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Balancing power supply and demand in remote off-grid regions by means of a novel micro-scale combined feedstock biomass generation plant

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SUMMARY

Providing electricity to a group of remote domestic or industrial customers can be achieved by a grid connection, or by an off-grid (island) generator. While the former can become costly and will likely be prone to disruption, the latter is normally based on fossil fuels, which makes fuel sourcing and transport critical. To overcome these obstacles, a novel micro-scale biomass generation plant was developed. This plant uses locally available renewable biomass feedstock to generate decentralized power at the point of demand and without the necessity of a grid connection.

In this paper, load simulations on the basis of a process simulation model of the plant are performed to achieve a continuous match of supply and demand. It is analysed which load characteristics and fluctuations have to be expected when generating for a remote group of domestic customers, and it is evaluated how the plant needs to be operated to always provide sufficient power. Additionally, the fuel storage system of the plant system is investigated: The plant does not employ electrical storage, but instead matches demand and supply by means of internal usage of heat and power and through fuel storage. Relative and absolute storage levels as well as the storage charge/discharge cycles are analysed, and it will be shown that the plant can easily accommodate severe load fluctuations. Finally, the plant load factors are evaluated, and the findings show that this design is an interesting alternative to common island generators or to a conventional grid connection for remote customers. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: micro-scale applications; decentralized electricity generation; stand-alone-systems; waste to power; gasification; anaerobic digestion; microturbine

INTRODUCTION

Providing electricity to remote areas currently results in two main options: setting up and maintaining a network connection to an existing distribution grid, or installing an island solution, based on fossil fuel-operated micro generators such as diesel engines and batteries to level out the demand and supply.

The distribution grid networks that exist in developed countries are however reaching an age which demands large-scale efforts for modernization

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and maintenance; additionally, questions of stability and reliability become more critical as the network is to be extended. In many developing countries, such infrastructure does not exist at all. Additionally, transmission losses increase with the length of the network, and thus especially for smaller remote developments it may not be economic to set up or maintain a grid connection [1–3].

The alternative to a grid connection is an island solution, which produces electricity close to the point of demand. It is however mainly based on fossil fuel technology, which makes fuel sourcing and transport important factors. Besides, these installations normally have high maintenance efforts for regularly replacing parts of the equipment, such as lubrication and batteries. Additionally, these rural electrification systems are currently only operated intermittently and for a number of hours per day, which means that the demand has to follow the available generation level [2,4,5]. In an environment of depleting fossil fuel sources and growing carbon awareness it may also not be suitable to set up ‘dirty’ fossil fuel generators, especially in remote and mostly rural areas.

To tackle all these obstacles, providing electricity at the point of demand by means of renewable and locally sourced energy carriers would be a highly interesting alternative. The main issue that such an option would need to overcome is that domestic and industrial demand for electricity is continuous, but fluctuating, which means that it varies over time. As electricity cannot be stored easily, generation therefore needs to follow the demand closely in order to provide reliable power.

Out of all renewables, only one fuel source can cope with such requirements: Biomass is available nonintermittently and can be easily stored; therefore, it provides major advantages over its competitors wind, solar or hydro power. Additionally, biomass in general is highly available, especially in regions that are remote and do not have grid connection, as they are normally close to agricultural amenities.

Most current biomass generation plant designs are optimized towards a large scale and therefore require a grid connection to match the supply and demand [6–8]. Given the comparably low energy density of biomass feedstock, sourcing and transport issues become critical for such systems [9]. Biomass-based generation can, however, also be adopted to provide electricity in a much more flexible way and in smaller scales. As long as sufficient feedstock is available for conversion into power, a biomass-powered plant can be operated to mirror load fluctuations in order to minimize or completely omit power import or export to a grid connection point. This design can then be scaled down to local power demand levels and thus large-scale applications and their problem of sourcing sufficient feedstock can be avoided.

The authors have developed a micro scale biomass-based power plant that is suitable to supply power on a flexible basis and that can be scaled to a level as small as $50\,kW_e$ [10]. This size can meet the typical power demand of remote villages or industrial customers such as farms. It also needs an amount of feedstock that can be provided locally and on an ongoing basis, and the fact that it utilizes both wet and dry feedstock additionally benefits and eases the local sourcing.

This plant, consisting of gasification and anaerobic digestion (AD) technology, converts biomass feedstock into a fuel gas, which is then used for generation in a microturbine (MT). The plant design was modelled in chemical engineering process software and after extensive feasibility studies the authors found that this design is both feasible and capable to generate electricity on a local level [11].

Special focus is laid on the fact that the plant design does not employ electricity storage at all. Instead of using large-scale battery stacks with their negative economic and ecological impacts, fuel gas storages form the integral storage systems of the plant. Fuel gas from gasification and AD is stored in order to be flexible enough to respond to load changes. This, combined with a power sink that uses the difference between power demand and generation to increase the system efficiency, results in a system that can provide power without the need to frequently exchange batteries and dispose of them.

This paper covers plant operation simulations that were undertaken in order to match the demand and supply. A network consisting of a

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number of domestic users and the power plant represents the application of the plant design in a remote village of domestic houses. It will be shown that the plant can be operated in a way that ensures continuous power supply to the customers without an external grid connection point.

To evaluate what level of flexibility is necessary and to understand the expected demand and its patterns, domestic load profiles will be analysed. These results will then be used to match the expected demand with suitable generation patterns, and special focus is laid on how to accommodate the load fluctuations. The plant design will also be analysed with regard to security of supply, robustness and reliability, and finally the storage facilities within the plant will be analysed and dimensioning issues will be addressed.

METHODOLOGY

Brief plant model description

The general plant design and structure have been described in great detail in a previous paper [10]. It consists of a simple fixed-bed gasification unit coupled to an anaerobic digester (AD) tank. While gasification as the substochiometrical oxidation of dry biomass such as wood chips or straw is a thermochemical process and generates a producer gas of mainly H_2, CO, CO_2 and N_2, AD as a biochemical process employs bacteria strains that digest wet biomass such as manure or vegetable waste and produces a biogas mixture of CH_4 and CO_2. Both producer gas and biogas are then used as a fuel for a microturbine (MT) as the power-generating unit of the plant, and fuel storages are used to enable plant flexibility and to avoid the necessity of electric storage. Most renewable power plants use extensive combined heat and power (CHP) technology in order to use process heat externally, for example for district heating. While this approach is certainly favourable as long as high heat loads exist, in general, most CHP plants lack an economic heat usage. Instead of using process heat for external heat loads, this design hence focuses on a high level of internal heat usage by recycling the main heat streams within the process, which leads to high overall efficiency levels. The plant process flowsheet with its main units is shown in Figure 1.

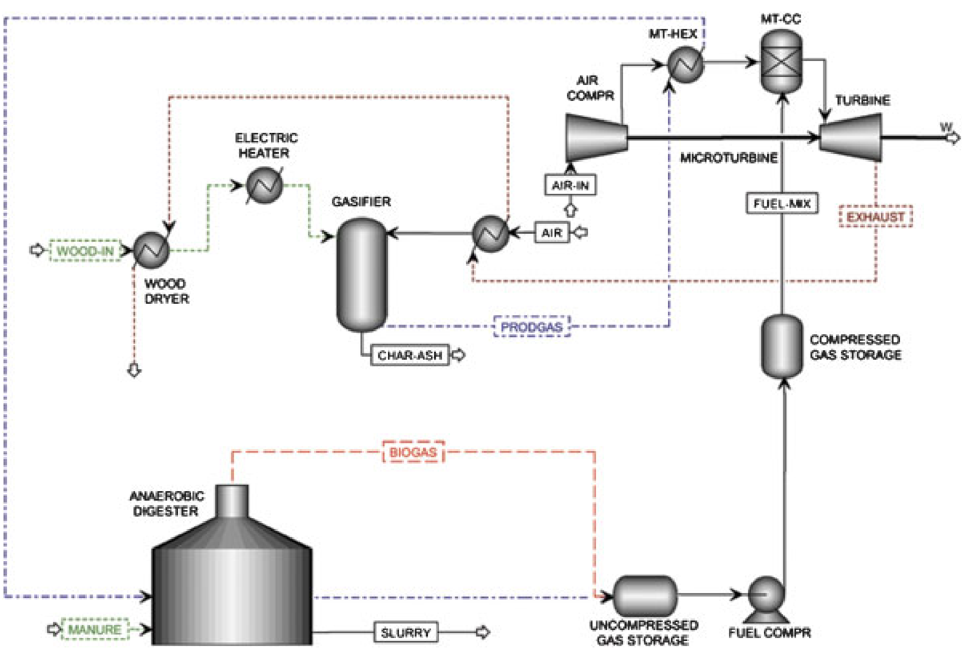

Figure 1. Combined feedstock micro-scale biomass generation plant design.

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Based on feasibility and scaling studies undertaken, it was found that this design could be scaled down to around 72 kW net base turbine power output. Considering the power amount necessary to drive the fuel compressor, this compares to a net base power output of around 58–60 kW. This minimum scale case is used as the base case for the simulations in this paper, and the feedstock input necessary to generate this power level is 112.5 kg h^{-1} of wet wood and 11 000 kg day^{-1} of manure.

In a second step, this plant design was modelled in detail by employing standard chemical engineering software. All single units of the plant are well-known chemical and/or mechanical processes, and the model set-up is based on conservatively chosen parameters that have been validated against operational plants and the available literature. The plant model provides realistic and feasible results that represent the actual plant operation. The model description as well as the feasibility study results and the underlying mathematical and chemical models were published previously in this journal [11], and this model will be used for the operational studies described in this paper.

Load profile data description

When providing a remote area of farmhouses and adjacent domestic buildings with electricity independent from the grid, a main issue that needs to be addressed is how to facilitate the security of supply. Power demand fluctuates significantly over the course of the day and depends on numerous parameters such as season, location, outside temperature, etc. To be able to analyse whether the plant can cope with such demand, it is essential to use realistic demand data for simulations.

The plant is designed to provide electricity to a remote group of domestic customers, such as a small village. Therefore, it has to accommodate the actual load profile of such a group of houses. The load profile of a single dwelling can be described as a very low constant load combined with a random aggregation of very high power spikes. This follows from the fact that in individual households electrical appliances are the main power consumer. Those appliances cause the high power spikes on an intermittent basis: they are switched on and off, but without giving prior notice and without following a fixed pattern. It is therefore impossible to exactly forecast an individual load profile and the timing of its power spikes [12].

For a group of, for example 50, dwellings, the resulting load profile, however, strongly differs from simply adding 50 individual household load profiles. The exact timing of power spikes in an individual load profile is random and cannot be forecasted, but two individual households have two different timelines of power spikes. Again, this follows from statistics and from the fact that no two households have exactly the same power demand patterns. While at one second of time one household might draw its maximum power, another household might not need any power at all, and vice versa at the next second [12].

The result of this behaviour is that the larger the group of houses is, the smoother or more flattened the resulting load profile will be. While it is nearly impossible to forecast the power spikes of an individual household, it becomes more and more predictable for a rising number of dwellings. This is the reason that the plant used for the studies in this paper is designed to provide a group of houses with ongoing power, and not an individual dwelling: for groups of around 50–100 dwellings, the resulting load profile can be deemed as sufficiently flattened to be used for operational analyses [12].

Obtaining useful and detailed domestic load data is, however, very difficult. Restrictions on publication of load data exist as they are classified as proprietary by the utilities who hold them. Openly accessible load data is rare. A source deemed as both usable for the feasibility and simulation studies to be undertaken, and appropriate in means of real underlying data has been the publication of residential load profiles from the 'IEA/ECBCS Annex 42 Subtask A' research project [13].

These data provides the average 5-minute interval load demands (in Watt) based on a group of 69 residential UK dwellings, which were monitored between 2002 and 2005. This means that for every 5 min, a data point provides the average power demand drawn during this period by all the

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houses, divided by the number of houses in the group. The data sets are exclusive of space heating and consist of pure electricity demand. The measuring was undertaken during a 2-year period, and flats, town houses as well as semi-detached houses were included in the group.

These data are presented on a 1-day time basis and are differentiated by weekday/weekend and season. Three seasons were determined: winter (December–February), summer (June–August) and two shoulder seasons covering the remaining months of the year.

As can be expected, significant load level differences for the three seasons exist in the data sets for both weekdays and weekends, which is shown in Figure 2.

During the weekdays, two main peaks occur, which correlate with the working time of dwelling inhabitants. Night-time demand for electricity is lower than the day-time demand. In contrast to that, a shifted demand pattern occurs on weekend days, and a less distinct morning peak can be found. A relatively steady increase in the demand

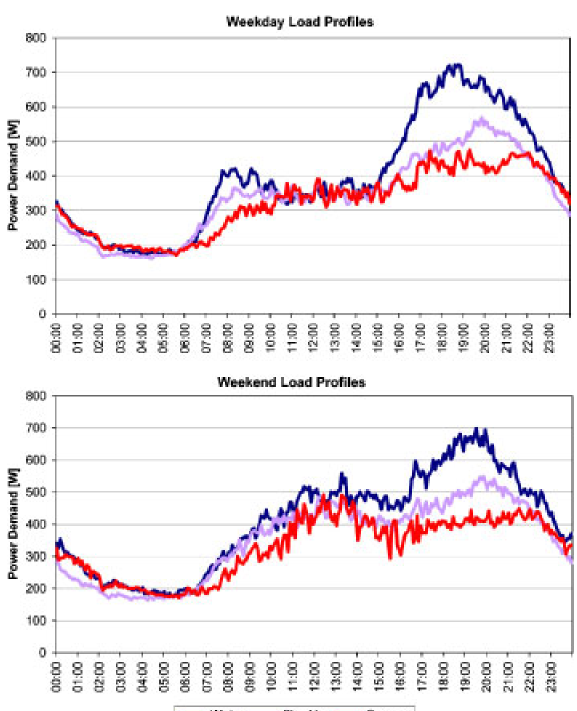

Figure 2. Seasonal household load profiles.

for electricity from the morning to the evening levels can be seen, and again the night-time demand is significantly below the day-time demand. These trends were expected and are well known in load profiling research; therefore, they indicate the usability of the data.

Discussing seasonal differences, the power demand is considerably higher in winter times than during the summer, especially during weekdays. While the intra-day patterns remain on a comparable basis within the seasons, their absolute level changes significantly. However, this result also has to be expected, as lighting demand or use of cookers increases during the cold seasons.

The data were collected between 2002 and 2005, thus a comparison with the current demand levels is necessary. Current absolute domestic electricity demand might be on a different level than provided in the source files; however, general patterns will remain the same. The average U.K. domestic electricity consumption for example has risen by 2.0% between 2002 and 2005, and fallen by 1.5% between 2005 and 2007 [14]. The focus of this paper, however, is to analyse the ability of the plant to cope with load patterns and fluctuations. As the general demand patterns that the data represent are still valid, it was decided to use the initial load data for the research and investigations to be undertaken, without manipulating it. Further work will include obtaining more recent load profiles that will enable to further validate this assumption.

A final evaluation was necessary to find a fitting number of houses that the power plant will provide with power. The plant size discussed above defines the minimum border of feasible scale and it was therefore decided to choose a demand pattern level that fits this scale. The original load profiles at each time interval provided the average power drawn by the whole group, divided by the number of dwellings. They were thus the proportionate per-dwelling load profile. For this study they were multiplied by a factor representing the number of dwellings to obtain the whole group's load profile. Evaluating the total net base power output levels and including suitable buffers for power increases, this multiplier was chosen as 120, which means that the load patterns in this study are set for a representative group of 120 dwellings.

SIMULATION RESULTS AND DISCUSSION

Simulation set-up

In order to consistently and reliably match the demand, several power generation algorithms have been evaluated. On the one hand, generation needs to be at least at a level of the demand, and this becomes critical as demand can change significantly within short periods of time, hence a buffer needs to be implemented to cover instantaneous demand increases. On the other hand it is necessary to minimize generation in order to use resources effectively and to not generate significantly above the demand.

A number of power steps were developed for the generation plant to meet the demand. In order to allow smooth plant operation, it was analysed which operation pattern provides a combination of sufficient power output and acceptable excess power amounts. A minimum power output of 50% of the nominal turbine power was chosen, as this level has been mentioned as the minimum level at which MT generation can still be achieved in an effective and stable manner [15].

Based on the maximum expected demand and including a sufficient buffer for increasing demand, a nominal power level of 100 kW was established, which in turn means that the minimum power output will be 50 kW. These levels also correlate well with available MT technology [16–18].

The area between those two boundaries can be divided into a discretionary amount of intermediate power steps; however, the more the steps, the more often will the turbine need to be adjusted. Each plant adjustment will influence the stability and will require some time; hence, there will be a trade-off between the number of steps and their impacts on the operation stability. Additionally, the MT as the generation unit of the plant needs around 20–30 s to adjust to a new power level [19], thus infinitesimal power adjustment steps are not realistic.

By analysing and minimizing the offset power and using sufficient buffers, it has been found that three steps, at 65, 75 and 85 kW, provide an energy efficient and reliable operation pattern.

Before running the load patterns against this generation profile, it was finally checked whether the generation steps are feasible and how they impact the plant operation.

Generation step analysis

Both conversion parts of the plant need to be operated on a constant and continuous level to enable the AD processes and to maintain the gasifier temperature distribution. This however means that a certain amount of producer gas and biogas will be produced continuously.

The plant is using heat streams within its own processes, hence it is necessary to understand the impact on the plant when adopting several power output levels while keeping the conversion rates constant.

The output power of the MT depends on the amount of fuel gas, which is fed into the turbine. As the MT air intake is calculated on the basis of the fuel gas amount, this will change accordingly when adopting different power steps. This mainly impacts the MT heat exchanger, which uses the producer gas exhaust heat stream. An increase of air intake in the air compressor will mean that the heat exchanger will also be operated on a higher air mass stream. This effect is shown in Figure 3, which depicts the MT air intake amount as a function of its power output.

As the heat exchanger has a set geometry that will not change when more air is flowing through it, the amount of heat to be exchanged between the air stream and the producer gas stream will remain relatively constant. This however means for a higher air stream that the air outlet temperature, which is the temperature after the MT heat

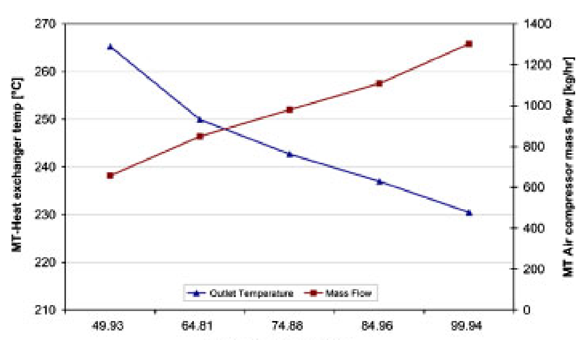

Figure 3. Power output variation impacts.

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exchanger, will change. This effect is also shown in Figure 3.

It can be seen that while the air mass stream increases with increasing power output, the hot air temperature decreases. However, the absolute level, from 265°C for half nominal load to 230°C at full load, does not influence the MT operation significantly, as the combustion chamber still provides sufficient levels of thermal energy for the exhaust gas to reach its maximum temperature level.

Other main plant parameters have also been checked and it was found that all parts of the plant can cope with changing the power output between half and full nominal power. Therefore, the MT operation on the chosen power steps is feasible, which means that this generation pattern can be used to try to match the demand.

Supply and demand analysis

For each of the three seasons that were discussed above, the daily demand patterns, rounded up to the next multiple of 5 kW, are shown in Figure 4. The *Winter Season* weekday and weekend profiles

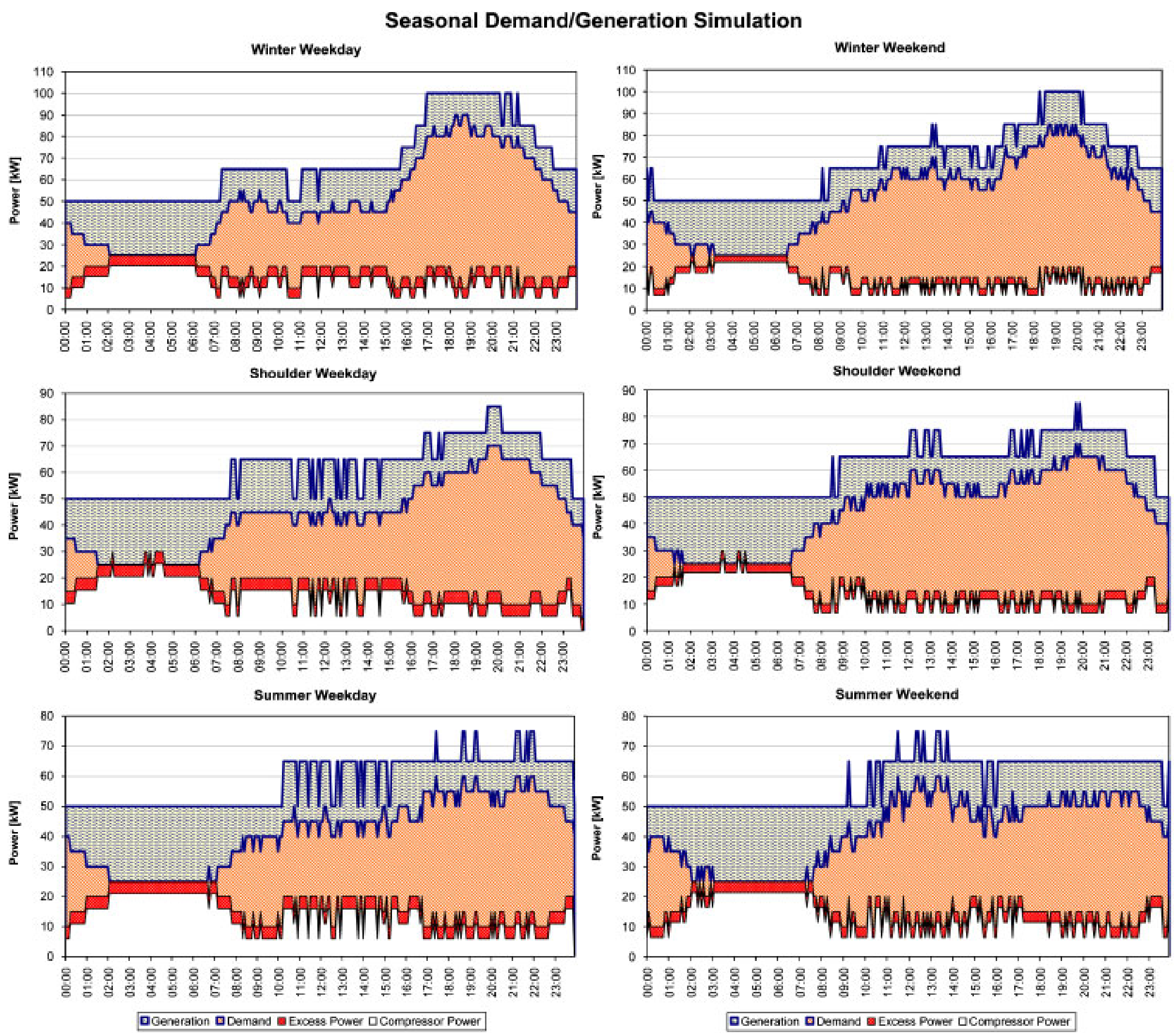

Figure 4. Seasonal demand and generation simulation results.

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are of the highest criticality with regard to their absolute level, thus they were analysed first.

Depending on the demand, the MT output was set to its respective power step of between 50 and 100 kW, using a control algorithm. As can be seen, the night-time demand falls sharply to levels of 25 kW, whereas the evening peaks reach values of up to 85 kW for the weekday and 80 kW for the weekend case. The difference in power generation between the demand curve and the generation curve can be defined as excess power and needs to be used within the process, as no electric storage is implemented. However, as the fuel compressor needs a certain amount of power to compress the producer gas/biogas mixture to the pressure level demanded by the MT, it acts as a compensator or sink of excess power.

The fuel gas conversion rates remain constant during the day, resulting in a constant output of uncompressed gas mixture, which needs to be compressed. However, there is no immediate need to compress this gas as long as storage is available, and this is why the fuel compressor can be employed as a tool to match supply and demand: it is operated on different power levels, depending on the amount of power available. As long as the whole gas amount is compressed during a longer overall period, such as one day, and as long as sufficient storage capacity is implemented, the MT will have sufficient compressed fuel gas to provide the demanded power levels. The variable compressor power level is shown in Figure 4, and it was calculated as the difference between generation and demand, including a buffer value called *Excess Power*, which is also shown in the graphs.

It can be seen that the power level of the compressor fluctuates between 5.3 and 20.3 kW for the weekday and between 7 and 22 kW for the weekend profiles. The resulting absolute value of the buffer indicates the criticality of the case, which means that a close match of demand and generation results in a low value of *Excess Power*. For both winter cases the buffer is between 3 and 5 kW, which provides sufficient levels for instantaneous power spikes, as will be discussed below.

Next, the demand patterns for the *Shoulder Season* weekday and weekend profiles were analysed. Compared to the winter profiles, a significant overall decrease in the power level can be seen. While the maximum demand reaches a level of 85 kW for the winter case, it only touches 70 kW for a maximum of 30 min during the shoulder season evening peaks. Simultaneously, the generation never reaches its full nominal power of 100 kW but stays below or at 85 kW for both weekday and weekend. This means that the total MT utilization factor decreases from 68% for the winter season cases to 61% for the shoulder season cases. However, as the main intention of the plant is to provide power continuously, a lower load factor has to be expected. This concept differs from conventional plant designs that aim for a large scale and high load factors, which mean flat output at nominal power, as they assume demand and supply can be matched by means of a grid connection.

The night-time demand during the shoulder season falls to 20–25 kW, which is also slightly lower than the respective winter demand. This means that the fuel compressor power range increases to 5–27 kW.

The *Excess Power* buffer level for the two shoulder season cases is also shown in Figure 4 and is slightly above the respective winter cases, which suggests that the shoulder season is less critical than the winter season.

Finally, the two *Summer Season* cases will be discussed. Again, the maximum demand level decreases and reaches a maximum value of 60 kW for the weekday evening peaks and for the weekend mid-day time. It is interesting to note that the summer season weekends are the only patterns where demand during the day is higher than evening demand, which might be related to a high demand for cooking and an otherwise low demand throughout the day.

However, apart from this change of the peak time, the demand profiles are similar, as the differences between daytime and evening are more distinct during the weekends than during the weekdays, and the night-time demands are significantly lower. For the summer period and especially for weekends, a nearly flat power demand can be seen, as the peak loses its distinction.

The generation pattern follows this lower demand and the MT power output reaches a maximum of 75 kW, which is one power step below the

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shoulder season and two steps below the nominal power. This results in a further slight decrease of the total MT utilization factor for the summer cases to 58%. The fuel compressor is operated in a range of 6–22 kW, which is also slightly lower than in the shoulder season. Again, the *Excess Power* buffer is slightly above its winter case value.

For an operation period of a whole calendar year, an average MT utilization factor can be calculated on the basis of allocating calendar days to the three seasons and to weekdays/weekends. This means that a calendar year consists of one winter season, one summer season and two shoulder seasons, with 65 weekdays and 26 weekend days per season. The overall average utilization factor for one calendar year can then be calculated as 62.2%, which as discussed above is an acceptable level considering the plant objective of continuous power supply.

Storage level and charge/discharge analysis

Both the MT output power and the fuel compressor power level are variable in order to level out the plant; therefore, gas storage becomes a necessity. Both conversion processes (gasification and AD) create a continuous flow of uncompressed gas, which, before being used as the MT fuel, needs to be compressed in the fuel compressor. The fuel compressor will be operating on several load levels as discussed in the sections above, so a certain amount of producer gas/biogas mixture will need to be stored in an uncompressed gas storage. Similarly, the amount of gas to be compressed does not necessarily equal the amount of compressed gas required by the MT, so the difference between those two amounts needs to be stored in a compressed gas storage.

To analyse sizing issues of both storages and to validate whether this operation pattern leads to an effective operation of the plant, it is necessary to evaluate the storage charge and discharge cycles as well as the absolute storage levels.

For each of the six demand profiles, the absolute levels of both the uncompressed gas storage (before the fuel compressor) and the compressed gas storage (after the fuel compressor) are shown in Figure 5. The scale of both graphs is m^3; however, it should be noted that the pressures are different: While the uncompressed gas storage has an atmospheric pressure, the compressed gas storage is maintained on a pressure of 5 bar to satisfy MT energy intake requirements.

In addition, Figure 5 also depicts the actual amounts of gas that are charged to or discharged from each of the two storages. The line named '*Uncomp Gas Dis-/Charge*' shows the volume of uncompressed gas mix being charged or discharged from the uncompressed storage. It equals the production amount minus the amount being compressed, depending on the current fuel compressor power. This means that it becomes positive when the fuel compressor compresses less gas than being produced, in which case the difference amount of gas is charged to the storage. It becomes negative when the fuel compressor compresses more gas than being produced, in which case the difference amount of gas is discharged from the storage. The scale again is volumetric with atmospheric pressure.

Simultaneously, the line named 'C*omp Gas Dis-/Charge*' shows the charge and discharge cycle for the compressed gas storage. Depending on the generation level of the MT, a certain amount of compressed fuel gas is needed. The line shows the difference between the amount of gas compressed by the fuel compressor and the amount needed by the MT. This means that it becomes negative when more compressed gas is needed by the MT than provided by the fuel compressor; this additional amount is then discharged from the storage. It becomes positive when the fuel compressor provides more gas than is needed by the turbine; this excess amount is then charged to the compressed gas storage.

In general, it can be seen that for the whole period of one day, the absolute storage levels of the uncompressed storage (the lines named '*Uncomp Gas Storage Level*') are balanced to zero. The total fuel compressor power over the whole day equals the amount of power that the compressor needs to compress the production volume, hence the storage start and end level must equal to zero. However, one can see that for all seasons, the night periods are the times of discharging uncompressed gas from the storage. This follows from the fact that the demand reaches its lowest levels during the night.

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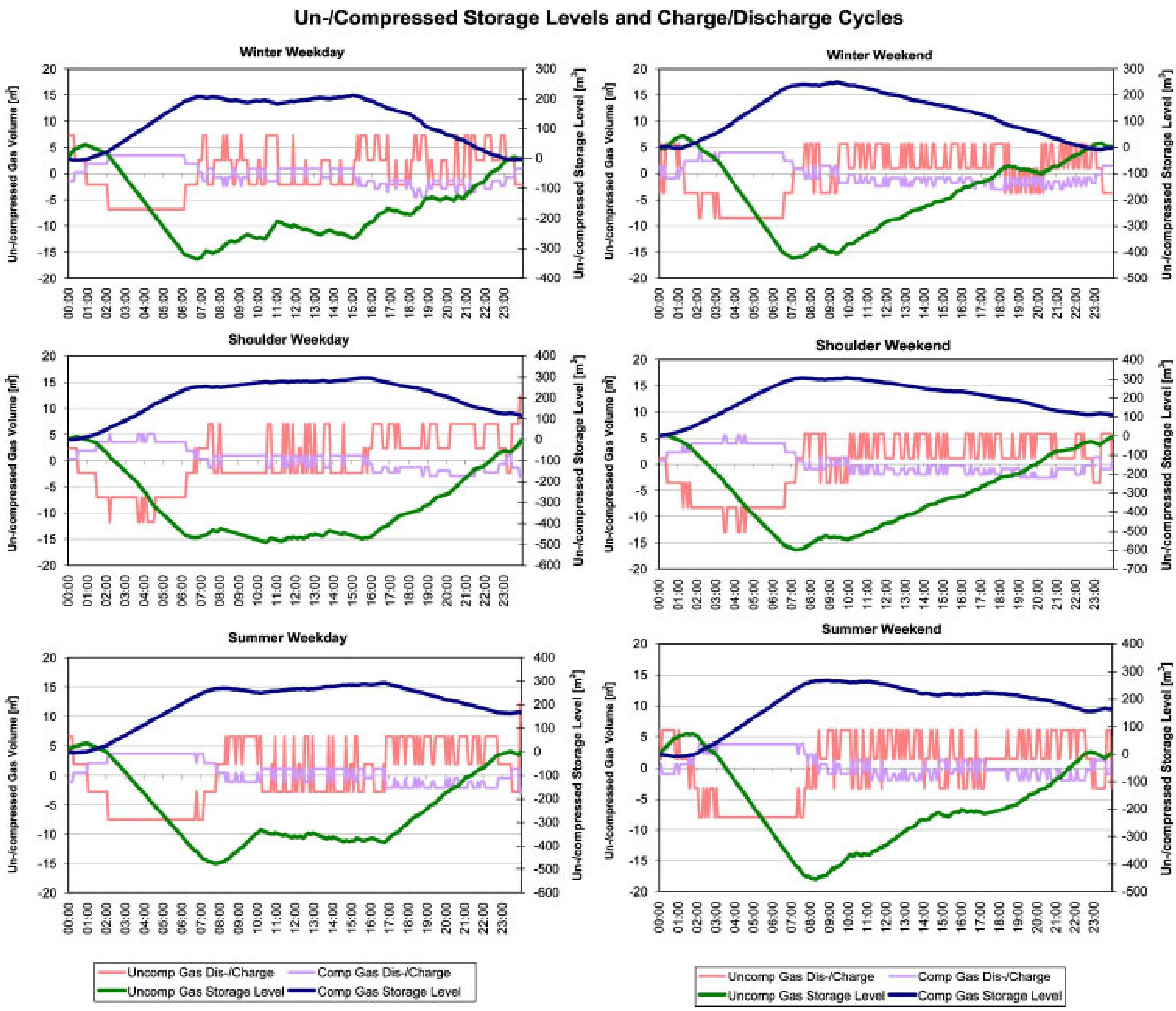

Figure 5. Storage levels and charge/discharge cycle.

As the MT is restricted to a minimum power output, the night times are the times of the highest fuel compressor power, which can be seen in Figure 4. Therefore, during the night the fuel compressor compresses more gas than is being produced, so it discharges from the storage. In comparison to that, during the day and evening peak times, the fuel compressor power is relatively low, as demand peaks and no power is 'left' for the compressor. So during those times, the fuel compressor compresses less gas than is being produced, and as a result the storage is charged with uncompressed gas.

The lowest absolute level of the uncompressed storage is the amount of gas that needs to be provided in order to ensure ongoing operation. It reaches its peak at a level of between 400–600 m^3 for the different seasons. Based on a gas production of 3528 $m^3\,day^{-1}$ for the discussed base case, which results from the raw feedstock intake rates mentioned above, this means that between 12–18% of a daily production needs to be provided as storage. Both from the point of view of the absolute storage level, which influences the storage costs, and from its relative level, which impacts the operation of the system, this size can be deemed acceptable.

In comparison to that, the compressed gas storage levels (the lines named '*Comp Gas Storage Level*') show a different pattern. Again, in the winter case, by definition, the total daily gas production rate equals the amount of gas needed by the MT, so all gas compressed will be used by the turbine throughout the day. As night-time power levels are low, the MT needs less compressed gas than provided by the compressor, and the storage is charged. Simultaneously, during the times of high turbine generation, the storage is discharged.

However, the compressed storage will just level to zero for the winter cases, while for the shoulder and summer seasons, it does not return to being empty. This follows from the fact that during shoulder and summer seasons, the total power generated by the MT over the whole day is below the respective values for the winter season, as discussed above. Table I shows that for both winter cases, the generation patterns result in the same amount of $kWh\,d^{-1}$ of generation. Compared to that, for the shoulder and summer seasons, the generation patterns are lower due to lower demand. Simultaneously, the uncompressed fuel gas amount required to generate the calculated amount of power is lower for the shoulder and summer seasons than for the winter season. As the gas production rate stays constant at $3528\,m^3\,d^{-1}$, this results in more gas being produced than being needed by the turbine. The relative excess gas ratio amounts to 9.2–9.5% for the shoulder season and 13.6–13.8% for the summer season, respectively. The absolute excess gas amount mentioned in Table I equals the amount that is left in the compressed gas storage at the end of the 1-day period in Figure 5; however, it should be noted that Table I states uncompressed volumes, while Figure 5 shows the compressed volume.

The absolute peak levels for the compressed storage reach between 200–300 m^3 of compressed gas. Based on the daily production of gas and converting uncompressed into compressed volumes, the storage needs to be sized to around 17–26% of the daily production, which again is on an acceptable level.

Given the amount of excess gas produced during the shoulder and summer seasons, and using the allocation of calendar days to an operation period of a whole year as mentioned in the section above, the average yearly excess gas production amounts to 8.2% of the total gas production. Therefore, it could be beneficial to decrease the average gas production rate accordingly. However, a further decrease of the gas production rate will impact the streams within the plant design, as heat exchangers use hot gas streams such as the producer gas stream for preheating parts of the plant, as discussed before. Therefore, an alternative to adjusting the gas production rate would be to use this excessive gas mixture as a source for additional power necessary to pretreat feedstock. For example, the gasifier feedstock needs to be provided in a certain particle size, thus a wood chopper would be necessary, which can be operated in intervals by extra power generated from the 'excess fuel gas'. Another possible use of this gas could be as a safety buffer for demand increase or

Table I. Generation comparison and excess gas calculation.

	Generation [$kWh\,d^{-1}$]	Gas demand [$m^3\,d^{-1}$]	Excess gas [$m^3\,d^{-1}$]	Excess relative [%]
Winter				
weekday	1624	3528	—	—
weekend	1624	3528	—	—
Shoulder				
weekday	1470	3192	336	9.5
weekend	1475	3203	325	9.2
Summer				
weekday	1400	3041	487	13.8
weekend	1403	3047	481	13.6

for unplanned issues such as quality problems with the fuel gas.

Demand fluctuation analysis

A final investigation analyses the amount and occurrence of fluctuations within the daily profiles. As described earlier, the plant needs to be flexible enough to accommodate sudden load changes, as there will be no electricity storage available. Therefore, it is essential that the generation always exceeds demand so that a sufficient buffer for higher loads exists. The algorithms that were employed to set the level of generation are based on the actual load profile demand; however, they were checked against changes in the demand from one data point to another.

It first needs to be remembered that the load profiles provide data in 5-minute intervals, while a real load profile will change more often. In reality, the load demand of a group of dwellings will change continuously [12]. This means that however fine a scaling is applied for load profiles, it will never provide the actual load, but will instead always provide a number of average loads for each time interval chosen. The actual load changes, however, are the ones that the plant has to cope with, hence the analysis in this chapter first has to evaluate to what extend the data available is representative for the actual changes. A more transient analysis that investigates the short-time actual load changes will remain a part of further work as it requires actual real-time demand changes, which are not available yet. The authors are currently obtaining load profiles on a highly detailed basis (far less than one second) and once this data is available, a fully transient analysis can be undertaken.

To understand whether the load profiles available can be deemed appropriate to characterize real load profiles, their characteristics need to be analysed. It was discussed above that load changes of an individual dwelling do not follow a firm pattern, but are random, and that this random distribution results in a flattened and smoother load profile for a larger group of households. The sampling interval of 5 min can also be treated as random, because during the sampling period a random time was chosen as the starting time of the interval. As the load changes do not follow a pattern, the sampling intervals will not regularly coincide with the actual load changes. For each interval, the data provide the average amount of power drawn, and this means that each interval will contain a random amount of actual load changes, which fell within the sampling interval. When comparing one interval with another, the difference between the two average amounts of power is compared, and thus the difference of the two random amounts of load changes. This however means that the characteristics of the available 5-minute intervals will not be different from lower sampling intervals, as long as they still are of a size that includes a number of different load changes. It was mentioned above that even 1-second intervals will include a number of load changes, as load fluctuates continuously. Therefore, the available 5-minute intervals will be a valid approach to characterize and analyse the change of demand over time, which is what this study aims for.

It has been shown experimentally that load ramping of a MT can be achieved without major impacts on the frequency and voltage of the output power; however, it will take around 30 s to adjust to a new power output [19]. This implies that the MT will never be able to immediately follow the load, but that it will need time to adjust to a new power step. Hence, the algorithms to be implemented for following the load will have to include sufficient buffers to accommodate load changes within the time period of adjusting the MT. Therefore, an analysis of the absolute fluctuations to be expected from one data point to the next was undertaken. The absolute demand fluctuations from one data point to the following are shown in Figure 6 for the six available profiles.

In general, it can be stated that the most significant fluctuations occur during the day-time, while during the night only lower levels of demand change are seen. This pattern is similar throughout all seasons and does not vary significantly between weekdays and weekends, although the increase of fluctuations is slightly delayed to the later morning hours on weekends.

These findings, however, correspond to the average activity patterns of inhabited dwellings.

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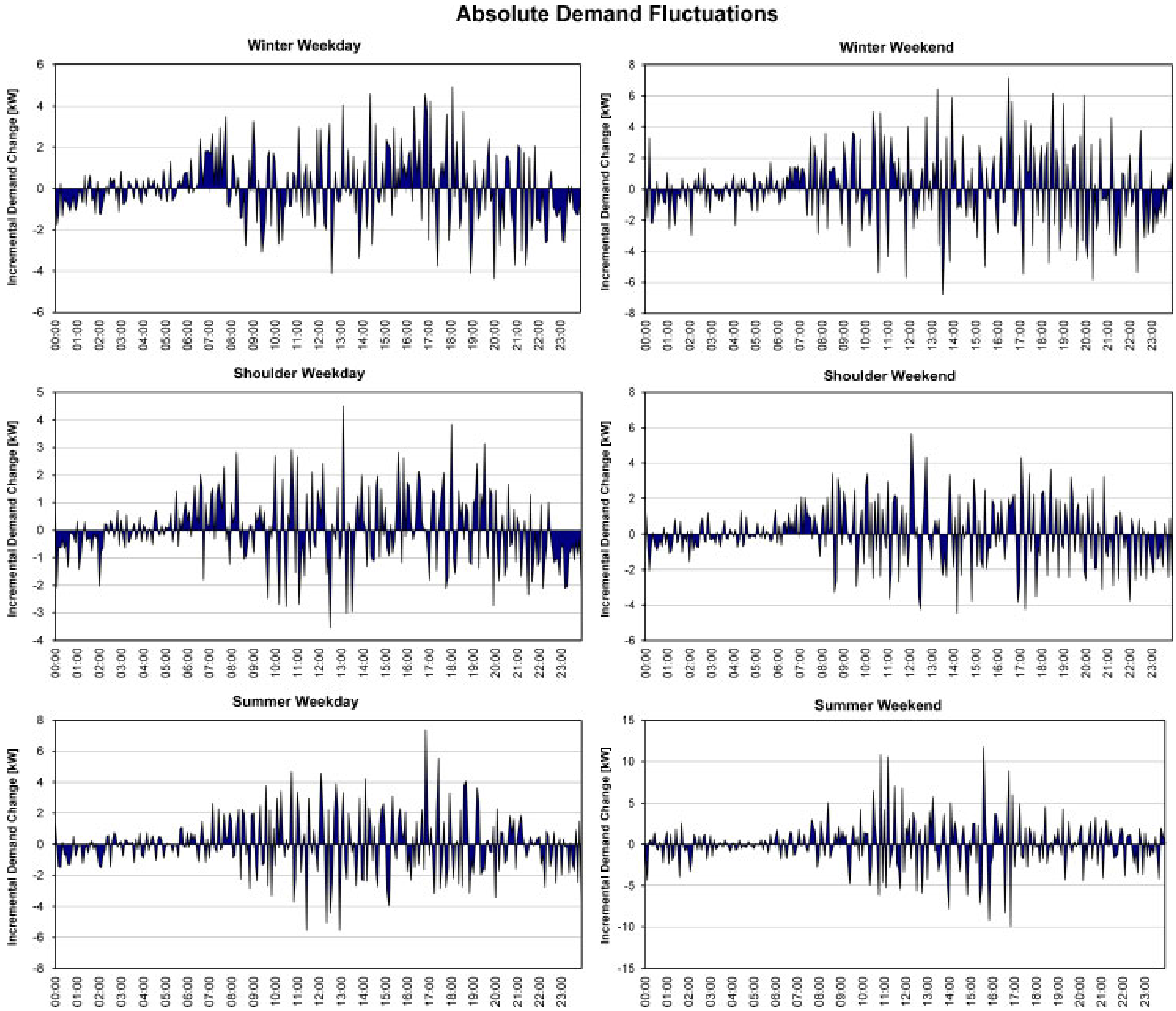

Figure 6. Absolute demand fluctuations.

During the night, comparably few appliances are switched on or off, so the demand is more stable than during the day-time or evening, where inhabitants use appliances intermittently.

Discussing the actual size of the fluctuations, it can be seen that for all profiles apart from the summer weekend profile, the peak fluctuations are below 8 kW. For the summer weekend case, they reach levels of above 10 kW, however, only on three (out of a total of 288) occasions. Table II provides the maximum absolute fluctuation as well as the average absolute fluctuation and their respective standard deviation values for the six cases.

Compared to demand increases, demand decreases can be treated with ease. Should the demand for power slump, then more power is available for the fuel compressor, which results in a higher fuel gas throughput. Therefore, the power decreases are of low criticality.

The plant, however, has to accommodate increases in demand by means of the buffers included in the calculation of the generation pattern. The buffers need to be of sufficient size, which means they need to be at least of the size of the fluctuations, and sufficient margins of safety need to be included as well.

Table II. Demand fluctuation analysis.

	Max. abs. fluctuation [kW]	Avg. abs. fluctuation [kW]	Standard deviation [kW]
Winter			
weekday	4.92	1.24	1.05
weekend	7.17	1.74	1.51
Shoulder			
weekday	4.49	0.92	0.79
weekend	5.62	1.26	1.08
Summer			
weekday	7.35	1.32	1.22
weekend	11.77	1.92	2.01

Table III. Safety margin analysis.

	Excess power [kW]	Min. comp. power [kW]	Margin of safety [%]
Winter			
weekday	4.72	5.27	203.3
weekend	3.02	6.98	139.5
Shoulder			
weekday	4.53	5.47	222.5
weekend	3.26	6.74	177.9
Summer			
weekday	4.01	5.99	136.0
weekend	3.54	6.46	85.0

As discussed previously, the buffers consist of a variable part and a fixed part. The variable part is the difference between the actual demand and the round-up value to the next multiple of 5 kW. The size of this will thus always be below 5 kW; however, it is difficult to evaluate what actual size this buffer will have in general. Analysing the size of the buffer for the available profiles results in levels between nearly 0 and nearly 5, which is the whole available buffer range. Averages are within a band of 2.3 and 2.7; however, the standard deviation, with between 1.3 and 1.6, is relatively high. Additionally, due to the way of measuring the load, the buffer size will always be of random origin, as instantaneous actual demand changes do not fall together with measurements at fixed time intervals. Therefore, this buffer cannot be allocated a safe value for this analysis and will be excluded, although knowing that additional safety exists, but cannot be guaranteed.

The fixed size buffer is the difference between generation and rounded demand. It consists of two parts, of which one will always be available: First, the amount of what has been called *Excess Power* in Figure 4, which is the difference between generation and demand plus fuel compressor power. This buffer will always be available for accommodating fluctuations. The remainder of it will have to be used up by the plant's power sink, the electric heater, as no power can be stored. As discussed in [11], the electric heater can compensate up to 6.25 kW of power on a continuous basis, and even higher power levels as long as they occur intermittently. The second part of the fixed size buffer is the actual amount of power dedicated to the fuel compressor. Although the fuel compressor should be operated on this power, in the event of a high-level power spike, the plant will override this allocation and use the fuel compressor power to meet the demand. As this can be done by automatic control, it will provide sufficient power to the demand as long as the fuel compressor can be switched to a lower power level. The level of the *Excess Power* as well as the minimum power available for the fuel compressor are stated in Table III; additionally, the margin of safety is given as a percentage of the respective maximum absolute fluctuation (being 100%) of Table II.

Analysing the level of both the *Excess Power* and the amount of power dedicated for the fuel compressor, it can be seen that there will always be sufficient power available to accommodate the demand fluctuations. Apart from the summer weekend case, the maximum increase in the power demand from one data point to the next can always be met by the buffer, and as the margins of safety are all above 100%, it can be concluded that even the highest peaks can be accommodated with ease.

For the summer weekend case, the margin of safety is below 100% due to the three extremely high single peaks. If those three peaks were excluded from the data set, a margin of safety for the summer weekend case of 101% would be the result, which means that the remaining peaks fall within the level, which can be accommodated.

It should at this point be mentioned again that with a rising group of dwellings the resulting load profile flattens and smoothens. The original load

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profiles were obtained from 69 dwellings [13]; however, the multiplier used for this study created a group of 120 dwellings. Therefore, the flattening effect of increasing the group size from 69 to 120 was not included. Increasing the number of households in a group has a significant impact on the absolute level of power spikes in a way that the larger the group, the lower the relative value of its power spikes. This however means that for a larger group of dwellings, the amount of the highest power spikes will be smaller, and for the given group of 120 houses the highest relative peaks would also be below the level of a group of 69 houses. The three peaks in the summer weekend profile can therefore be accepted as exceptional peaks that result from the methodology. The values for the other cases show that significant margins of safety were implemented even on the basis of the highest available peaks; therefore, it would be unreasonable to conclude that those three peaks would also need to be accommodated. A very conservative approach has been chosen and the authors are confident that this exclusion can be accepted.

It can therefore be concluded that the plant is able to cope with absolute and relative demand fluctuations with ease, and that it can reliably provide power on an ongoing basis. Additional work however needs to investigate in more detail the transient behaviour of the power system based on actual real-time demand changes that occur, in order to provide further proof that the fluctuations of the profiles used in this study are realistic.

CONCLUSIONS AND FURTHER WORK

A novel micro-scale biomass plant has been designed to provide reliable renewable energy to customers in remote regions. While the current focus of biomass power generation is on large-scale plants that provide flat base-load electricity and use an ageing and costly grid infrastructure, this design uses locally available feedstock to generate power at the point of demand. Instead of optimizing the plant for a flat base power output, this design accepts lower overall load factors and excess power generation and instead focuses on the ongoing power provision and flexibility of operation. It can thus provide decentralized reliable energy and help remote areas to gain energy self-sufficiency.

While the plant description and modelling was covered in a previous paper in this journal, in this paper it was shown that the plant is able to meet the local domestic demand for power on an ongoing basis. Flexible power generation was achieved using domestic load profiles. For a group of 120 dwellings of domestic use, the daily demand ranges within a minimum of 25 kW to up to 85 kW for a winter weekday, compared to 25–60 kW for the summer weekend. This very high level of demand variation can be accommodated by the plant with ease. By applying different generation steps between half load and full nominal load, the output can be adjusted to the demand. By including sufficient load buffers, the plant can cope with those load changes, and it can still be operated in a smooth and stable manner. It has thus been proven that the plant is able to provide the needed amount of power on a 24/7 basis during all seasons.

Apart from the flexibility of operation, the plant provides another unique design feature: electrical storage such as batteries was avoided, which provides significant benefits with regards to maintenance, economic and ecological impact. Fuel gas will be stored to provide capacity for adjusting the power if necessary, which is a more suitable alternative to electrical storage. The sizing of the gas storages was investigated and found to be on acceptable levels: to provide sufficient storage for the plant, absolute maximum storage levels will not exceed 20 or 30% of the daily gas production for the uncompressed or compressed gas storage, respectively. Those storage volumes can be implemented with ease and result, together with the technology applied for the remaining plant units, in a conveniently sized local power plant.

The ability of the plant to accommodate instantaneous load changes was also evaluated in this paper. Especially for domestic power demand, intermittent appliance usage results in power spikes and slumps, which becomes critical for local generation without grid connection, as those fluctuations need to be met by sufficient generation.

The plant design can be adjusted quickly to accommodate higher loads by switching power from the fuel compressor and electric heater, which act as the power sinks of the system, to the demand, and vice versa in case of power slumps. The plant can thus meet the demand continuously without power cuts or demand-side management, but by generating the above demand and utilizing this 'excess' power within its own processes for higher efficiency.

By using realistic load profiles of a fitting size, the criticality of ongoing power supply for highly changing loads was addressed and resolved. Further simulations will be focused on a detailed transient analysis. Additionally, different load patterns such as farm-scale or industrial load profiles will be analysed to prove whether this design can also be employed for such customers, and an economic analysis of the plant will be undertaken to compare this novel form of rural electrification to a conventional grid connection.

It has been shown in this paper that the novel combined feedstock micro-scale biomass generation plant design is able to supply ongoing reliable power to remote domestic demand. This design marks a milestone in the field of biomass-to-power applications research and shows an alternative to often-preferred centralized large-scale power plants.

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