resulting in very high feedstock prerequisites and thus pre-processing costs.

So far, a broad range of designs have been introduced for both large and small scale applications. Rapid, fast and flash pyrolysis seem more viable for larger scale units due to the high heating rates necessary and the more intensive particle pretreatment, and due to the comparably low gas and oil yields of conventional pyrolysis, only few commercial applications have been found [18, 22, 23]. Another obstacle of pyrolysis is the water dilution of the bio-oil and its corrosivity due to the broad range of organic and inorganic compounds solved. Thus the application of bio-oil for electricity generation technology seems rather difficult [33] and gasification is the preferred option.

2.1.3 Liquefaction

Whereas gasification and pyrolysis mainly produce the intermediate fuel with endothermic chemical reactions and require a certain temperature level, liquefaction tries to cleave the large biomass feedstock macromolecules by applying high pressure and only low levels of heat. Common process parameters are temperatures of around 200-400°C and pressure ranges of 50-200bar [10, 34, 35]. The main products of liquefaction evidently are liquid fuels with a similar consistency of pyrolysis bio-oil. However, oil yields are lower than for pyrolysis processes, and given the very high pressures of the liquefaction reactor and associated equipment, there are only a few examples of commercially available liquefaction processes. Thus liquefaction is in the earliest stage of development and does not seem viable for small applications [10, 35].

2.1.4 Thermochemical Conversion Technology Ranking

The following table summarises the findings of the preceding investigations and ranks the applicability of the different thermochemical conversion technologies. Assessments vary from ‘---’ for ‘very poor’ to ‘+++’ for ‘very good’.

<table>
<thead>
<tr>
<th>Table 1: Ranking of thermochemical conversion technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion level</td>
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<tr>
<td>------------------</td>
</tr>
<tr>
<td>simplicity</td>
</tr>
<tr>
<td>plant cost</td>
</tr>
<tr>
<td>conversion time</td>
</tr>
<tr>
<td>applicability to scale</td>
</tr>
</tbody>
</table>

From this it can be concluded that gasification shows strong indications to be best-suited for thermochemical micro-scale applications.

2.2 Biochemical Conversion

Highly water-diluted biomass such as sludge, manures or vegetable waste can hardly be treated economically in thermochemical conversion reactors due to the energy input necessary to heat the feedstock to the temperature needed for the conversion and to vaporise the water. For feedstock with significantly more than 50% moisture content, it is normally not viable to apply thermochemical conversion technologies. Alternatively, biochemical treatment at comparatively low temperatures becomes a more economic solution. The two main processes are anaerobic digestion (AD), where biomass is converted by bacteria, and fermentation, using yeasts to convert biomass. While AD is the standard solution for treating very high dilution levels, fermentation can also be applied to biomass containing lower amounts of water.

2.2.1 Anaerobic Digestion

Anaerobic digestion as the bacteria-driven conversion of biomass to biogas in the absence of oxygen results in depletion of the biomass’ oxygen content for the metabolisms [36]. To achieve this, biomass is filled into a reactor and kept at the respective temperature level needed by the bacteria present. Three different bacteria strains can be categorised, resulting in three main temperature ranges of AD processes: psychrophilic (−15°C), mesophilic (−35°C) and thermophilic (−55°C) [37, 38].

The digestion reactor feedstock is normally fed stepwise (plug-flow) or continuously (steady-flow), and gas production is enhanced by mixing or stirring. Biomass retention times of 10-20 days are common, however part of the volume is replaced by new feedstock in intervals [36]. All three AD temperature levels are comparably low and therefore easier to provide, for example by using exhaust heat from generation or other plant processes.

In addition, AD plants can cover a wide range of scales as well as feedstock: practically all livestock slurry as well as organic farm wastes and even cellulose-containing material can be treated in AD plants to produce biogas, and by-products of AD are settled fibre usable for soil conditioning and liquid fertilizer which can be used on the farm without additional treatment [33, 36, 39].

In general, around 30-60% of the digestible material is converted into biogas, a mixture of around 45-75% of CH₄ and the remainder of CO₂. The feedstock utilisation rate depends on the temperature of the reactor: thermophilic reactors in general provide the highest biogas yields, whereas psychrophilic reactors are seen as less promising [40]. Despite this, most commercial farm digesters are mesophilic reactors because they seem to be more stable than their thermophilic counterparts [41, 42].

When considering plant sizes, it has been mentioned in literature that a methane yield of around 1m³ per m² of reactor volume per day can be achieved when using common technology such as stirring reactors. For typical livestock dairy management, around 1000 of sludge per head can be expected [41, 43], and it can be calculated that seven cows produce the equivalent of biogas to operate an engine of 1kW power [39, 41, 44].

2.2.2 Fermentation

Fermentation processes convert biomass into Ethanol (EtOH) and consist of two consecutive steps: first, biomass starch is converted to sugars using enzymes, afterwards the sugars are fermented to EtOH using yeasts. The solid residues of fermentation, which still contain considerable amounts of biomass, can then be used for combustion or gasification. The water-diluted alcohol, containing around 10-15% EtOH, needs to be distilled to higher concentrations before being usable as fuel [10]. Typically, sugar cane and sugar beet are used
for fermentation. Wood and plant wastes can theoretically also be fermented, although present technology is still in the prototype phase [10, 45, 46].

EtOH as the final fermentation product allows easier handling and storage when compared to gases, but due to the intensive feedstock pre-treatment, the necessary temperatures and the diluted intermediate product, the fermentation process is more complex than anaerobic digestion. Furthermore, methane as the main product of AD is rated as the ideal fuel because it is a comparatively clean fuel and a broad range of methane-based engines for heat and electricity generation are available [36]. Thus, despite the given advantages of storage and transport, fermentation processes are in general less suitable for micro-scale energy production than gas producing technologies.

2.2.3 Biochemical Conversion Technology Ranking

As for the thermochemical conversion technologies, a ranking of the applicability of biochemical conversion technologies for small scales is shown in Table II. Again, assessments vary from ‘---’ for ‘very poor’ to ‘+++' for ‘very good’.

As a result, AD seems more promising and viable for micro-scale applications, especially due to its simplicity and lower plant cost.

### Table II: Ranking of biochemical conversion technologies

<table>
<thead>
<tr>
<th></th>
<th>AD</th>
<th>Fermentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>conversion level</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>simplicity</td>
<td>+++</td>
<td>---</td>
</tr>
<tr>
<td>plant cost</td>
<td>+++</td>
<td>--</td>
</tr>
<tr>
<td>conversion time</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>applicability to scale</td>
<td>+++</td>
<td>-</td>
</tr>
</tbody>
</table>

3 GENERATION TECHNOLOGIES

A biomass-driven generation plant can supply electricity and/or heat, the latter normally in the form of hot water of around 70-90°C. Alternatively, heat can be supplied in the form of steam or hot exhaust gas, or it can be applied to the processes e.g. for drying or preheating. Thus more intermediate fuel can be produced and stored to enhance the total process efficiency.

This chapter covers the main ways of converting the fuel into electrical energy: the first part describes heat-driven applications running on raw biomass feedstock, and the second part describes technology based on the use of liquid and gaseous fuels.

3.1 Heat-Driven Generation

Heat-driven generators produce shaft motion by using raw biomass feedstock and thus do not employ any conversion technologies. The feedstock is directly converted into heat by combustion, a process that generates temperatures of around 800-1000°C [10]. This heat is then used to run the engine. In general, combustion processes are very simple to set up, however they suffer from relatively low efficiencies of around 10-25% [47, 48]. The process is inherently slow and needs significant time to respond. Two main technologies running on combustion heat have been widely acknowledged in literature: Stirling engines and Externally Fired Microturbines.

3.1.1 Stirling Engines

Stirling engines are designed to use a cycle of heating and cooling a working gas; the gas is compressed, heated and expanded and then it is cooled. Due to the expansion it produces work at a piston. The net work produced is thus the piston work minus the work needed to compress the gas. A generator unit then converts the piston motion into electricity. Exhaust heat can be used for hot water in combined heat and power (CHP) applications using heat exchangers. Similarly, heat exchangers are also employed to transmit the combustion heat to the gas in the heating zone and to cool the gas in the cooling zone. [49]

In general, the working gas used in stirling engines is helium or hydrogen [49, 50], or compressed air due to its better availability [51]. The output power of stirling engines depends on the working gas pressure and on the temperature difference between the hot and cold zone [50, 52].

A number of stirling engines have been designed, tested and applied [17, 50, 51, 53-56]. However, their electrical efficiency has been rated as rather low and in the range of 20-25% [51, 52, 57, 58]. Also, since they are based on a continuous combustion process, most stirling engines are designed for steady state operation in base-load and heat-driven operation [59]. Part-load operation seems difficult and results in significantly lower efficiencies [60].

One of the main advantages of stirling engines is their fuel flexibility. All biomass suitable for combustion can be used to generate heat. Given the large range of commercial combustion grate and furnace technology, basically all feedstock is suitable. Since they use indirect heating, dirty feedstock can be used because apart from heat exchanger issues, tars are not an operation constraint due to having no direct engine contact. Additionally, most stirling engines can continuously run for long periods of time because their moving parts do not come in direct contact with the fuel. Operation cycles of 8,000-10,000hrs are common [17, 55], so the engines are well-suited for remote locations with a constant need of electricity, however, they are still regarded as less mature than other generation technology [33].

3.1.2 Externally Fired Microturbines

Microturbines are gas turbines for a power range of less than 500kW. Although most turbines employ combustion chambers and expand the combustion air to generate shaft motion, some designs use heat exchanger technology similar to the stirling heat exchangers to heat the turbine working gas. In this case, the process is called Externally Fired Gas Turbine (EFGT) and the engine can be operated based on all combustion fuels, similar to the stirling technology.

In EFGT applications, biomass feedstock combustion provides the heat to be transmitted to compressed air used in the turbine. A high temperature heat exchanger, fired by a combustion furnace or grate, is employed to heat precompressed air. This hot air is then continuously expanded in the turbine and a generator, mounted on the turbine shaft, generates power. The expanded hot air at the turbine outlet can be used in CHP applications or within the process [61].

Due to material constraints and limits, the heat exchanger temperature limit is around 900-1100°C. Therefore the temperature limit of the compressed hot air to be expanded in the turbine is around 800-900°C [61-
microturbines which directly uses the combustion flue gas of 900-1100°C, a lower level of work and thus efficiency can be achieved. Levels of 20-25% were reported for the comparably low number of EFGT plants in operation [58].

When considering load flexibility, a test study revealed that although fast load changes can be applied by using a heat exchanger air bypass valve to rapidly lower the temperature of the working air volume, this results in very poor part-load efficiencies. Instead, variable speed operation caused by adjusting the amount of air being expanded in the turbine has been found as the best operation mode under part-load [64]. However, it has been mentioned that due to the steady combustion process being uncoupled from the turbine operation, the externally fired gas turbine is less able to cope with fast load changes [65]. Finally, the high temperature heat exchanger requires special materials due to the high temperature differences on both sides of the exchanger surface as well as corrosive combustion flue gases [66].

3.2 Fuel-Driven Generation

In contrast to the combustion-heat based generation engines, both microturbines and reciprocating engines can directly run on biogas, producer gas or liquid fuels such as ethanol or bio-oil. There are, however, significant difficulties when running microturbines on bio-oil due to the corrosivity of the fuel [33].

3.2.1 Microturbines

Microturbines (MT) are small, predominantly aeroderivative turbines using a comparably simple design and a generator directly mounted on the turbine shaft [67, 68]. Air is compressed, heated and then expanded in the turbine to produce motion. A recuperator can be used to preheat the compressed air with the exhaust gas heat before entering the combustion chamber. This increases the turbine efficiency by around 5%, however the turbine exhaust gas temperature is lowered from around 600°C in simple cycles to around 300°C in recuperative cycles and there is a significant cost impact [58, 69-71].

A number of suppliers have designed turbines down to 30kWe [67, 68, 72, 73], in both CHP and power-only applications. The further design provides hot water of around 70-90°C, whereas the latter provide an exhaust gas stream of high temperature.

One of the advantages of microturbines over internal combustion engines is their high exhaust gas temperature and therefore the possibility to use this heat within the process [7, 58]. Microturbines can also be run on fuels with varying calorific values, and special designs for compressed low-calorific biogas or producer gas are available [74, 75].

Another major advantage is their low maintenance need. Microturbines use air bearings and single shaft technology, and together with a smooth rotation of the turbine, very long maintenance cycles of up to 10,000-15,000hrs of continuous operation can be achieved [67, 73, 76-78].

Finally, due to their constant combustion, emission levels are far below those of reciprocating engines [79-81], and given their price range of around 1000-1900€/kWe [69, 74, 82] they are a promising alternative to reciprocating engines.

In terms of fuel efficiency, microturbines employing recuperative cycles result in efficiencies of around 25-35%, which is around 5% less than reciprocating engines [7, 58, 83], and they have a comparably robust efficiency behaviour under part-load, albeit also slightly below that of reciprocating engines [77, 79, 83, 84].

Microturbines can be operated comparably easily: by regulating the amount of fuel and/or air input, the power output can be adjusted. Two operation modes have been discussed in literature: constant speed/variable temperature mode, where the air mass flow is kept steady and the combustion temperature is regulated, and variable speed/constant temperature mode, where the air mass flow is adjusted, but the combustion temperature is kept steady. A number of tests have shown that the variable speed mode achieves significantly better part-load efficiencies [79, 83, 85], so although a more advanced alternator is needed due to the varying revolution speed, variable speed operation can be applied to better accommodate rapid and frequent load changes.

A number of tests were performed to investigate the transient behaviour of microturbines [70, 71, 86]. A microturbine can be started within around 5min from cold start and around 2min from warm start, and after around 1min the electricity supply begins. Shutdowns of the turbine result in a stop of power export after around 30s. When applying load changes, ramping times of around 15-20s between two power output levels were achieved in grid-connected mode, and slightly better results have been found for stand-alone tests by using on-board batteries to immediately cover the transient period and to provide the startup power.

As a summary, microturbines are considered suitable for single power source microgrids being able to cope with fluctuating loads.

3.2.2 Gas Engines and Internal Combustion Engines

Gas engines can be defined as Internal Combustion Engines (ICE) running on gases such as natural gas, producer gas or biogas. Most gas engines are spark ignition engines, whereas ICE can be either compression ignition or spark ignition engines, however, most ICE can also be converted to run on gas.

Gas engines and ICE have been in commercial operation for decades, in units ranging from a few kWt up to several MWt, and with price ranges of around 500-1000€/kWe [45, 77, 82, 87, 88]. Gas engines are described as robust against fuel quality changes [89], however their exhaust gas temperature is rather low with around 80-100°C [7, 82], which makes further usage of it difficult.

Gas engine efficiency lies in the range of 30-40% [7, 57, 58, 82] with a decrease under part-load operation similar to microturbines [90].

One problem in using bio-derived fuels is that, due to that H2S as a by-product of AD is highly soluble in oil lubricants, frequent lubrication changes are necessary and maintenance cycles (oil and filter changes) can be as frequent as every 500hrs [16, 20, 77, 78, 91]. This effect highly reduces the applicability of those engines in rural and remote areas, especially when they are intended to run as the single generation unit and no skilled personnel is at hand [16, 78].

Finally, reciprocating engine emission levels, especially in terms of CO and NOx, are significantly higher than those of other generators. Differences of up to an order of magnitude were reported [80, 81, 84], and especially when running on biomass fuels, it has to be
taken into consideration whether high amounts of emissions from reciprocating engines are acceptable.

In terms of flexibility of operation, reciprocating engines again perform better than other generation technologies. Reasonable load changes can be adopted very quickly, and the suitability for fluctuating loads is high, hence they were the standard solution for emergency gensets. However, microturbines with battery packs are increasingly replacing diesel emergency gensets due to their better maintenance behaviour [72, 73, 78].

3.3 Generation Technology Ranking

The following table summarises the technical and operational behavior of the generation technologies discussed earlier and ranks them based on their applicability for the desired micro-scale applications. Again, assessments vary from ‘---’ for ‘very poor’ to ‘+++’ for ‘very good’.

<table>
<thead>
<tr>
<th>Table III: Ranking of generation technologies</th>
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<tbody>
<tr>
<td>Stirling</td>
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<tr>
<td>full efficiency</td>
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<tr>
<td>part efficiency</td>
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<tr>
<td>load flexibility</td>
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<tr>
<td>investment cost</td>
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<tr>
<td>maintenance</td>
</tr>
<tr>
<td>emissions</td>
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<tr>
<td>development level</td>
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</tbody>
</table>

It is concluded that, despite their higher investment cost, microturbines seem a better alternative for providing energy to remote customers, especially in remote areas where maintenance and operation ease are of key importance. Additionally, the comparably high load flexibility of microturbines should provide strong incentives, and when the market for microturbines starts to mature, decreasing price differences between microturbines and ICEs can be expected, which will further promote the employment of this technology.

4 COMBINED PLANT DESIGN PROPOSAL

From the above, it can be concluded that gasification and anaerobic digestion seem probable for the intended scale of 5-50kWe. When considering remote farms as a major target group, they can provide considerable amounts of organic waste which can be used as biomass feedstock.

Given that a farm typically has both livestock management and plant cultivation, both wet and dry biomass will be available. Thus it will be worth examining ways to use both feedstocks by combining thermochemical and biochemical treatment.

A plant consisting of a co-current fixed-bed gasifier and a thermophilic anaerobic digester is considered to be the best solution to provide both efficient waste management systems and the production of considerable amounts of biogas and producer gas. This fuel can then be used in a microturbine to provide both electricity and heat. It also offers the advantages of long maintenance cycles and good response to load changes. Lastly, a microturbine can be operated autonomously by remote or preset control and thus the absence of skilled personnel on site will not be an issue.

The proposed plant will be required to instantaneously cover the electrical load demand of the customer, which will consist of electricity needs for farm houses and adjacent buildings. As a result, a highly transient and fluctuating load demand curve is expected.

Existing plants are designed to operate as base load applications, and the grid connection is used to import any extra energy used. Common stand-alone or island applications employ batteries to instantly cover the load change and to allow sufficient time to change the generation output of the engine. However, batteries as well as other electricity storages result in maintenance efforts and losses.

Instead of trying to mirror the load demand with the generation output and covering the transition interval with electricity storage, our proposed plant will be designed to run on a comparably steady load. This normally results in a surplus of electricity generation, so an electricity sink in the form of an electric feedstock heater will be activated. This will result in better conversion efficiencies due to drier feedstock, and thus more intermediate fuel gas will be produced. This gas can then be stored more efficiently than the electricity surplus.

In terms of the customer heat demands, it has been found that in general they are significantly lower than the process heat output from the unit. Unfortunately, times of high electricity demand do not always cohere with times of high heat demand and thus not all heat can be used by the customer. Therefore, the proposal aims for a high level of internal usage of the process heat.

Figure 1 shows a flow chart of the desired plant, and the main parts are described in the following sections.

4.1 Generation unit (Microturbine)

The generator is a microturbine compressing air of ambient temperature. A heat exchanger will be employed to use the thermal energy of the producer gas and to preheat the compressed air before it enters the combustion chamber. There, air and fuel gas released from the storage system will be mixed and burnt. Since a pressurised gas storage is used, the fuel gas does not need to be compressed before it enters the combustion chamber. The high turbine exhaust gas temperature will be used within the gasification unit as described below.

The turbine will be in the size of 30-50kWe and it will be operated on variable speed mode between half- and full load. As mentioned earlier, the time interval...
needed to change the turbine speed and thus the electrical output is in the range of several seconds. The turbine operation will be comparably steady, and load steps following the time of day will be used in a way that it is always secured that the turbine produces at least the load demanded by the customer.

The gas needed to run the turbine will be a mixture of producer gas and biogas, as shown in figure 1. This results in a higher calorific value compared to running the turbine on producer gas alone, and the two gases can be stored in the same storage system. Turbine operation on varying calorific values has been proven to be possible and stable, so variations in the ratio of biogas and producer gas should not be a critical topic.

4.2 Gasification unit
A simple fixed bed co-current gasifier is used to process crop wood and other suitable dry farm waste to generate producer gas. After being shredded to the right particle size, the feedstock stream will be dried in the wood dryer, further using the heat of exiting producer gas.

The co-current reactor design has been proven to be usable with varying biomass feedstock moisture contents, so the unsteady activation of the electric heater will positively affect the gasification yield without detrimentally affecting its steady-state operation in times of high electricity demand. Part of the dried biomass feedstock and unconverted biomass char can be burnt in the combustion chamber to provide sufficient heat levels for a continuous high temperature gasification agent stream. The hot producer gas will then be used to preheat the compressed turbine air, followed by drying the biomass feedstock in the wood dryer. After those two heating cycles, the producer gas will have a relatively low temperature, however it can still provide sufficient heat for the digestion unit.

4.3 Anaerobic Digestion unit
The anaerobic digestion unit of the plant will process highly diluted farm waste such as manure or food and vegetable waste. A simple plug-flow or steady-flow thermophilic digester design will be employed to ensure low design cost and the highest gas yields for the comparably uniform feedstock flow.

The sizes of the anaerobic digestion and gasification reactors will be chosen depending on the amount of livestock and suitable dry feedstock material available on site. It must be of a suitable size such that enough biogas and producer gas are produced to continuously be able to meet the customer power demand.

4.4 Gas storage system
The gas storage system will play a key role within the plant. It will be the main energy storage system and will be sufficient in size to be able to completely cover the peak load demand.

Both the biogas and the producer gas are compressed to a pressure level sufficient to be able to operate the microturbine on the gas mixture. Both gases are stored in one pressurised tank. This enables a mixing of the two gas streams and thus results in a more balanced calorific value of the gas mixture.

5 CONCLUSION AND OUTLINE OF FUTURE WORK
For a micro-scale biomass unit, a fixed-bed gasification reactor coupled with simple anaerobic digestion tanks offers a viable combined plant solution. In terms of generation equipment, microturbines show many advantages over conventional internal combustion engines with regards to maintenance and flexibility.

The plant design described in this paper is able to autonomously cover the electrical demand of a remote customer providing sufficient amounts of biomass waste. A design consisting of both wet and dry feedstock processing and a flexibly-running microturbine can support or even replace a weak grid connection. Although the project of developing such a plant is still in an early stage, it is a very promising alternative for rural areas.

6 REFERENCES


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