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NOVEL COMBINED FEEDSTOCK MICRO-SCALE BIOMASS GENERATION PLANT FOR REMOTE POWER SUPPLY - MODELLING AND SIMULATION RESULTS

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ABSTRACT: Providing power to remotely located areas by using conventional grid-connection can incur high losses and prohibitive costs. Generating power locally is a suitable alternative, and using renewable energy carriers brings further benefits by attaining energy self-sufficiency. A biomass generation plant using locally available feedstock to produce electricity is an efficient way of providing remote areas with competitive and reliable electricity. A novel micro-scale plant design combining thermochemical and biochemical treatment has been developed. It can provide electricity to a level as small as 50kWe, which fits the size of a remote village. This paper describes the modelling and simulation of the plant design in chemical engineering simulation software. It also covers studies undertaken to address sizing issues, to match domestic demand estimated by load profiles, and operation simulation results. It will be shown that such a system is a feasible and economic solution for reliable and continuous remote power supply.

Keywords: decentralised electricity generation, stand-alone-systems, micro-scale, gasification, anaerobic digestion, microturbine.

1 INTRODUCTION

Matching demand for electricity in remote areas currently means setting up a grid connection. As this can become costly and prohibitive especially for smaller customers with low expected demand, local generation could prove an economic alternative. Generation technology using biomass has numerous advantages over other renewable energy sources, such as no intermittency, high regional availability and employing well-known chemical process designs to name but a few. Especially for remote regions, biomass based power generation and supply could therefore be a milestone in achieving energy self sufficiency.

Research into biomass power system design and operation is currently limited to optimising large-scale plants for a base load power supply. Although this approach may be suitable in areas with well-operated network systems, a stable grid connection is not available everywhere. A micro-scale biomass generator suitable to provide sufficient power on a local basis could eventually replace grid connection and current fossil-fuel based generator sets used for power islands. Such a system can prove very beneficial, as remote locations normally have high regional availability of biomass feedstock. However, currently available biomass plant designs are unable to cope with volatility and fluctuating power demand, which has to be expected when meeting local demand.

A novel micro-scale biomass based generation plant has been modelled by the authors. Developed to be operated in remote regions and not depending on a grid connection, this plant can meet local demand and provide power on an ongoing, flexible basis. It uses both main feedstocks normally available, which are wet biomass such as sewage sludge or manure, and dry biomass such as wood.

This paper covers a brief model description and simulation results when running the plant in a way which can cope with load profile patterns.

2 SIMULATION METHODOLOGY

The micro-scale biomass plant designed by the authors combines both thermochemical and biochemical treatment. This plant consists of a simple fixed bed gasification system, and an anaerobic digestion reactor. Both convert biomass feedstock into fuel gas, which runs a microturbine, the power generation part of the plant. The whole design has been described in detail elsewhere [1, 2] and can be scaled to a fitting size for remote villages or farms, whose demand is in the region of 50kW.

The plant design enables flexible operation by adjusting the power output of the generator. It can therefore meet volatile demand patterns, which is crucial for local generation.

Another focus was laid on choosing robust technology and ensuring long maintenance cycles to enable the design to be operated in remote areas.

The general design of the plant and its main parts are shown in the process flowchart in Figure 1.

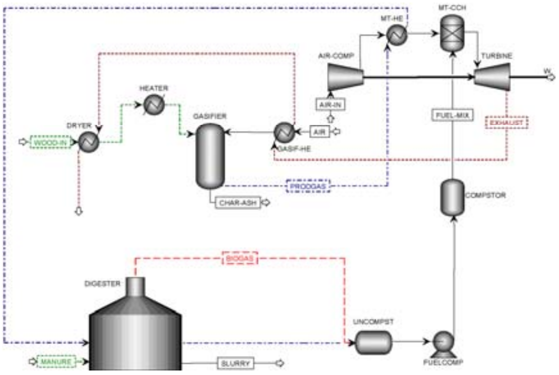

Figure 1: Biomass plant process flowchart

A detailed simulation model of this plant has been set up in chemical engineering software. The plant was modelled using the Aspen Plus environment, which provides a large number of chemical models for each of the main parts of the unit. The methodology of modelling has been described in a separate publication elsewhere [3], however its main conversion and generation parts are briefly described in the following section.

2.1 Dry feedstock conversion - Gasifier

Woody biomass is a complex mixture of a large number of different organic molecules and can hardly be modelled as a conventional chemical substance. However, it can be described by means of its proximate and ultimate analysis, using values from literature [4-6]. As those properties only vary very little between different feedstocks, they can be assumed to be constant.

The biomass molecules mainly contain carbon, hydrogen and oxygen atoms, as well as minor nitrogen and sulphur residues. Inside the fixed bed gasification reactor, they are decomposed by partial oxidation. Air is used as the gasification medium, after being preheated in a heat exchanger. The preheated airstream and the biomass stream are converted into producer gas, a gas mainly consisting of nitrogen, carbon monoxide, hydrogen and carbon dioxide.

This process is modelled using the ‘Minimisation of Gibb’s Free Energy’ approach [7]. The Gibb’s free energy of a system is the thermodynamic potential which measures the maximum amount of non-expansion work available from a system. It is defined as

$$G = H - TS \tag{1}$$

For changes of a system, such as chemical reactions, a negative difference in Gibb’s free energy between the initial and the final state results in the chemical reactions being favourable and thus likely to happen. It can be expressed as

$$\Delta G = G_2 - G_1 < 0 \tag{2}$$

Using the ‘Minimisation of Gibb’s Free Energy’ approach for modelling chemical reactions therefore provides information about which reactions will influence the system in the most thermodynamically favourable way.

Modelling a fixed-bed gasification system with the Gibb’s approach and assuming chemical equilibrium are an appropriate way of simulation and provide realistic results, as has been mentioned in literature [8, 9].

2.2. Wet feedstock conversion - Anaerobic digester

Anaerobic digestion (AD) is a well-known process employed in farming and waste water treatment industry for decades to treat sewage sludge or farming manures. The underlying chemical reactions form a very complex process, as a large number of microbial conversion steps happen consecutively and/or simultaneously. The wet feedstock is decomposed and biogas is formed, which is a mixture of two main components: 60% methane and 40% carbon dioxide. Additionally, water vapour and hydrosulphide can be found in traces [4, 10].

Accordingly, the AD model in this study calculates that a certain amount of biomass feedstock is converted into biogas inside the digester tank, while the remaining components are unconverted biomass and microbial cells, which form the slurry stream exiting the reactor.

AD processes, due to the microbial reactions and the growing of microorganisms during biogas production, are comparably slow and therefore need to be continuous. Manure needs to remain in the reactor for a long period of time, in general around 20 days. The digester model acknowledges this and for a manure intake of 11ton/day, a total tank size of around 200m^3 can be estimated. 1/20 of this volume is replaced each day by new manure, while the remaining manure needs to be kept at the temperature range suitable for AD processes to take place.

This however means that heat losses from the tank to the surrounding environment occur, which have to be accounted for, especially during the long periods of operation. The total heat demand of the AD reactor consists of the heat losses of the tank and the heat to warm up new manure from ambient to the temperature range of 35°C, at which conversion reactions occur. It can be described as

$$Q_{AD} = Q_{loss} + Q_{warm} \tag{3}$$

The heat losses from the reactor to its surroundings are calculated using Newton’s law of cooling, with an overall heat transfer coefficient based on own calculations and available literature [11, 12]:

$$Q_{loss} = UA(T_d - T_{amb}) \tag{4}$$

The heat demand to bring the new manure to the reactor temperature follows an equal approach:

$$Q_{warm} = mc(T_d - T_{amb}) \tag{5}$$

2.3. Power Generation - Microturbine

A microturbine has been chosen as the generation unit of the plant. Microturbines are aeroderivative turbines and consist of an air compressor, air preheater, a combustion chamber and an expansion turbine. The turbine and the compressor are mounted on the same shaft, and the available net shaft work can be calculated as

$$W_{avail} = W_{shaft} - W_{compr} \tag{6}$$

The microturbine model employed in this study follows this basic structure. In the first step, an ambient air stream is compressed to a pressure of 3.35bar. It is then preheated using the producer gas exhaust heat in the microturbine heat exchanger. Afterwards, it enters the combustion chamber, where it burns the compressed producer gas/biogas mixture from the fuel storage. The high pressure exhaust stream is finally expanded to atmospheric discharge pressure in the turbine.

All turbine performance parameters in the model follow microturbine specifications as mentioned in [13, 14].

2.4. Gas storage system, feedstock pre-treatment and power sink

The fuel gas compressor and storage system forms the capacity storage within the plant. Both gasification and AD are continuous processes and cannot be adjusted quickly. Therefore, by storing sufficient amounts of fuel gases, the plant output power level can be changed by flexibly running the microturbine. Hence the gas storage replaces electric storage such as batteries and provides a buffer for volatility of demand.

The producer gas stream from the gasifier is mixed with the biogas stream from the AD, and the combined stream is then compressed to a pressure level of 5bar before being stored. This is necessary as the microturbine requires a minimum energy inflow for operation.

The compressor is modelled based on parameters mentioned in literature [14], and its power requirements are relatively constant, due to the continuous gasification and AD operation.

The feedstock pre-treatment takes place in both the wood dryer and the electric heater, whereas the second also forms the power sink of the plant system.

The microturbine exhaust stream is a high-temperature air stream which can be used in the wood dryer to use its thermal energy and decrease the wood moisture content, which results in a better quality producer gas. It reduces the biomass moisture content from an initial value of 60% for fresh wood biomass [15, 16] to around 10%. This value is further reduced in the electric heater, depending on the amount of power available for this power sink.

The plant will be the single generation unit and has to meet residential or industrial demand. This means that a balance between demand and generation needs to be achieved at each unit of time, as no electricity storage is available.

The microturbine therefore needs to generate at least the amount of power demanded. It however cannot instantly change its output when demand increases; instead, it needs around 20-30s to adjust to a higher or lower power level [17]. This means that the microturbine generation always needs to exceed the demand in order to ensure reliable supply. A logical consequence of this is that a certain amount of power needs to be 'used up' within the system to achieve a match between generation and demand. This amount of 'excess power', which can be calculated as the difference between available turbine power, power demand of the fuel gas compressor and demand,

$$W_{excess} = W_{avail} - W_{gascompr} - W_{demand} \qquad (7)$$

will be used in the electric heater to further decrease the biomass moisture content.

3 SIMULATION RESULTS

The results from running the gasification and AD model show close comparison to literature values from similar projects. The generation part of the plant has been checked and was able to use the fuel gas for power generation. Scaling simulations were undertaken in order to find out about sizing limitations and correlations between feedstock input and gas output. Those results will be described below and show that the plant operation is both feasible and realistic.

In a second step, ongoing plant operation was simulated. By using domestic load profiles from [18], it was tested whether the plant can be run in order to mirror the load patterns and thus provide ongoing power supply.

3.1 Plant scaling, gas production and generation rates

One main intention of the plant design was incorporating efficient internal heat management. In order to check suitable plant scaling alternatives, the raw feedstock inputs have been varied. As the heat streams of the two conversion subsystems are connected to each other, a certain correlation between wood and manure intake will lead to the most efficient process. This correlation has been found by varying the feedstock, and the result of this optimisation is shown in Table I. Based on this, the producer gas and biogas production rates are drawn over the feedstock intake in Figure 2. Finally, based on the use of the produced fuel gas, Table I also shows the overall available power.

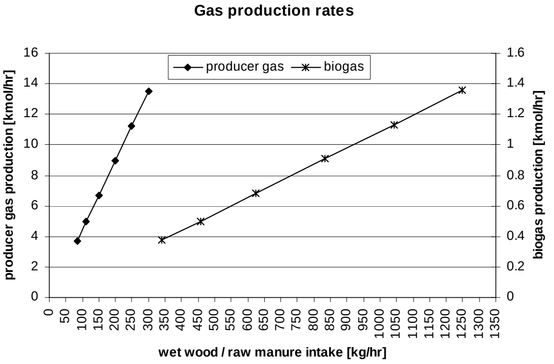

Figure 2: Producer gas and biogas production rates

A wet wood intake of 112.5kg/hr and a manure intake of 11t/day have been chosen as the base case, called 'B1' in Table I. They were found as the minimum size of the plant system. When trying to further decrease the size of the system, the heat losses in the AD increase to a level which cannot be compensated by the internal heat usage anymore. With falling digester size, the heat losses from the reactor to its surroundings raise in proportion to its total heat demand. They already reach more than 50% of the total AD heat demand for the base case B1. The AD heat demand is provided by the producer gas, which leaves the gasifier at a temperature of around 750°C. When decreasing the gasifier size, less producer gas is available, and thus the AD heat demand exceeds the heat available when scaling to lower intake levels than used in B1.

Table I: Feedstock Intake and Resulting Power Generation

Case name	Woody intake [kg/hr]	Manure intake [t/d]	Net power [kW]
B1 (base case)	112.5	11	60.418
B2	150	15	80.541
B3	200	20	106.732
B4	250	25	132.449
B5	300	30	157.924

It can be seen in Table I that the net system power, which is the available turbine shaft power less the constant fuel gas compressor power, has a range of 60-160kWe. Given the average individual domestic demand obtained from the load profiles used, this would translate into a group of ca. 50-150 dwellings. Alternatively, industrial demand of similar size could be supplied with this design.

The base case raw feedstock intake 11t/day of manure would translate into a cattle herd of 100 cows [19], and the intake of 112.5kg/hr of wet wood should not provide obstacles for a remote area, as plenty of woody biomass is normally available in such locations. Therefore, the base case can provide a small village with locally sourced power.

3.2 Load mirroring operation

In order to understand whether the system can provide ongoing power supply, domestic load profiles were used to understand the patterns in demand and to evaluate fluctuations which need to be expected. The load profiles used were domestic 5min interval profiles, differentiated into weekday and weekend and into summer, winter and shoulder season. A more detailed description can be found in [18].

As the microturbine needs around 20-30s to adopt a higher or lower power level, it will not be able to instantly follow load changes. Therefore, the turbine will generate an amount of power which is above the demand, and the 'excess' power is diverted to the fuel compressor and the electric heater. In a first step, the load profiles have been adjusted to represent the demand of 120 dwellings, and this profile was then rounded up to the next multiple of 5kWe. The difference between the actual amount and this rounded demand forms part of the excess electricity to be consumed by the power sinks.

Both a winter weekday and a summer weekend case were investigated for this study, as they provide the two extreme cases. Demand is on its highest level during the winter weekday, and falls to its lowest levels during summer weekends. The winter weekday demand curve is shown in Figure 3, and the volatility of demand can clearly be seen: the demand finds its minimum during the night with around 25kW, before a first peak in the morning hours occurs. After a comparatively steady demand during the day, the main peak can be seen in the evening, where up to a maximum of 85kW are demanded, before decreasing in the late evening back to the night level.

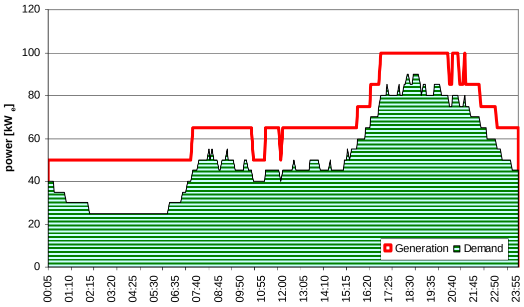

Figure 3: Generation and demand on a winter weekday load profile

Similarly, the generation and demand patterns for the summer weekend case are shown in Figure 4. Compared to the winter weekday case, two main differences occur. Firstly, the absolute level of demand is significantly lower, its maximum peak level decreases from 85kW to 60kW. Secondly, whilst the peak is very distinct for the weekday pattern, the weekend profile shows a comparably constant demand during the day. However, night demand is still considerably lower.

To meet the demand with the microturbine, it was chosen to fix the generation to five load steps: full nominal load, half nominal load and three intermediate stages. This means that the turbine will only be allowed to have those five output levels, and that it will continuously run with at least 50% of its nominal power. This has been mentioned as a minimum level for maintaining both acceptable turbine efficiency and steady and smooth operation [20].

For the cases discussed and the generation pattern described, the turbine will generate 50kWe, 65kWe, 75kWe, 85kWe or 100kWe, as shown in Figure 3 and 4 with the thick red generation curve. Depending on the load, the turbine will be set to its respective output level, and by using a buffer algorithm, the demand will always be met.

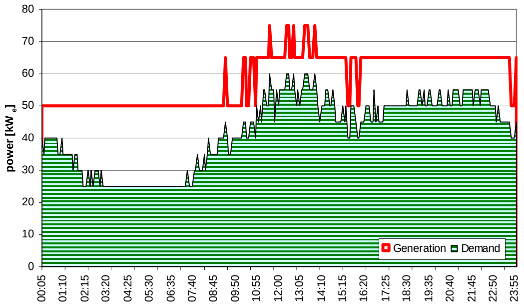

Figure 4: Generation and demand on a summer weekend load profile

When comparing the generation curves in Figure 3 and 4 with the net power level of the base case B1 in Table I, one can find that the maximum power levels are different; in Table I, the net available power is mentioned as 60kWe, whereas in Figure 3, a maximum level of 100kWe occurs. This results from the fact that Table I shows the turbine output assuming a flat generation during the whole day and including the fuel gas compressor power, whilst the graphs show the variable power output depending on the load.

In order to compress the continuously produced fuel gas, the fuel compressor needs around 15kWe. However, the fuel gas compressor can either be operated constantly on a fixed power level, or it can be operated on variable power, depending on the amount of power available. In times of low demand such as during the night, even running the microturbine on half its nominal load results in a massive over-generation, whereas during peak demand, the turbine is hardly able to provide sufficient power when the compressor demand needs to be met as well.

Instead of facing these problems with a larger turbine, the authors have decided to uncouple the fuel gas compressor from the steady operation of the gasifier and AD. Produced gas will first be stored in an intermediate uncompressed storage, and will be compressed when sufficient power can be diverted from the turbine. Once compressed, it will then be stored in a compressed gas storage, from which it can be discharged timely and fed into the turbine, in order to adjust its power output.

This uncoupling of the fuel compressor results in two major benefits of the whole plant system: the fuel gas can be compressed during non-critical times, and the fuel compressor can be operated on different power levels, which result from the difference between generation and demand.

This compressor operation pattern is indirectly shown in Figures 3 and 4 as the difference between the generation and the demand curve, as this is the amount of power available for the compressor. It therefore runs on various power levels from less than 10kWe to more than 30kWe. During the evening peak times, when the turbine runs on full load to meet demand, the compressor will not operate at all, and during times of low demand, the compressor will run on up to 30kWe of unused turbine power.

This operational cycle can be implemented successfully, as long as over a longer overall period, such as a day, the compressor receives sufficient power to compress the whole gas produced during that day. Graphically, this means that the area between the lines in Figures 3 and 4 needs to be of a certain size, equivalent to the compressor being operated on 15kWe flat power for 24 hours continuously.

Additionally, the compressed fuel gas storage needs to provide sufficient compressed gas for the turbine to run, even when the compressor is not providing sufficient compressed gas. Similarly, an uncompressed storage needs to provide sufficient uncompressed gas for the fuel compressor in times of high levels of compressor power, as conversion remains constant and will be lower than this volume. However, both issues can be addressed with ease by sizing the storages sufficiently.

By uncoupling the fuel compressor, the plant system is able to provide power in a reliable way and on an ongoing basis. Although it necessitates both uncompressed and compressed gas storages, the benefits that this operation provides for the whole system exceed the costs of these storages, especially due to its relatively low costs.

A final analysis has been undertaken in order to understand the charge and discharge patterns of such a fuel system. As discussed, production of the fuel gas will be continuously, in order for the gasification and AD processed to remain stable. In contrast to that, the generation follows a certain pattern during the day, which means that in times of high demand, the microturbine needs more fuel gas to reach its full nominal power output, whereas during low demand periods, the turbine will require a smaller amount of fuel gas when running on half load. Therefore, both the storage charge and discharge cycles as well as the absolute storage levels are shown in Figure 5 for the winter weekday and in Figure 6 for the summer weekend case.

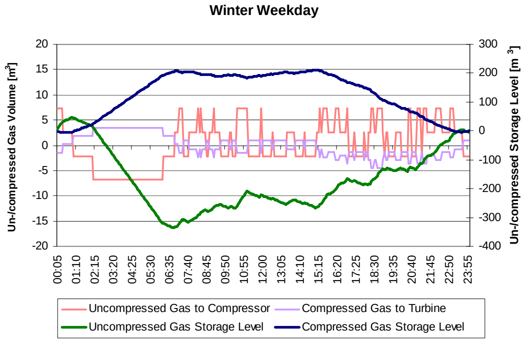

Figure 5: Winter weekday absolute storage levels and charge/discharge cycles

The gas production rate remains constant during the whole cycle of one day. This total amount of gas produced during the one-day interval equals the amount of gas necessary to run the turbine in order to meet the demand for the day. This follows from the fact that the size of the plant and the size of the group of dwellings it is supposed to supply with electricity need to match. As the winter weekday case is the case with the highest absolute demand, the storage levels for this case will return to zero at the end of the one-day period.

In contrast to that, for the summer weekend case, overall generation is below the winter weekday levels, thus for the whole day, the microturbine generates a lower amount of power. As gas production rates remain the same, this means that a certain amount of gas will not be used by the microturbine. The fuel compressor power remains the same, therefore all produced gas is compressed and the uncompressed storage level equals to zero. However, as the microturbine needs less gas, the compressed gas storage level does not equal to zero at the end of the one-day period, and a certain amount of gas remains in the storage.

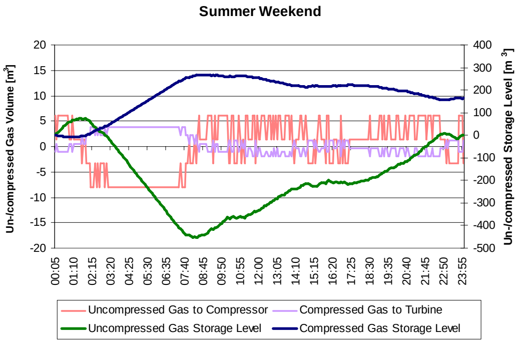

Figure 6: Summer weekend absolute storage levels and charge/discharge cycles

The actual amount of compressed gas required by the microturbine is shown in Figures 5 and 6 as the violet ‘Compressed Gas to Turbine’ curve. The amount of uncompressed fuel gas that is led to the fuel compressor is shown as the coral ‘Uncompressed Gas to Compressor’ line. It can be seen that the turbine gas demand exceeds compression during the evening peaks, thus the values turn negative, i.e. the compressed gas storage is discharged. In contrast to that, the fuel compressor throughput exceeds the turbine demand during the night period, hence the values turn positive. A mirrored pattern occurs for the coral line for the compressor: During the night, the compressor operates on its highest power levels and thus compresses more gas than being produced, so the uncompressed gas storage is discharged. In contrast to that, during the peaks the compressor is set to low power and more gas is produced than being compressed, thus it is charged to the uncompressed gas storage.

Given the total level of both storages and the daily gas production rate, it can be calculated that storages will need to be sized to between 20 and 30% of the daily production for the different cases, which is on an acceptable level. The system will therefore always be able to provide the amount of fuel needed by the turbine in order to meet the load in time.

3.3 Ongoing plant operation

Evaluating the demand and generation patterns as done above reveals information on whether the plant system is able to cope with total load levels and with fluctuations in demand during the course of a day. It has been shown that the plant can be operated to match demand by applying storages of an acceptable size. Analysing the storage levels, information was revealed for the plant operation of a one-day period, however especially for the shoulder and summer period, it is essential to analyse ongoing plant operation and performance.

Over longer periods such as one month, the demand patterns will follow a scheme of alternating weekdays and weekends. The plant generation patterns will also follow this scheme accordingly, and weekday and weekend demand patterns will alternate. As shown above, generation and demand are levelled out during the course of one day, which means that ongoing generation can be obtained by applying this pattern, and the plant operation can be automatically adjusted to the season and to whether each day is a weekday or weekend.

The storage levels however show a different pattern. As described, the total amount of power available for the fuel compressor during the period of one day equals the amount of power necessary to compress the total gas production volume of that day. This means that for all seasons, the uncompressed storage level will return to the initial level at the beginning of the one-day period. Therefore, sizing issues of the uncompressed storage can be addressed by analysing the individual daily load profiles and optimising the storage.

In contrast to that, the uncompressed storage level only returns to its initial value in the winter period, as the gas production equal the demand of gas for generation. During the shoulder and summer period, some gas will not be needed by the microturbine as overall generation is lower. This however results in an increasing storage level for the compressed storage when running the generation plant continuously. At the end of each day, a certain amount of excess gas will remain in the storage, therefore this level continues to increase. This is shown in Figure 7, which provides storage levels for both the uncompressed and the compressed gas storage for the three seasons and a randomly chosen 30-day interval (1-5 being weekdays and 6, 7 being weekends).

The uncompressed gas storage levels (red line) fluctuate around the zero value during each day of the discussed period, however they do not significantly increase over time and remain at the daily values discussed above. As can be seen, for the compressed gas storage levels (blue line) this is just true for the winter season. Only in this season, the absolute storage level returns to its initial value, whilst for the other two seasons, the storage level increases continuously.

There are two main alternatives to handle this situation. Either the plant design is changed accordingly and gas production rates are decreased, or the excess gas is used alternatively. The first possibility however was found to not be suitable. The plant design employs high levels of internal heat stream usage, as described above. It was found that the level discussed in the base case scenario is on the minimum border of feasibility, which means that for further decreasing the ratio between the main conversion and generation units, feasibility problems will occur. The hot producer gas stream for example is used in heat exchangers, and if the plant system is minimised further, the streams will not be able to provide sufficient heat any more. Therefore, it was decided to not adjust the gas production rates and to accept the fact that excess gas will be produced.

The second possibility and the chosen alternative is to use this excess gas. For the shoulder and summer season, the amount of excess gas accounts for 10-16% of the daily production. For a whole calendar year and the distribution of days to each of the six profiles, an excess gas production of 8.2% of the total gas production can be calculated.

This amount of gas should therefore be used to provide a sufficient reserve in case of outages of the conversion units or in case of demand for higher generation. Using part of the excess gas as a security of supply means that in case of faults within the gas production units, the microturbine will still be able to provide power to meet the demand. Additionally, using part of the excess gas to be prepared for higher temporary loads such as during construction or similar activities and then being able to generate above the generation patterns described will also enhance the plant flexibility.

In case neither of those two occur and to prevent storage levels exceeding the limits, the excess gas can still be flared off. The authors are aware that this design will impact the overall plant efficiency to some extent, however it was chosen to focus on the flexibility and reliability of supply and thus accept that under some circumstances fuel gas may not be used. However, as the overall excess gas rate lies below 10%, it provides an acceptable level for such measures.

4 DISCUSSION AND CONCLUSIONS

This paper marks the way to a new idea of generating power. Instead of employing large scale generation plants and using grid technology to reach customers, the authors have designed a plant solution that can meet demand locally. By combining well-known biomass-based conversion technology to a micro-scale generation plant, fossil fuel dependency can be overcome. Instead, locally sourced and highly available feedstock can be converted into renewable energy and provide an off-grid solution for small customers that otherwise may not have the benefit of a secure and stable grid connection.

The author’s novel combined feedstock plant employs gasification and anaerobic digestion technology to convert feedstock into a biofuel, and microturbine technology to generate power. It can provide electricity on an ongoing basis and can be scaled to levels of 50kWe.

A detailed and conservatively designed plant model and extensive simulations have been undertaken in Aspen Plus, a standard software environment for chemical process simulations. The simulations provide realistic results of the plant operation when compared to literature values and have proven the feasibility of the plant.

By using domestic load profiles, it was demonstrated that the plant operation can follow load patterns and that it can be a reliable single source for electricity. High load fluctuations, which have to be expected in an off-grid application for domestic or small industrial customers, were accommodated by the plant without major problems or obstacles. This was achieved without the need of large scale electrical storage, and thus avoids all ecological and economical implications of battery or other electrical storage. Instead, cheap and reliable gas storage facilities provide sufficient capacity.

By using these intermediate fuel storages as a buffer, this plant design has proven to be able to cope with load fluctuations by adopting different output levels. Steady plant generation can be achieved by adopting a simple control algorithm, and storage sizing issues were addressed successfully. Matching demand and supply at each instant of time can be achieved by generating excess electricity and employing a power sink within the process to consume this excess power.

This plant design provides a number of major novel approaches in rural electricity provision and in applying renewable energy sources, and further simulation studies to be undertaken will reveal more of its potential.

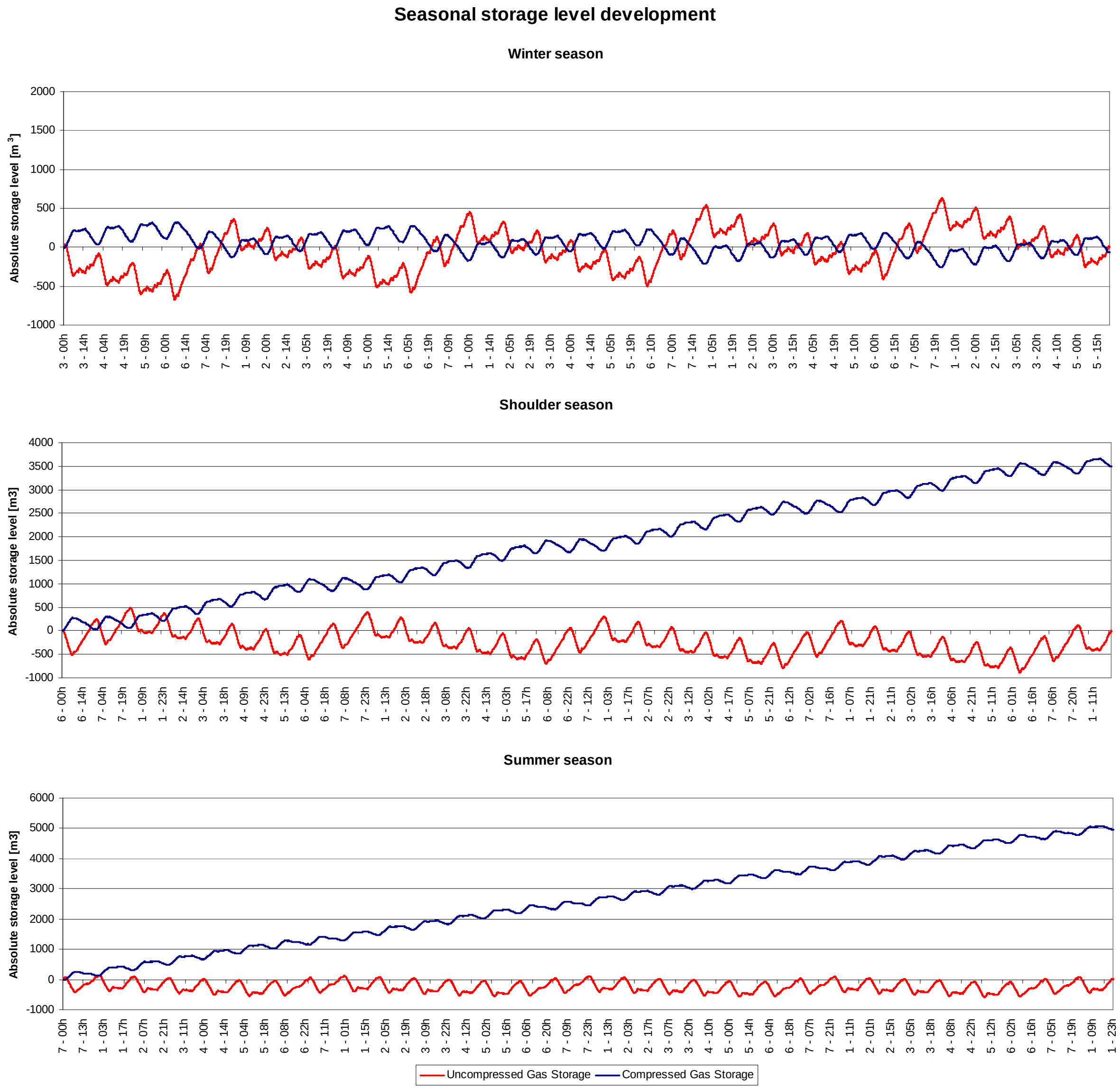

Figure 7: Seasonal storage level development for a one-month period

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