Integration of biogas systems into the energy system

Technical aspects of flexible plant operation

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Integration of biogas systems into the energy system

Technical aspects of flexible plant operation

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Executive Summary

Energy systems of the future

The climate emergency requires vast changes in how we produce and use energy. The electricity sector includes for ever increasing portions of intermittent renewable electricity such as from wind and photovoltaic (PV), neither of which are dispatchable. Innovation and ingenuity will be required by electrical utilities in matching supply to demand and in monitoring and control of grid frequency and voltage. Producers and consumers of energy will face significant changes in the energy market, particulary associated with times of production of energy and times of use of energy. The integration of energy vectors will be essential in facilitating PV during daylight hours, wind power on windy days and renewable sources of dispatchable energy such as from bioenergy. The need to cope with the changes in demand for energy over the day, the week or the season results in technical requirements for the energy supply system such as start up time, capacity increase and decrease rate, and time to shutdown. The requirements from different energy sectors or specific customers differ substantially. Gas is also a major component of the heat sector both for district heating which is seasonal in nature and for industries which have a more constant demand but very large scale of energy requirement. Renewable gaseous fuels (including for hydrogen and biomethane) have great potential to decarbonise transport fuel use in haulage and intercity buses. The demand profile here depends on the logistics of the vehicle use and whether the renewable gas facility is situated adjacent to the filling station for the transport fleet or is at a remove from the transport fleet and uses the natural gas grid to serve gas to the transport fleet.

Flexibility of biogas systems

Flexibility in this report represents the ability of a biogas plant operator to control operation in a manner to best match the output of the biogas plant with the demand of the users of the provided energy be they in the electricity, heat or transport sectors. Demand oriented, flexible operation requires a controllable and scalable interaction of all components of the biogas production and utilization process. The achievable degree of flexibility of the overall plant depends on the installed capacity of the components and the controllability and response characteristics of each component. Additionally the availability of storable feedstock for the biogas facility has to be considered when manipulation of the whole production chain is taken into account.

Biogas systems can also serve as a sink for electricity produced at a time of low demand and as such can reduce curtailment and constraint of intermittent renewable electricity. Hydrogen produced via electrolysis may be used to upgrade biogas to biomethane through the action of hydrogenotrophic methanogens which utilise hydrogen and carbon dioxide in the biogas to generate methane ($4H_2 + CO_2 = CH_4 + 2H_2O$). The process typically increases the methane output from a biogas facility by 70 %.

Integration of the biogas systems into the energy system

Biogas is a versatile energy carrier which can be used to produce electricity, heat and after upgrading serve all functions of natural gas, including transport. Biogas systems are highly scalable in their energy output according to the demand from the particular energy sector. The flexibility of biogas systems can facilitate electricity production at a dynamic schedule to match an electricity demand profile, while facilitating voltage and grid stability. As a decentralised component of the overall energy system biogas systems can function as an infrastructure hub for local energy consumers in rural areas. Biogas can play an essential role (together with PV and wind) as part of a virtual power plant in local distribution energy grids. Biogas systems can operate as a biological battery in coupling the electricity and gas grids using surplus electricity to produce hydrogen to react with biogenic CO_2 in biogas producing biomethane and increasing the output of biomethane (typically by 70 %). Innovation and ingenuity will be required of biogas operators in future energy systems. This report highlights how the operator can match biogas supply and demand for energy as electricity, heat or transport biofuel across the larger future energy system.

Table of Contents

1. Flexibility in the context of biogas systems **6**

1.1 CHARACTERISTICS OF ENERGY DEMAND 6

1.1.1 Electricity 7

1.1.2 Heat 10

1.1.3 Fuel 11

1.2 FLEXIBLE OPERATION FOR BIOGAS SYSTEMS WITH ON-SITE ENERGY PROVISION 11

1.2.1 Definition of flexibility from the plant perspective 11

1.3 BIOMETHANE PRODUCTION, GRID INJECTION AND POWER TO GAS SYSTEMS 12

2. Technical aspects of flexible plant operation **13**

2.1 TECHNICAL REQUIREMENTS FOR A FLEXIBLE OPERATION 13

2.2 ECONOMIC ASPECTS 14

2.3 CHARACTERISTICS OF PLANT COMPONENTS 14

2.3.1 CHP and related components 15

2.3.2 Gas management 16

2.3.3 Digestion process 18

2.3.4 Process control 20

2.3.5 Impact of flexibility on components 20

2.4 FLEXIBLE OPERATION – BENEFITS OF TECHNOLOGY AND SECTOR COUPLING IN A FUTURE ENERGY SYSTEM 21

2.5 EXEMPLARS OF FLEXIBLE OPERATION 21

2.5.1 Demand driven biogas in Germany 21

2.5.2 Virtual power plant in Switzerland 23

3. Power to methane systems **26**

3.1 THE ROLE OF BIOGAS IN SUPPORTING FURTHER INTEGRATION OF RENEWABLES 26

3.2 INTEGRATING BIOGAS SYSTEMS AND POWER TO GAS 26

3.3 METHANATION 28

3.3.1 In-situ biological methanation 28

3.3.2 Ex-situ biological methanation 29

3.3.3 Biological methanation system development 29

3.3.4 Variation in process design and energy use 30

3.4 PTG – BENEFITS OF TECHNOLOGY AND SECTOR COUPLING IN A FUTURE ENERGY SYSTEM 31

3.5 EXEMPLARS OF BIOLOGICAL METHANATION 32

4. Discussion and Conclusion **34**

1. Flexibility in the context of biogas systems

Flexibility in the terms of this report represents the ability of a biogas plant operator to control operation in a manner to best match the output of the biogas plant with the demand of the user(s) of the provided energy. With future increasing share of intermittent variable renewable electricity in the energy system the overall design and operation of biogas facilities for energy provision, transportation and use will change significantly. This is further complicated since the characteristics of energy supply from biogas facilities depends on the availability of the primary renewable energy sources, the feedstock for the biogas system. Operators of biogas facilities within the framework of new decarbonised smart energy systems will need to optimise operation to find solutions to the challenges of plant design and operation which results from this energy market and the inherent complexity of biogas systems.

The connections of biogas facilities to energy users are as individual as the design of biogas plants. Biogas plants can deliver electricity, heat or gas (raw biogas or upgraded biomethane). The user of the biogas in all three cases maybe directly connected to the biogas facility or to a gas, heat or electricity grid. When biogas is sold as a gas vector, it can be delivered to an external gas utilization facility, it can be upgraded and fed into a natural gas grid or it can be used to supply a fuelling station for vehicles. In any of these cases the time function of the demand for energy can be different. In many cases, biogas plants provide combinations of energy carriers, as electricity and heat or electricity and gas with different demand characteristics. This is the complexity on the energy supply side. On the energy production side there is further complexity as biogas plants can have very individual designs and use different technologies and substrates. The combinations and permutations of biogas production and biogas supply define the conditions for flexible energy provision.

The report synthesises demand characteristics of different energy users and discusses implications of this for the operation of biogas plants. Technical aspects of components of flexible biogas systems and the plant operation which result from such flexible operation are discussed. The components discussed include combined heat and power (CHP), gas storage, gas transport and gas treatment as well as requirements for peripheral structures such as transformation systems or heat storage.

The report will also include description of more innovative technologies such as Power to Gas (electrofuels) as a method for sector coupling, potentially integrating the electricity grid with the gas network. Ideally at times of over supply of variable renewable electricity, hydrogen may be produced via electrolysis, reducing curtailment. This hydrogen may be used to upgrade biogas to biomethane through the action of hydrogenotrophic methanogens which utilise hydrogen and carbon dioxide in the biogas to generate methane ($4\,H_2 + CO_2 = CH_4 + 2\,H_2O$). The process typically increases the methane output from a biogas facility by 70 %. Electrofuel systems allow for further integration of renewable electricity and can form part of a wider cascading energy system when coupled with biogas systems.

The report will not address all conditions required for implementation, which are numerous and are essential when considering practical implementation of such a system. Many of these are geographic specific such as substrate availability, location of the facility in terms of access to electricity and gas grids, heat sinks or fuel consumers. In addition the legal framework, policy, incentives for renewable energy and whether these incentives encourage time specific production of renewable energy, are all essential in assessing the viability of such a system.

1.1 CHARACTERISTICS OF ENERGY DEMAND

The increasing share of renewables in energy systems has and will result in a change of operating energy system. The demand profile is not only a function of the consumption, but is also a function of the varying supply from intermittent electricity supply such as from wind and solar (Figure 1). Variable, intermittent and uncontrollable supply results in an increasing demand for control on other energy suppliers, on grid operation and also on the consumer side.

Biogas plants have a dispatchable and controllabe energy output. Energy provision from biogas plants can be powered up and down on demand and in some cases biogas plants can even function as an energy sink. Examples of this are the so called power to heat process or when feeding hydrogen produced from electricity (in times of low demand for electricity) to a biogas facility in a biomethanation process. This characteristic of control is a valuable attribute for biogas systems when compared with other renewable energy forms. Biogas plants can help to balance the fluctuations resulting from intermittent renewable electricity.

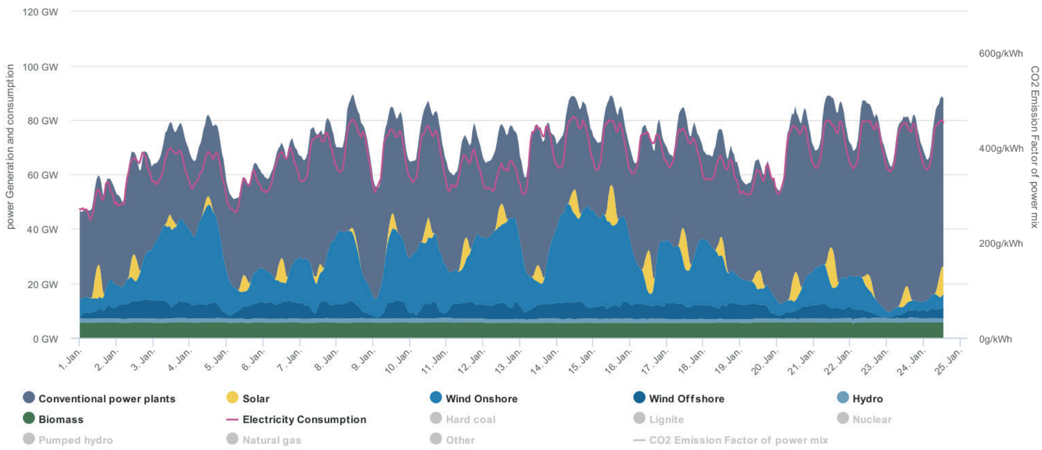

Figure 1: Time function of electricity supply and demand in the German electricity system in January 2020 (Source Agora Energiewende)

The variations in the configuration of the biogas system depending on its role as an energy supplier to either a direct customer or a grid (electric, heat or gas) are numerous. Electricity to the grid requires different variability and services than the direct supply for an industrial process. Other variable energy demand profiles can be found when satisfying heat demand to a district heating system, to agricultural or to industrial processes. Additionally the time function for heat and electricity demand might be completely different but each have to be complied with in case of a CHP application with customers on both the electricity and heat demand sides. A different energy demand profile is found for an on site fuelling station for natural gas vehicles. The characteristics of every possible situation of every individual plant in response to the particular demand profile of a consumer or a number of consumers cannot be covered in this document. Therefore the focus of this report shall be geared to the technical aspects associated with flexibility of a biogas facility. The following section will give a short overview of the energy demand of potential end users.

1.1.1 Electricity

Electricity and electricity products are traded by many producers within several markets and as such the conditions for the participation within the markets are bound by standards. Flexibility or dynamics in these markets come from the provision of energy based on renewables. The more dynamic energy supply is in the market, the more balancing activities are required to match demand and provision. This translates into higher requests for energy provision on demand to stabilize the electrical grid and to cover fluctuating demand. Within these markets biogas facilities must find their niche. The two major markets are the electricity market and operating reserve/balancing energy market.

Electricity can be dealt on markets like the European Energy Exchange (EEX), Nord Pool or Nodal exchange as well as within the so called over the counter (direct) trade. The trade follows specific products such as intraday or day ahead trade with conditions including deadlines for bidding and award of contract timing and delivery conditions.

Instruments include for over the counter (OTC; off-exchange), spot market and power derivates electricity, where electricity is traded. OTC products and derivates have long times to market of weeks, months or even years. The main market for renewables is the spot market; in Europe a major player is the EPEX Spot in Paris. The spot market consists of the day ahead and intraday market. Within the day ahead market electricity is offered with a deadline of 12 am (noon) for the following day at 24 h intervals. In case of deficiencies the intraday market can balance demand and supply. A continuous trade of blocs (e.g. an hour or 15 min) is permitted up to 5 minutes prior to the call. In case there are remaining differences between demand or supply due to unforeseen events or imprecise prognoses, these are covered by the instruments of the ancillary services.

In essence the markets are an instrument to align general demand and supply. The responsibility for the system and the guarantee of quality, reliability and certainty of electricity transmission and distribution might be held within different entities. Permanent monitoring and control need to hold grid frequency, voltage, load of utilities within acceptable tolerances. Usually this is dealt with by means of ancillary services, which can include frequency stability, voltage stability and restoration of supply and operational management. For the plant this can result in increase or decrease of power output, again the services are bound to specific activation times and specific duration of service. Primary, secondary or tertiary control have to be available within 30 seconds, 5 min and 15 min respectively (BNetzA, 2020).

Primary control requires the shortest response time and in case the measures via primary control are not sufficient to stabilize the grid, the secondary and tertiary measures have to be activated. In Germany for instance, experience shows that claim of secondary control lasts usually 5 to 10 minutes (Degenhart et al., 2015).

Potential contractors for control services have to prove within a pre-qualification procedure that the technical preconditions (e.g. activation time) for the desired control services can be realized on site. For some of the products the minimum bidding amount is larger than a single biogas facility can provide (e.g. secondary and tertiary control are bundled to a minimum of 5 MW in Germany); provision of “virtual power plants” which organise a pooling of plants can offer the necessary capacities at combined scale.

A completely different situation can be seen, when industrial or agricultural processes are directly provided with energy. The process or the industry defines the time function and amplitude of energy demand. As an example, the energy demand of a dairy farming enterprise may be given as per Figure 2. The energy demand can be adjusted within limits to the production, still a significant variation of energy needs to be covered in case of a self-sufficient energy supply. In such a case the security of supply needs to be developed by the producer and consumer directly. The course of energy demand does not follow a given standard so the supply has to be fitted to the individual case. If the energy demand profile can be adjusted and potential intermediate storage capacities sourced for smoothening the demand, then demand and production can be aligned.

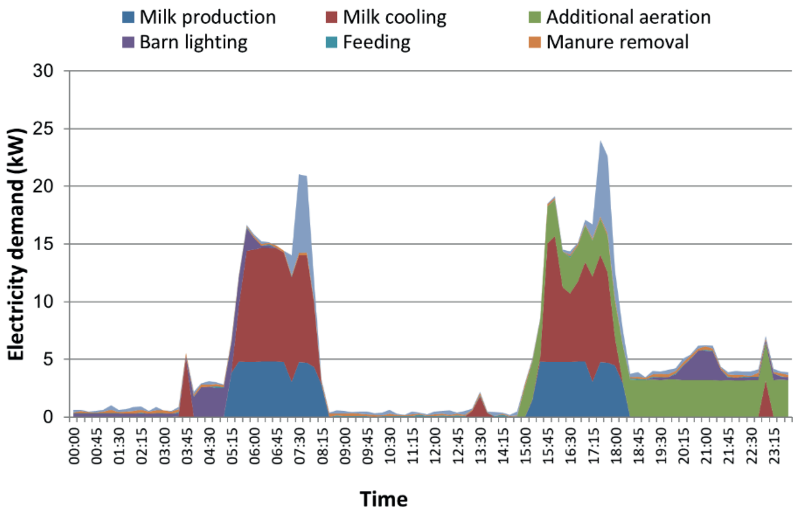

Figure 2: Electricity demand of a dairy farm in summer (Neiber, 2020)

In case the biogas plants wants to apply for the "standard" electricity markets the resulting form of operation of the plant can be organized as below (Daniel-Gromke et al., 2019b):

Weekly schedule: A weekly plan according to prices on the spot market is created, where appropriate in combination with ancillary services. Changes on short notice due to unforeseen changes in demand or supply are not possible.

Daily schedule: On the previous day a schedule is generated for the next 24 hours, the operator has to confirm the schedule and takes care of the realization of the schedule. This is a typical procedure for day ahead markets. The schedule can be optimized under consideration of latest prognoses until 12 am. Figure 3 gives an example of the price development of the day ahead market on the European Energy exchange (EEX) in 2020.

Figure 3: Example of daily price development of day ahead market in 2020 (Auction Day Ahead, 60 min, Germany, 31 of January 2020, Baseload (Source: EPEX SPOT))

Real time control: Here an immediate reaction is possible, hence the participation on short notice within the Intraday market is possible. Based on the market data an optimization of the schedule down to 15 min blocks is realized. This allows a reaction to price variations or changes due to unforeseen changes within the pool of the virtual power plant (e.g. disturbances at other plants). The operator needs to allow external access and remote control of the plant by an external entity.

Table 1: Main characteristics of basic schedules for flexible operation (Daniel-Gromke et al., 2019b)

	Weekly schedule	Daily schedule	Real time control
Brief description	Weekly fixed schedule	Next day individually optimised schedule	Optimised during the day
Serviceable markets	Day ahead Ancillary services	Day ahead Ancillary services	Day ahead, Intraday, Ancillary services
Technical effort, remote control	low, optional remote control (ancillary services require remote control)	Medium, Indirect or direct remote control (ancillary services require remote control)	High, Direct remote control (ancillary services require remote control)
Restrictions	Biogas production (substrate availability), number of starts and stops of CHP, gas storage capacity, heat demand, limits of capacity utilization, min/max performance		
Flexibility/revenue	low	medium	high

The different markets or the direct supply of a process require different levels of technical flexibility of the biogas plant as well as automation and remote control.The upgrade of the plant for flexible operation requires additional technical effort and consequential costs. The higher the congruence of market development (price development) and plant operation the higher the technical effort, but also the possible revenues (Table 1). Detailed analysis is required to find a economic match of both.

1.1.2 Heat

In case of gas utilization on site via CHP the exploitation of excess heat is an important asset to improve financial returns and the sustainabilty of the plant. Time function of heat demand is highly dependent on the type of heat sink. A major heat sink for agricultural biogas plants include heating of residential and social buildings, heating of barns or heat supply for district heating systems. The fourth major heat sink (Figure 4) are drying processes in the agricultural sector.

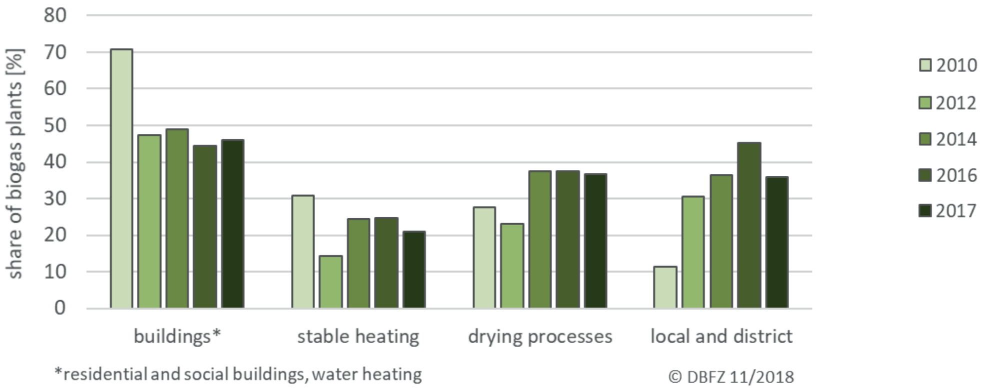

Figure 4: Development of main heat utilization in Germany for 2010-2017 (Daniel-Gromke et al., 2019a)

All of those heat consumers have a distinct seasonal behaviour. Heat for heating buildings is needed during the cold season and accordingly the demand is dependent on the weather conditions and/or temperature outside. Drying processes for agricultural products are used to capacity after harvest. The dynamics and the demand of heat users do not generally compliment the demand profile for electricity. Usually revenues for electricity are higher than for heat and consequently the electricity customer has priority. However, once heat supply is under contract, the operation of the biogas facility needs to be controlled in a way that ensures that the requirements of the heat customer are covered as well. Assessing the energy demand profile of the heat consumer and the time dependent heat output capacity of the biogas plant allows estimation of the potential to satisfy the heat demand of the consumer with the heat output of the biogas facility. Additional infrastructure including for heat storage or additional heat provision from peak load solutions might help to optimize flexibility options for the plant.

The heat demand of buildings depends on the temperature of ambient air which dictates the demand for district heating (Figure 5). A similar pattern may be noted for heating of offices, houses and animal housing. It is also important to note that the heat demand of the biogas plant itself is usually also the highest during the cold season and consequently the amount of heat available for sale to external consumers is reduced by this amount. In case the biogas facility does not represent the only supplier to cover the demand of a consumer, an optimization of capacity utilization might be possible.

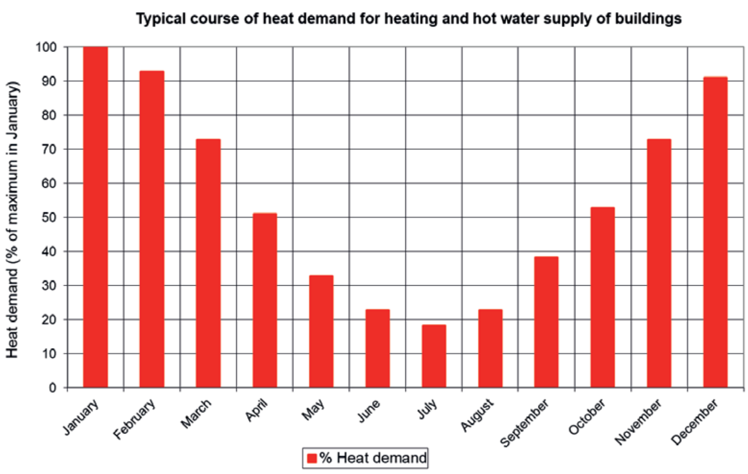

Figure 5: Typical heat demand for heating and hot water supply of buildings with mixed residential and industrial use (Jan Liebetrau, Rytec, own data 2020)

1.1.3 Fuel

Provision of gaseous fuel based on biogas usually requires upgrading of the biogas to biomethane of natural gas quality. For use as a transport biofuel the gas is either fed to a natural gas grid for use at an off site fuelling station on the gas grid or the fuelling station is connected directly to the biogas plant. The latter may reduce overall costs, since grid injection and transportation in the grid are not required. A third option which is in widespread use particularly in Sweden and in Finland includes for storage of compressed biomethane in cylinders (typically at 200 to 250 bar) and road transport of the compressed biogas cylinders to a fuelling station at a distance from the digester. It is also possible to transport compressed biomethane from the biogas facility and inject to the gas grid again at a distance from the biogas facility. This is sometimes termed a virtual pipeline.

Flexibilization of plant operation is only an issue in case of direct supply to an on site fuelling station. In such cases fuel consumption translates directly into gas demand at the biogas plant and consequently plant operation has to adjust accordingly. Depending on the type and structure of the consumer the fuel consumption can be quite different: a truck fleet operates during particular hours; public transportation may require a constant fuel output; agricultural machinery follows the seasonal nature of farming activities. Limited operational time of the fuelling station has also to be considered.

Obviously fuel demand curves can look quite different (Figure 6). Other than the characteristics of a fleet with known operational data and a given overall demand, the demand of a commercial fueling station without a defined demand from a fleet is quite unpredictable. Either there is a natural gas fueling station which can be replaced or it might be necessary to sustain a time period with low demand to “develop” the local market for the fuel.

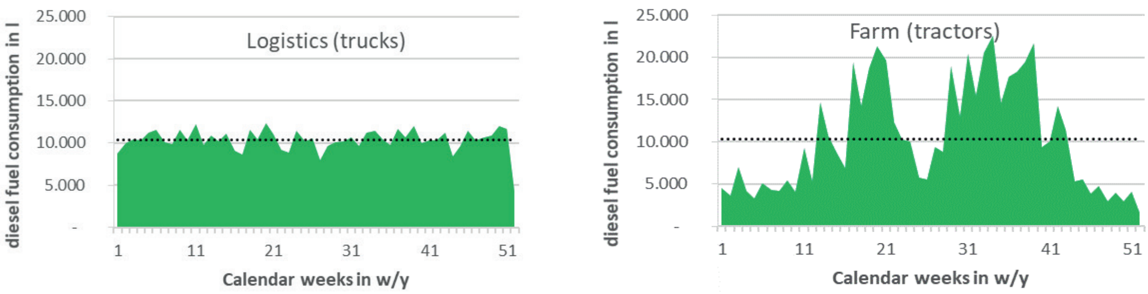

Figure 6: Aggregated fuel demand function for a truck fleet and an agricultural business. (Gögköz et al., 2020)

The fuelling station may offer a potential combination with other utilization options such as electricity production. However in this case the gas utilization requires the investment in two separate gas utilization technologies (a generator set and a gas upgrading system), but offers some advantages such as: a more constant gas utilization rate (less gas storage required); heat production to satisfy the parasitic demands of the biological process itself (and other purposes); and more flexibility to optimise revenues if prices of the energy products change.

1.2. FLEXIBLE OPERATION FOR BIOGAS SYSTEMS WITH ON-SITE ENERGY PROVISION

1.2.1 Definition of flexibility from the plant perspective

The technical flexibility of biogas plants with on site energy provision may be characterised by different criteria, which describe time dependent process parameters. These criteria include (Dotzauer et al., 2019); start up time, capacity increase and decrease rate, time to shutdown, part load operational range, minimal part load and maximum and minimum continuous load. These criteria define the flexibility of the biogas facility. The assessment of these technical criteria indicate to what degree the plant can meet the demand/requirements of the particular energy market served as described in the foregoing.

An important component for flexibility is of course gas utilization. This unit defines the design limits, in particular the reaction time over a short period of time. If the load change is of significant duration, upstream processes will be affected. Then all processing steps starting from substrate delivery and feeding, gas production and gas management until the actual energy provision will need to align to deliver the desired flexibility.

When looking at the plant parameters/characteristics the following are very significant in designing or assessing the flexibility of the plant (adapted from Daniel-Gromke et al., 2019b):

- Gas utilization
  - Technical limits;
  - Ratio of installed capacity to average energy output;
- Available gas storage capacity and capacity limitations of all affected plant components;
- Equipment for monitoring and control;
- Availability of flexible feeding and controlled gas production rate
  - Design and dimensions of related components of the plant;
  - Substrates used and availability of these substrates;

Most applications have a CHP unit on site and accordingly the capacity and characteristics of operation of the CHP are crucial and can be a bottleneck for flexible operation.

Since CHP installations typically have an attached heat utilization, the combination of the CHP with a power to heat installation is an option to improve the flexibility of the overall plant. Power to heat can help to reduce the electricity output of the plant faster than the reaction time of the CHP or can offer services to the grid by making the electricity producer an electricity consumer.

Power to gas (PtG) as an addition to CHP operations would require a combination of two distinct technologies which compete for operation time. Both need as much operation time as possible to maximise revenues. In the case of a grid connection the combined system can either feed electricity to the grid or take electricity from the grid. Additionally the gas produced within the power to gas system needs to be stored; it does not make sense to use electricity to make hydrogen to upgrade biogas to biomethane and then to use immediately in the CHP system to make electricity. The combination of CHP and Power to Gas would require very specific conditions and optimisation. It may be that a small CHP facility would serve the parasitic demands of the biogas facility and offer an element of flexibility in output energy vector. A more obvious combination is a power to gas unit (including for electrolysis and biomethanation), a tertiary gas upgrading system (to ensure gas grid specification) and grid injection.

1.3 BIOMETHANE PRODUCTION, GRID INJECTION AND POWER TO GAS SYSTEMS

In the case of a direct feed of biomethane into the natural gas grid the biogas plant does not require flexibility. The grid with its transportation, distribution and storage capacities provides a complete disconnection of gas utilization and gas production. The grid allows a complete separation of gas production from time, location, type of gas utilization and conversion rate of gas utilization. The high availability of the grid and the extent of natural gas grids in most industrialised countries add to the benefits of biomethane applications. As regards flexibility grid injection offers great potential in that the injected gas can serve all functions of the existing natural gas grid and can avail of weeks of storage inherent in the system. Consequently biomethane applications offer most options for the overall energy system, in particular as potential changes in use of the natural gas have no impact on the biogas facility. Biomethane may be used from the grid for electricity, heat and transport fuel and change in use has no impact at the biogas production stage.

Due to disconnection of gas production and utilization the flexibility of biomethane applications is completely within the gas utilization and does not affect the operation of the biomethane production and injection. In the following section the focus of the report will be on the on site energy provision. Considerable flexibility in operation comes with the use of a power to gas unit connected to the biogas production facility.

2. Technical aspects of flexible plant operation

Flexible operation in the context of this report is defined as the controlled variation of the energy output of the plant. Any variation in the energy output results in long term reduced utilization of the installed capacity. The lower the capacity utilization, the higher the variability and flexibility options. The time period of the energy production can be shortened to take advantage of periods where the highest prices are available for energy generation; this is effected through design of the system with "overcapacity". However, overcapacity means also periods of times with idle assets, which leads to increased costs, in particular capital costs, of the flexible energy system. As a consequence, additional income from flexibile operation has to pay off the additional costs of the flexible energy system.

2.1 TECHNICAL REQUIREMENTS FOR A FLEXIBLE OPERATION

Biogas systems usually have a defined average output, given by the gas potential of the substrate and relatively constant throughput of biomass feedstock. Standard design is an average energy output close to the installed capacity with continuous operation leading to high capacity utilization. Flexibility is achieved by installing extra capacity which leads to a reduction in average energy output. The order of magnitude of "overcapacity" is defined of course by the flexibility needed and the capex and opex of the extra capacity.

On the technical side, for flexible operation the following aspects need to be considered (adapted from Daniel-Gromke et al., 2019b):

- Matching capacity of grid access point;
- Accessibility and equipment for external control of the plant if required;
- Duration and course of capacity changes;
- Dimensions and design of gas storage, conditioning, and gas transportation system;
- Assessment of existing CHP in terms of remaining time to maturity, maintenance cost, technical issues and availability;
- Existing commitments for external heat provision and potential demand for addition of heat storage to guarantee heat supply in times of reduced electricity output;
- Availability of space and area for construction of additional components such as additional gas storage or larger co-gen set;
- In case of services for the grid operators, pre-qualification of capability;
- Decision on type of operation with resulting needs for process control whether direct reaction on demand with unknown course or fixed standard up and down operation;
- To control gas production rate, knowledge is required on availability of storable substrates, substrate characteristics (degradation kinetics), controllability of biogas production and design and capacity of substrate feeding systems.

Since the regulations for grid access, emissions, permission of operation depend on local conditions, some general potential regulatory considerations include for:

- Changes in the permit for operation;
- Changes in the emission regulation for the plant relating to part load operation of CHP;
- Permission for construction of new components.

A good starting point for a successful flexible system includes a well maintained and functioning biogas plant in the first place, adequate size of existing gas storage capacity, planned schedules for operation, the proper assessment of necessary overcapacity, preliminary discussions with grid operators and contractor for direct marketing.

2.2 ECONOMIC ASPECTS

Any flexible operation results in necessary installed overcapacity which reduces capacity utilization and increases costs especially capital expenditure. However, flexibility and provision on demand can increase the degree of utilization of energy provided due to, for example, reduction of heat losses due to unused cool down of engine and reduction of grid losses in an electricity grid charged to capacity. It also addresses new markets and can optimise overall energy utilization by integrating biogas applications into larger systems. Costs and revenues are highly individual and not the focus of this report. Since the economy of every measure has to be reasonable for efficient implementation the following aspects have to be considered:

- Capex and opex for a given degree of flexible operation,
  - Additional installations;
  - Additional maintenance effort;
  - Costs related to decreasing capacity utilization;
- Revenues and contracting conditions for the energy products;
- Long term prognosis of the energy markets.

Additionally costs include training and availability of qualified operators.

An overview on the share of additional investment on a new construction (500 kW average output to a 1,000 kW installed CHP capacity) is given in Figure 7. Clearly the installation of additional CHP capacity represents the most cost intensive portion.

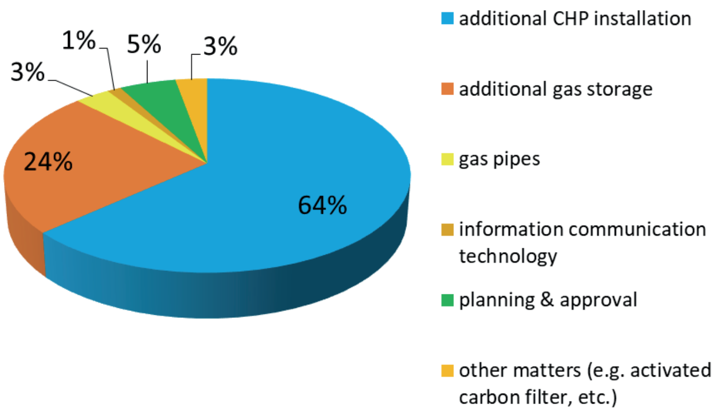

Figure 7: Distribution of additional costs for a flexible operation (Source: DBFZ)

2.3 CHARACTERISTICS OF PLANT COMPONENTS

Flexibilization and provision of dispatchable energy requires not only a fit between the proposed gas utilization and demand, but consideration and design of other connected components such as gas storage, gas transport and gas treatment as well as peripheral structures such as transformation systems and heat storage. In general the crucial components for flexible operation of a biogas plant can be structured under the following categories:

- CHP and related components;
- Gas management;
- Gas production;
- Process control.

2.3.1 CHP and related components

When energy is sold as heat and power the operation of the CHP set is core to flexible plant operation. The operational regime for the CHP generator sets depends on the demand for electricity and the number and installed capacity of the CHP generator sets. Potential operation modes are on/off and part load operation.

Part load operation

Part load operation means operation at a reduced capacity utilization level. CHP systems usually have a limit of minimal possible part load; typically manufactures would recommend to operate the CHP above 50 %. Part load operation leads to a significantly reduced efficiency (Degenhart, H., Schneider, M., Wachter, D., 2015) and increased emission values (Effenberger et al. 2016; Tappen et al. 2017).

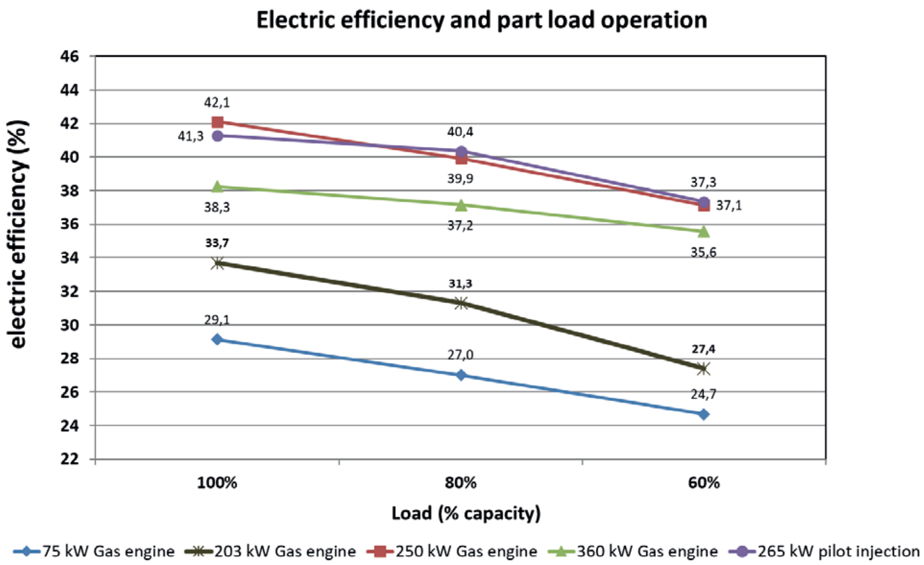

Figure 8: Part load operation and efficiency of selected biogas CHPs (Tappen et al. 2017)

Figure 8 shows examples of reduced efficiency of a few specific biogas CHP units with reduced capacity. Additional data on one of the examples shows the concurrent increase of methane slippage (Table 2). The loss in efficiency is compensated by an increase of gas delivered to the engine.

Table 2: Part load and methane slippage (Lichti et al., 2018)

	100% Load (203 kW)	90% Load (183 kW)	80% Load (162 kW)	70% Load (142 kW)	60% Load (122 kW)
Efficiency	33.7%	31.6%	31.3%	29.5%	27.4%
CH_4 slippage	0.47%	0.52%	0.58%	0.65%	0.74%

Part load operation has a penalty of increased slippage, reduced efficiency and reduction in cumulative energy output, which has to be considered when calculating the economics of flexible operation. Part load operation however has advantages: no start process is necessary; the CHP does not cool down which reduces condensation related issues; continuous heat production; and the capacity increase rate is higher than starting from "off mode".

An alternative option is so called start stop operation. According to a given schedule, the engine is operated in full load or it is shut down.

A shut down of the CHP leads to a cool down of the combustion engine and downstream components. For a quick restart, reduced wear on the components and reduced condensation a static heating is necessary to maintain a certain temperature within the unit. Prelubrication is also an adequate measure to avoid potential damage to the components. A maximum number of starts per day is usually defined by the CHP provider. The starter has to be capable of handling many starts without failing. Since the start up process takes some time and requires a short period of operation without load or with reduced load, this also leads to elevated gas consumption (Holzhammer et al., 2014). Maintenance of the CHP set has to be adjusted to the changed operation. In case of several CHP generators on a site with start stop operation, the operational hours of the units will be significantly reduced and down times will be more than they were designed for. Start stop operation will require adjusted maintenance schedules and this might increase costs per operational hour and per unit of energy produced. Full service contracts should be orientated on the operational hours and numbers of starts per day (Holzhammer et al. 2014).

When the decision for a specific type of operation has to be made, it should be considered, that with increasing electrical capacity of a CHP unit usually the electrical efficiency increases as well. A larger unit in start stop mode will likely produce energy with a higher efficiency than several smaller units in start stop mode.

When turning a hitherto constant operation of CHP system into a flexible operation, the heat supply of the digesters still needs to be satisifed. In case of numerous periods of down time of the CHP unit(s), installation of heat storage or alternative heat sources might become necessary.

The increasing number of plants operating in flexible mode in Germany has led to a reaction in the industry. The CHP producers have renewed or adapted the following components (Daniel-Gromke et al. 2019b):

- Preheating of cooling water and oil (min. 60 °C);
- Optimized starter and starting procedure of the CHP;
- Recirculation of air in air conditioning;
- Electric oil pressure build up prior to the starting procedure;
- Constructive condensation traps;
- Stainless steel finish at weak points due to sulphuric acid in condensate;
- Remote monitoring and control options for the CHP – PLC;
- Changing requirements for biogas quality (sulphur content, temperature, moisture).

Progression of electricity production is in most cases (except in the case of internal energy use) given by the power trader. The plant operator and the contractor for electricity/heat trade need to have bidirectional data exchange. A professional operation should have an automated data exchange between process control system of the power trader and the plant control system of the biogas plant.

Besides operational status and availability of the CHP unit(s), additional information such as presently stored biogas amounts can support the precision and security of the energy provision. With shorter reaction times given by the electricity product (in particular balancing energy or ancillary services), an automated data transfer and direct remote control becomes obligatory. Some electricity traders offer standardized communication toolboxes, which are integrated into the CHP – PLC. Additional consideration might be necessary to monitor the emissions from the CHP unit. Start stop and part load operation will have an impact on these emissions. Standard regulations refer to “normal” (full load) operation which might not be representative in case of significant part load operation periods.

2.3.2 Gas management

Flexible plant operation will not only have a major impact on the CHP operation. The larger the deviation from average output the more the gas management of the facility needs to adjust to the resulting change in gas demand. Gas flow rate and gas quality for the CHP are crucial parameters for a predictable operation.

In contrast to stationary plant operation, where gas consumption and gas production are nearly equal and constant, flexible operation leads to periods of imbalance between gas consumption and gas production. This again leads to variation in the filling level of the gas storage system and the flow rates between the gas domes and through gas transportation pipes. Gas treatment such as gas drying and H_2S removal will also be impacted. In the case where the plant design and the dimensions were originally set for constant operation, an analysis has to be undertaken to ensure that the new gas production rates can be treated efficiently by the existing gas treatment components. In case of controlled manipulation of the gas production, the specifications of safety devices such as pressure relief valves and flare need to be assessed for new flexible operational conditions.

In general the management of gas storage has to ensure that gas is available on demand with a defined quality and minimization of gas losses and unwanted emissions. Dynamic operation of biogas storage capacity increases the risk of extreme filling levels of gas storage and therefore the risk of creation of conditions which lead to flaring of excess gas or fugitive emission of gas through pressure relief. Consequently the flaring of excess gas must be set to be triggered by the gas level in the storage system to avoid emissions via the pressure relief valve.

The full utilization of the storage capacity of several corresponding gas domes might require additional installation for control of the stored gas amounts and for forced gas transportation. Standard equipment does not allow a manipulation of pressure levels in the inflated air cushion of double membrane roofs. Without this option, the filling level in the domes would be set by the arbitrary set pressure conditions which would not allow the use of full storage capacity.

A crucial component of gas management is the precise measurement of the filling level of the gas storage system. This is the weak point of many installations. There are several types of gas domes and due to different constructions details, different methods for measuring the filling level are applicable. The selected solution should read the filling level precisely over the whole range of levels and provide an online available reading of the level. Besides the precise measurement of the filling level, the consideration of external effects on the measured gas level must be assessed. Gas demand, gas production and weather changes (in particular temperature, sun radiation and barometric pressure) are necessary to forecast filling levels and to avoid critical conditions such as over or underpressure situations. Model based prognosis can support such predictions (Stur et al. 2018). Particular attention has to be payed to gas pipes. Changing throughput and resulting loss on pressure might require the installation of new piping with larger cross sections or additional gas blowers. Increasing amounts of condensate has to be expected as well.

In summation the following items should be considered during operation (Reinelt et al. 2019):

- Effect on the gas storage filling level due to
  - gas demand and gas production,
  - weather conditions,
  - biological and physical effects in the digester medium,
  - planned and unplanned interruption of operation of connected plant components;
- Structural upgrade of affected components for increased gas flows (in particular pipe dimensions, gas treatment components, safety devices such as flare and pressure relief valves);
- Assessment of functionality and availability of gas storage capacity and gas transportation between several gas storage systems;
- Triggering of the secondary gas utilization unit (e.g. flare) at specificed limits of the filling level of the gas storage to avoid emissions.

Potential measures for a plant upgrade might be necessary and include (Reinelt et al. 2019):

- Installation of additional (clean) gas storage;
- Upgrade of sensors for precise filling level evaluation;
- Installation of a gas management system between the gas domes via a controllable blower for inflation air;
- Upgrade of gas transportation within gas transportation lines;
- Upgrade of gas treatment devices.

In general, the limits of the gas management system needs to be assessed for stable and emission free functionality at maximum and minimum storage capacity and respective flow rates of biogas. Technical upgrades might be necessary to meet these requirements.

2.3.3 Digestion process

Gas production is upstream of gas utilization and storage. As such manipulation of the gas production rate is beneficial for increasing flexibility of energy output. Most common standard design of biogas plants employ a constant, close to ideal, continuous feed to facilitate a constant growth rate of microorganisms, a constant temperature in the digester and avoid peaks of volatile fatty acid concentration or variation in gas quality. When flexibilization that can be obtained through manipulation of the volume of the gas storage reaches its limits, the consequent next step is the manipulation of the gas production rate. This allows long lasting changes up to and including seasonal variation of energy provision.

The gas production rate depends on the process technology (CSTR, plug flow, anaerobic filter etc.), the feeding rate and the substrate characteristics, in particular specific methane potential and degradation rate of the specific substrate. There are methods described below that can be used to manipulate gas production rate. Technically the most simple way is the manipulation of the feeding rate or type of substrate to achieve a controlled variation in the gas production rate (O'Shea et al., 2016). Another method is to choose or change the process technology of the plant to provide more flexibility; an example is to separate energy rich substrate fractions and convert this fraction to methane in high rate digesters (Wall et al., 2016; Hahn et al., 2014). Both methods are realized in several research projects.

Control of gas production rate:

The manipulation of the gas production rate can be achieved by control of feeding rate and by variation of the type of substrates. For example source segregated food waste was shown to have a far higher specific methane yield (398 L CH_4/kg VS) than cattle slurry (132 L CH_4/kg VS) by O'Shea et al. (2016). Flexible plant design based on control of the feeding rate and variation in the type of substrate requires:

- storage of the substrate for specified time periods;
- variation in the feeding rate;
- Separate feeding of substrate types and respective variation in these feeding rates.

Silages based on energy crops are already stored for a long time. Storage capacity is part of an energy crop based installation and as such no great changes are required. Silage can be deployed on demand within the limits of normal operation of silage pits. For waste/waste water streams or manure based facilities storage capacities are not necessarily installed. Some substrates cannot be stored for a long time.

For the implementation of control of the gas production rate via the feed rate, it is crucial to know the degradation characteristics of the substrates. The degradation rate of substrates can differ quite significantly; adding straw with bound carbon and slow degradation is very different to addition of sugar beet silage to a process (Herrmann et al., 2016) . The degradation of the substrate and the associated gas production rate follows a substrate specific kinetic behaviour. The precise prediction of this process to inform the feeding events to match an energy demand requires the use of a dynamic model (O'Shea et al., 2016), especially in the case of changing substrate combinations.

In the scientific community the standard tool for modelling the gas production rate is the Anaerobic Digestion Model Number 1 (ADM1: Batstone et al., 2002; Thamsiriroj and Murphy, 2011). However, for practical commercial applications this system is complex and simpler models for prediction of gas production rates are used (Weinrich, 2018). In assessing the literature on modelling and control of biogas systems, it can be stated that the models used for control vary widely in structure and complexity. A transfer of constants or information gleaned from other processes or the use of data from lab based experiments extrapolated to full scale commercial applications is not always feasible. Gas potential data might be available from several analyses and may be universally available but come with a caveat or an uncertainty. The kinetic model for batch trials were shown to be not equivalent to those of semi-continuous laboratory trials (O'Shea et al., 2016) and the kinetic characteristics of substrates from these lab based assessments may not be readily applicable to large commercial processes.

In order to get a robust and sufficiently precise process prediction the challenge is to find a compromise between effort for process monitoring (online sensors, offline tests and data evaluation), complexity of the model and necessary or available computing power. The implementation of process control in existing plants as a retrofitting measure is difficult since process control systems are highly individualized and plant operators will be reluctant to leave decisions about the plant they are used to making entirely to a computer.

Process control for flexible operation has been demonstrated in several publications. The basis of the process is often a model based controller which predicts the gas production rate and gives a feeding rate based on given or estimated substrate characteristics. An example is the model predictive control algorithm presented in Mauky et al. (2016). This includes feedback from the system response with set variables of substrate type and feeding amount. The control variable is the gas storage filling level. The controller has been tested and validated at two research biogas plants in Germany (DBFZ, Leipzig and University of Stuttgart). Figure 9 shows the course of gas storage filling level and gas production rate according to controlled feeding of an electricity generation on demand facility. The limits of the capacity of the gas storage were not exceeded due to the manipulation of feeding rate.

During the development it became obvious that other, additional variables need to be included to obtain a comprehensive control approach. Two examples are given here. Firstly the storage capacity of the gas dome is highly dependent on the temperature of the gas and the temperature varies to a great extent depending on ambient temperature and radiation from the sun. Secondly the economic evaluation of operation represents a crucial criteria for the decision as to how to direct the process. The cost of substrates, revenues for electricity and heat, technical limitations and contracting requirements require on-going evaluation and optimization.

In practice the control methods used tend to be rather simple. Feeding control is realised by a simple on/off control combined with feedback to process response (e.g. Envitec 2010). Such systems are reliable and have been proven in practice. The limitations to the system are that they cannot predict the time dependent behaviour of different substrates; the control method can provide prognosis only for constant substrate mixtures and utilise experience based estimation of the process behaviour.

In synthesis it can be stated that dynamic process control is far from state of the art; the use of dynamic models is mainly limited to use in an academic context. However, the benefit of such a control system is evident. Even for maintenance and other incidents which involve scheduled or undesirable process shutdowns it is advantageous to be able to reduce and ramp up gas production rates in a controlled manner.

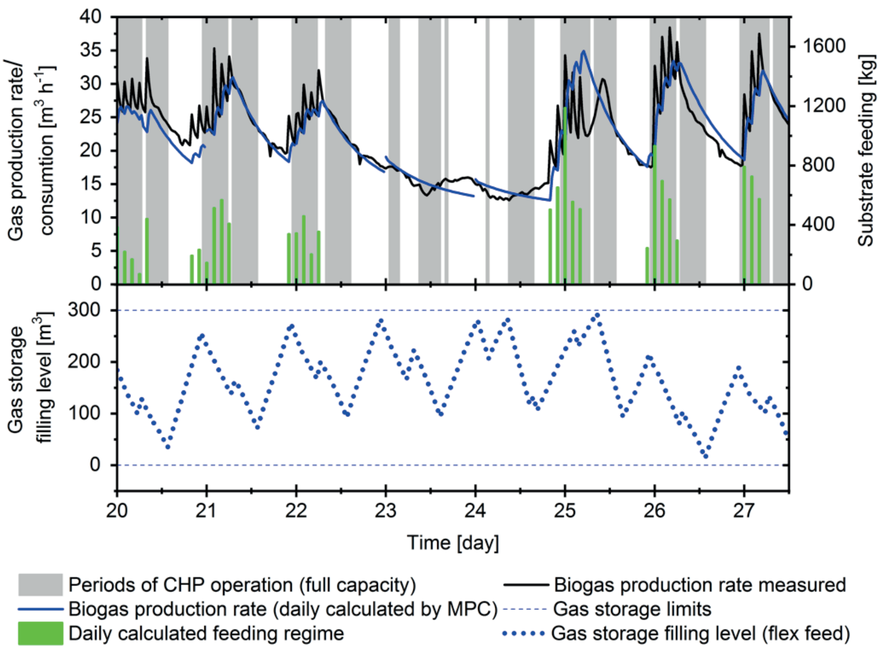

Figure 9: Example of a control of gas production rate and resulting filling level of gas storage system (adapted from Mauky et al., 2016) MPC: model predictive control.

2.3.4 Process control

Starting from the control of the gas production rate it becomes obvious that a more comprehensive optimization of the overall process is necessary in order to optimize crucial parameters which influence technical reliability and economics (Figure 10). The more profound and comprehensive the control system, the more sensors, complex models, actuators and computing capacity it requires. Such systems are beneficial in any case as they help to optimize operation of a biogas plant from technical and economic perspectives; for flexible systems they are essential.

In case of a new installation, the overall technical system and the control system can be designed to match the requirements of flexibility. The control system can be developed according to the needs of the operators and be integrated into the overall process control.

In case of adaption of existing plants the solution is not as easy. Plant design and control systems are usually individual solutions for individual plants. The designer of the existing process control from years past may not be available or may not be the provider of choice for an extension or adaptation. New sensor arrays, actuators, data collection, data storage and transfer, integration of new software or routines might have to be customized for each plant.

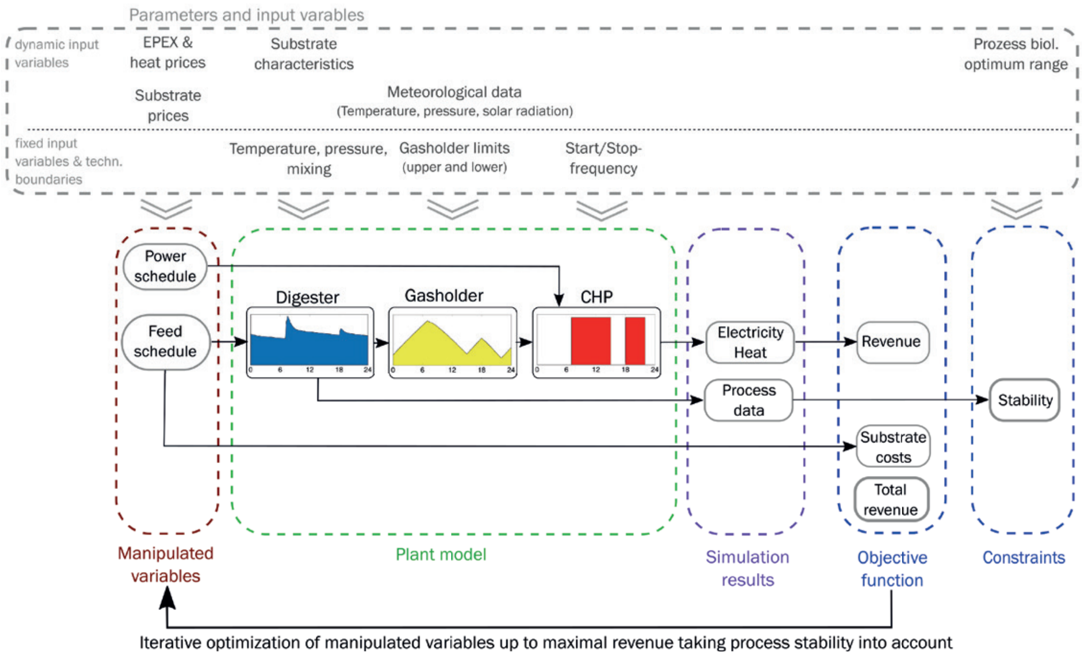

Figure 10: Example for a more comprehensive process control considering technical and economic requirements (data from DBFZ) (EPEX: European power exchange – market for electricity)

2.3.5 Impact of flexibility on components

Flexibility requires change in operation and therefore technical changes of components and of control systems are necessary. In the case of a flexible operation the order of magnitude of fluctuations of mass and energy flows has to be determined and it has to be checked if the existing (or designed) system is capable of handling the new situation. It is necessary to check all affected components to make sure that no bottlenecks compromise the flexibility of the system. Obviously all gas related and energy related components and connected ancillaries are affected. Consideration is also required for feeding control components.

2.4 FLEXIBLE OPERATION - BENEFITS OF TECHNOLOGY IN A FUTURE ENERGY SYSTEM

When looking at the different energy vectors and sectors it is obvious that the organization and technology of making the energy available to the customer differs considerably. The demand side of energy (be it electricity, heat or fuel) does not follow similar patterns. Consequently strategies and technologies employed to balance fluctuations with the sectors are quite different. Nevertheless, the provision of a controllable and scalable energy output based on the biogas process has advantages for transportation of the energy vector and the degree of utilization of energy.

Within the electricity grid the management of feed in reduces transmission losses and required grid capacities (Trommler et al., 2016). The maximum grid load can be reduced. Within the heat sector, the highly seasonal demand can be covered. The possible combination of energy vectors, such as combined heat and power or electricity or gas offers various possibilities for the use of biogas systems as an energy provider (such as CHP), an energy sink (such as power to heat) or an energy converter (such as power to gas or power to heat).

Last but not least biogas systems function wherever the substrate is available. This results in a decentralized distribution of applications, which can be used as an infrastructure hub for local energy consumers in rural areas.

Biogas systems are technically able to provide controlled energy to the sectors of electricity, heat and fuel or provide renewable gas for natural gas infrastructure. However, the substrates for biogas production are limited so it is the task of authorities to steer the utilization of substrates to sectors where the resources are used most efficiently for the overall target of greenhouse gas reduction.

2.5 EXEMPLARS OF FLEXIBLE OPERATION

2.5.1 Demand driven biogas in Germany

In Germany the upgrade of plants necessary for flexible operation was funded by particular incentives for renewable energy (since 2012). It is now mandatory for newly constructed facilities to have at least twice the installed capacity of gas conversion compared to the average energy output. Accordingly the potential for flexibilization has increased and is made mandatory.

In June 2019 there were 3,146 Biogas plants with an overall capacity of 2,022 MW_{el} eligible for a flexibility premium; this is an extra incentive for flexible plants (Data from DBFZ and Federal Network Agency and Transmission provider). Additionally there were 191 CHP units, equivalent to a capacity of 169 MW_{el} operated based on biomethane (Daniel-Gromke et al., 2019b).

Despite this positive development it needs to be stated that actual flexible operation is not the state of the art. The additional investment necessary to enable the plant to be fully flexibile is financed by a flexibility premium. Since this also includes an option to install new CHP capacity, a number of plant owners opted for the upgrade of the plant.

However, incentives for flexible operation are organized in a such a way, that operators can increase their revenues by any additional income they generate from flexible operation. In the actual market situation the revenues to be gained by optimizing the energy output according to market prices or ancillary services are not high. There is a particular situation prevalent in Germany at the moment (2019), whereby old fossil based units are producing over capacity and the market is flooded with cheap fossil energy which levels the fluctuations from renewables.

The necessary regulating measures are offered by many biogas developers and prices are consequently low. The future situation will change with an increasing number of fossil based (agreed coal phase out) or nuclear plants (agreed nuclear phase out) going offline by 2030. But with an unclear future for most biogas applications (as of 2020) it is not clear, how many of the plants will still be operational, when 2030 is reached.

At present, when operators assess technical and economic considerations of truly flexible operation, most decide to stick with constant operation.

Biogas plant Langewedel – Bioenergie Langewedel GmbH & Co KG

Basic information:

- Commissioned in 2010;
- Substrates include for over 50 % liquid cattle slurry and dung, less than 30 % corn silage with the remander of feedstock comprised of cereal crop silage and cereals;
- Flexibile operation in place since February 2019;
- The average output is 380 kW;
- Installed capacity of 1,900 kW via two CHP units;
- The maximum gas storage capacity (at average gas production) is 60 hours;
- The volume of storage is 15,000-19,000 m^3 utilising additional clean gas storage on top of a lagoon;
- Heat storage of 1,000 m^3 of hot water

Marketing concept:

- Individual electricity market oriented operation for the following day (day ahead market) and participation in "intraday" market;
- Both CHP units have approximately 1,800 h/a full load operation;
- Remote control from electricity trader;
- The contractor can directly access the process and process relevant parameter;
- Additional income expected in 2019 of more than 1.5 ct€/kWh;
- Operate with a maximum of 2 starts per day with a minimum of 1 hour of operation with both CHP units in full load, shift of electricity production to winter;
- The heat from the CHP unit is used to heat buildings and barns and dry digestate;
- 95 % of available heat is used.

Economy:

Investment of €1,600,000 is covered by the flexibility premium. Additional income is generated from the spot market.

Future perspectives:

The future of the facility is based upon improved heat utilization by accessing a district heating system, flexible electricity production and further increase of manure in the substrate mix.

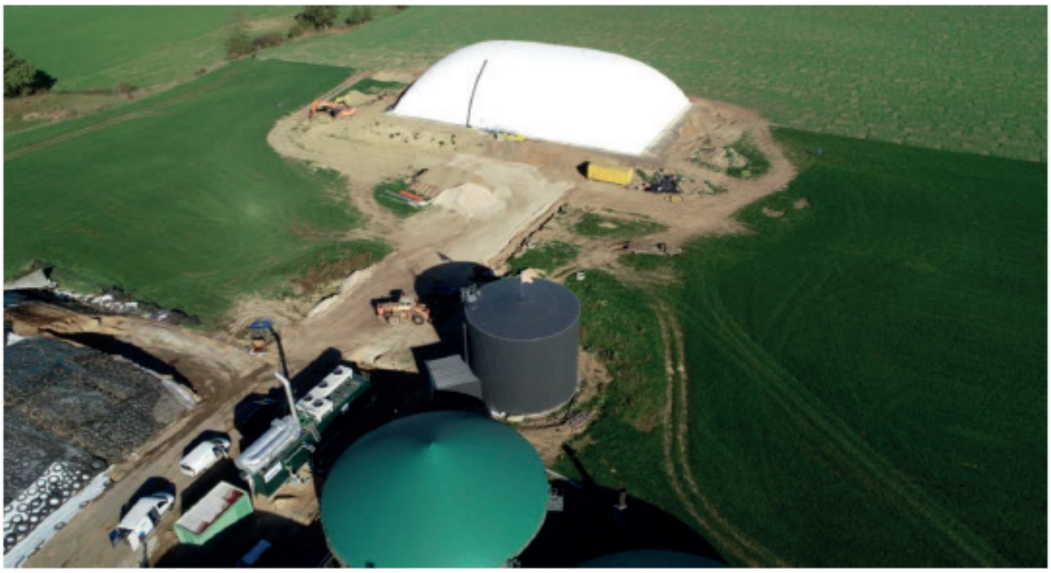

Figure 11: Bioenergie Langwedel GmbH & Co. KG

2.5.2 Virtual power plant in Switzerland

The Swiss virtual power plant "Fleco Power" represents a marketplace to match flexibility of producers and users of new renewable energy. The flexibility of over 80 biomass, small hydroelectric and photovoltaic plants with a nominal power of 30 MW is bundled and marketed as control energy to Swissgrid, the Swiss electricity grid operator.

In Switzerland, the share of renewable energy in the electricity mix has risen steadily in recent years. This trend will increase with the implementation of the Swiss Energy Strategy 2050 which strongly fosters capacity expansion of new renewables. With the revised Swiss Energy Act, in force since 2018, feed-in tariffs (KEV) for both new and existing renewable energy plants were transformed into a feed-in remuneration system (EVS). This had severe consequences for operators of PV, small hydro and biogas installations. The new system introduced the remuneration model of direct marketing, in which plant operators are responsible for selling their own electricity at the market. Existing plants with an output of more than 500 kW and all new plants are obliged to use this model. Small existing installations are also free to switch to direct marketing. For smaller producers with nominal power of less than 500 kW, who make up a considerable portion of the renewable energy market, it is a high hurdle to enter direct marketing.

Most of the new renewable energy capacity however will still be added through small and decentralized installations. Local distribution grids will be (and in some cases already are) a source of problems for voltage maintenance and grid stability. An efficient solution to this problem is to control the flexibility of the decentralised producers. Swissgrid, Switzerland's electricity grid operator, permanently coordinates nationwide electricity production with consumption, thereby ensuring a stable electricity grid. To balance out unforeseen fluctuations, Swissgrid draws on a network of large to medium sized suppliers who can increase or reduce the production output of their power plants at short notice if necessary. The electricity distribution network thus can be relieved by a targeted increase or reduction of the feed-in of renewable electricity (control energy).

In order to make this flexibility available for smaller and decentralized facilities, there are three requirements: central control signals; intelligent control hardware; and incentives in the form of remuneration for participants and organisational structures. In 2015, the company Fleco Power developed a system for the integration of all three requirements into one product. Fleco Power bundles the production capacity of decentralised electricity producers, including photovoltaics, small hydropower and biogas installations (figure 12). Fleco Power is continuously active (24 hours a day, 7 days a week) and it appears as a virtual power plant based on exclusively new renewables. Thanks to an intelligent control system, the plants appear on the market as one large power plant. Fleco Power uses secure communication channels and a cost-efficient hardware based on the Internet of Things (IoT) to coordinate a call for control energy between all available plants. These react to a request from Fleco Power based on individually agreed

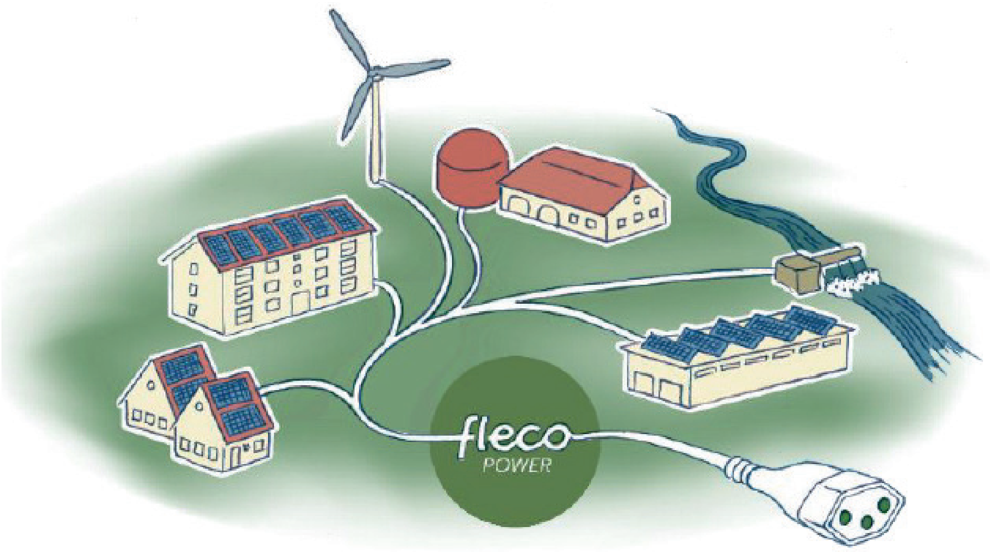

Figure 12: Fleco Power Structure to combine flexibility of decentralized installations

parameters. The local process and its electricity demand is always guaranteed to take priority over a request for control energy. According to current legislation, the flexibility of decentralized plants belongs to their owners, as described by a contractual relationship with each participating decentralised installation.

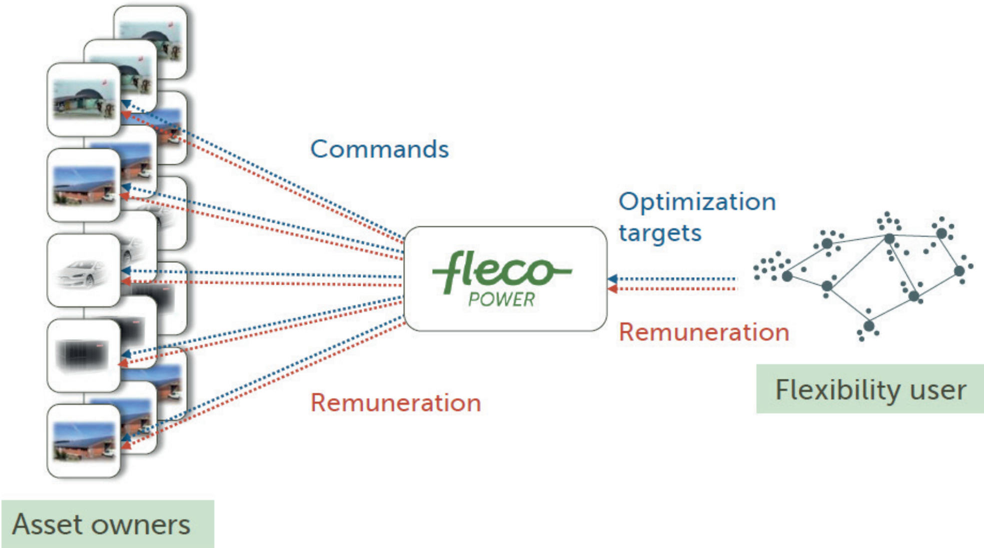

Figure 13: Fleco Power remuneration and command flows

The Fleco Power model distributes benefits between all participants (Figure 13)

- Plant operators contribute to grid stability and the future of the electricity grid; they further strengthen local and decentralized electricity production. For this they receive additional revenues through remuneration from Fleco Power.
- Fleco Power profits from being recognized as a key player in the electricity market selling in excess of 200 GWh of energy annually. It has become the largest independent direct marketer in Switzerland with a market share of around 20 %.
- Swissgrid achieve a reduction in operating and investment costs due to a better short-time leveling of electricity production and demand. In addition, it has the opportunity for fast and risk-free implementation of innovation projects. Overall this system facilitates voltage and grid stability in the network.

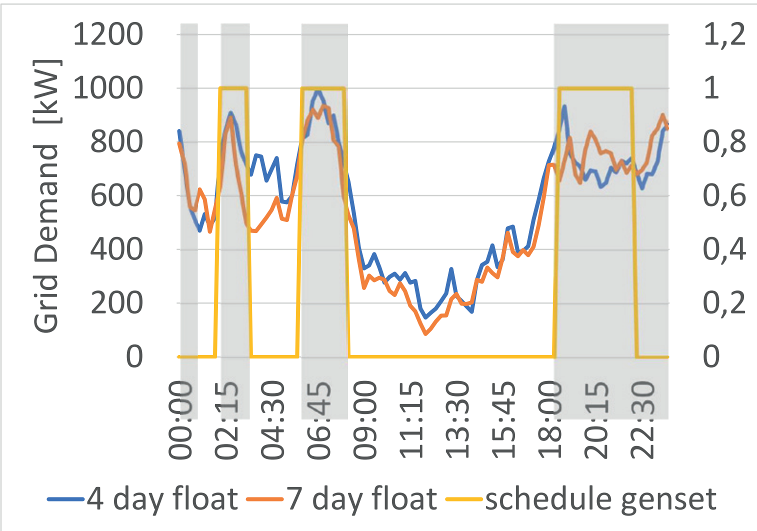

Figure 14: Example of a 1-day flexibility control time course of a biogas installation in Switzerland in Autumn.
grey: peak load time windows. blue/red: Historical load curves of electricity demand.
yellow: biogas CHP timetable

Figure 14 gives an example of a flexibility control time course of a typical Swiss agricultural biogas installation. Of the two CHP units, each with an installed electrical power of 250 kW, one was made available to the virtual power plant Fleco Power for control power. Historical load curves of electricity demand are shown as red and blue curves. On this basis, time windows of peak loads (boiler peak at night, start of work in industry in the morning hours, household consumption in the evening hours) in the electricity distribution network were determined, (shown as grey bars) at which time it was proposed to support the grid with electricity production from the biogas facility. The strong influence of prosumer PV electricity production (which takes load away from the grid during sunlight hours) is clearly evident even in the autumn months. During these midday hours, the electricity consumption on the distribution grid is minimal, while the evening peak is influenced by the end of PV production.

The timetable for the biogas plant, shown in yellow, was chosen so that the peak load of the biogas plant could be called up during the identified peak load periods (timetable value 1). The available peak load hours for the day were taken into account, which were periodically communicated by the plant operator. For the assessed day in October this was 8 hours.

The example shows the case where the full load hours of the 250 kW CHP unit are not sufficient to cover the demand during the entire peak load hours. Therefore, a prioritisation was carried out, whereby the load hours in the late evening and early morning hours were deprioritised on the basis of empirical values.

The night peaks of electricity demand which could not be absorbed by CHP peak load production are clearly visible. This highlights the requirement that enough positive flexibility must be available, e.g. in the form of larger biogas storage volumes, to allow for permanent intervention.

Fleco Power offers a technology platform, which enables a cost-efficient control of decentralized renewable energy plants in the distribution network. The most important innovations are the use of "Internet of Things" hardware and the consistent use of timetable control instead of real-time communication. This opens up the opportunity for the Swiss energy system to make the distribution grids more cost-efficient by making better use of existing resources. In this way, challenges such as the expansion of decentralized renewable energy or electromobility can be addressed without major investments. The greatest challenges for the implementation of the concept in the Swiss energy system were identified as the quality of the existing grid models, the lack of urgency of the issue of flexibility management among distribution system operators and insufficient standardisation of interfaces.

Further information can be attained at *https://flecopower.ch/*

3. Power to methane systems

3.1 THE ROLE OF BIOGAS IN SUPPORTING FURTHER INTEGRATION OF RENEWABLES

Much of the current global strategy for decarbonisation involves an increase in the share of variable renewable electricity (VRE) in the electricity network. This has been particularly evident with the growth of the wind and solar energy sectors over the last decade. Due to the intermittent nature of these VRE devices, there will be a requirement for additional grid balancing since neither can be controlled nor dispatched on demand. In essence, VRE is a fluctuating energy resource that is often hard to predict and forecast. An example of this is wind energy in Ireland. At times there is a significant resource of wind and the electricity produced can be considered of low carbon intensity. However, when the wind is not blowing, the wind resource in Ireland is typically backed up by fossil fuels (often combined cycle gas turbines (CCGT)) and as a result, the carbon intensity of electricity increases. A further issue is when the supply of VRE exceeds demand and additional challenges are subsequently encountered on the electricity grid such as curtailment, constraint and other inefficiencies.

In 2017, the share of renewable energy supply in electricity (RES-E) provided by wind turbines in Ireland was 25 % (SEAI, 2019). The RES-E target for 2030 is 70 %. If a capacity factor of 35 % is considered then in a very simplified manner the scale of the challenge may be exemplified in that it is plausible that in 2030 there will be periods of time when wind power at particular periods may provide twice (70 % / 0.35 = 200 %) the average demand for electricity. Eirgrid (the electric power transmission operator in Ireland) has managed to handle 65 % variable non synchronous renewable electricity and has an objective of increasing system non-synchronous penetration (SNSP) to 75 % by 2020. SNSP is defined by Eirgrid as "real-time measure of the percentage of generation that comes from non-synchronous sources, such as wind and High Voltage Direct Current (HVDC) interconnector imports, relative to the system demand." Such oversupply issues have been predominantly associated with wind turbines but are also applicable to any other intermittent VRE devices such as solar and wave systems.

Biogas can offer a potential solution to electrictity demand supply mismatch due to its flexibility. Biogas systems can act as a vehicle for further integration of renewables such as VRE by providing a mechanism for energy storage (power to methane), as a renewable option in providing the base load requirement for the wider energy system and additional flexibility (as discussed in previous sections). This can be achieved by combining biogas production (anaerobic digestion) with power to gas (PtG) technologies resulting in the production of electrofuels. The utilisation of PtG provides a mechanism for demand side management by storing surplus electricity from VRE devices as a gas.

3.2 INTEGRATING BIOGAS SYSTEMS AND POWER TO GAS

Anaerobic digestion is a key technology in providing a sustainable future for existing gas infrastructure. To ensure gas of grid injection quality, the carbon dioxide from biogas must be removed through an upgrading process. This has been traditionally achieved through biogas upgrading via water or chemical scrubbing, membranes, or pressure swing absorption; typically at high cost. Finding a potential use for the separated carbon dioxide is a subject of much interest to biogas system operators. This requires a circular economy approach and preferably offers a route for carbon capture.

PtG is one potential method of interest. In a PtG system, surplus renewable electricity is used to split water via electrolysis to produce hydrogen and oxygen ($2H_2O = 2H_2 + O_2$). As mentioned, this surplus renewable electricity can arise at times when the electricity supply from a wind turbine exceeds consumer demand. Thus, the PtG process requires a change in energy vector from electricity to gas. Three electrolyser technologies can be used, namely the alkaline electrolysis cell (AEC), proton exchange membrane (PEM) and the solid oxide electrolysis cell (SOEC). The key characteristics of each are shown in Table 3 (adapted from Buttler & Spliethoff, 2018, Schmidt et al., 2017, and McDonagh et al., 2018). The AEC and PEM are currently the two technologies of most merit and selection of electrolyser is typically evaluated on a system efficiency and cost basis. The SOEC is considered for potential future applications due to it's higher process efficiency but is currently at a low technology readiness level (TRL).

The electricity supplied to the selected electrolyser can be on a fluctuating basis (surplus VRE) or on a base-load scenario relative to a set number of run hours. Recent studies have indicated that PtG systems will not be able to rely solely on curtailed electricity as the lack of run hours will negatively affect the process economics which results in a high levelised cost of hydrogen (LCOH). Even as the share of VRE in the electricity network increases in the future, it is still anticipated that the sole consumption of otherwise curtailed energy will not be viable due to low capacity factors (McDonagh et al., 2019). However, by engaging with the electricity market and increasing the bid price for electricity, a higher number of run hours can be generated and ultimately amount to a lower LCOH.

Table 3: Selected technical characteristics for different electrolysers in a Power to Gas system in 2020 (adapted from Buttler & Spliethoff, 2018, Schmidt et al., 2017, and McDonagh et al., 2018)

Electolyser type	AEC	PEM	SOEC
Operating cell temperature (°C)	60 - 90	50 - 80	700 - 900
Operating pressures (bar)	10 - 30	20 - 50	1 - 15
Hydrogen production rate (m^3 H_2/hour)	<1400	<400	<10
System energy consumption (kWh / m^3 $H_{2(HHV)}$)	4.3 - 5.4	4.3 - 5.3	3.9 - 4.4
Hydrogen purity (%)	>99.5	99.99	99.9
Cold start time (min)	60 - 120	5 - 10	hours
Maturity of technology	Mature	Commercial	Demonstration
Process efficiency ($\%_{(HHV)}$)	65 - 82	67 - 82	80 - 90

The hydrogen produced from PtG can itself be used as an energy carrier, however often the storage infrastructure required for hydrogen is expensive and underdeveloped. Most existing gas grid infrastructure can accept a low percentage of hydrogen but there are plans for increased percentages of hydrogen to be carried in the gas grid. Indeed when considering plans to decarbonize gas as an energy vector hydrogen has a significant role both in steam methane refoming with carbon capture (termed blue hydrogen) and in generation from VRE (termed green hydrogen). For example Gas Networks Ireland (GNI) in their Vision 2050 document (GNI, 2019) sees 37 % of natural gas replaced with biomethane and 13 % with hydrogen; the remaining 50 % of energy associated with natural gas will involve carbon capture and storage processes (CCS) typically at large gas users. Hydrogen has also been mooted as a potential future transport fuel (hydrogen fuel cell technology).

In this report we assess the interaction of hydrogen from Power to Gas systems with biogas systems. The addition of a further step whereby the produced hydrogen is combined with carbon dioxide (CO_2) may result in the production of an electrofuel methane (CH_4) through a Sabatier reaction ($4H_2 + CO_2 = CH_4 + 2H_2O$); this is termed power to methane. The reaction is exergonic (the change in free energy is negative, the reaction is favourable and heat is given off). The process is termed methanation. The carbon dioxide sourced for such a process should ideally be cheap and concentrated. Since biogas typically comprises of 40-50 % carbon dioxide it is seen as an ideal supply stream for methanation. The conversion of electricity to gaseous energy vectors is complemented by the large-scale storage available in many countries in the form of existing gas grid infrastructure. This allows for easier transportation and distribution of the electrofuels produced.

3.3 METHANATION

Two forms of methanation exist – biological methanation (or biomethanation) which is typically applied at smaller scales and catalytic methanation which is more typically at larger scale.

Biological methanation is a process in which hydrogenotrophic methanogenic archaea consume both hydrogen and carbon dioxide in a biological Sabatier reaction to produce methane and water as a by-product ($4H_2 + CO_2 = CH_4 + 2H_2O$). A number of configurations are available to conduct the biological methanation process. The carbon dioxide in biogas can be sent to an adjacent ex-situ biomethanation reactor where it is combined with the hydrogen generated from renewable electricity or, the hydrogen can be sent directly to the anaerobic digester, known as in-situ biomethanation. Details on both configurations are provided in the following sections.

A catalytic methanation process is an alternative option for methanation systems. However, this technology requires much higher temperatures and is suited to larger scale projects (above 5MW). Catalytic methanation maybe considered somewhat less flexible in matching to a biogas system than biological methanation. The microbial nature of biomethanation lends itself to stop, start, part load operation and as such may be said to be flexible in connecting to smaller more intermittent supplies of hydrogen as would be seen with VRE devices such as wind and solar. Catalytic methanation is also less tolerant of impurities that exist in biogas streams (which can cause catalyst poisoning). The focus of this report will be biological methanation and its potential integration with biogas systems.

3.3.1 In-situ biological methanation

For an in-situ biological methanation system, the hydrogen generated from VRE is added directly to the anaerobic digester (where the organic feedstocks are biodegraded) for increased methane production. This is illustrated in Figure 15. The methane content leaving the in-situ reactor can vary and thus further upgrading of the biogas may be required if it is to be used as a substitute for natural gas (or as in Figure 15 for a natural gas vehicle (NGV)). This can be undertaken using the existing biogas upgrading system at the plant.

The shortcomings of in-situ biological methanation are primarily associated with the increase in dissolved hydrogen (and associated increased hydrogen partial pressure) added to the biogas system. Specifically, the elevated hydrogen levels in the reactor can cause imbalance in the production and consumption of hydrogen. This influences microbes producing hydrogen (acetogens) as the increase in hydrogen partial pressure leads to a positive Gibbs Free Energy and more unfavourable reactions (Voelklein et al., 2019), which can lead to inhibition of intermediate fatty acid production (butyrate and propionate) affecting the normal anaerobic digestion process (Rusmanis et al., 2019).

In-situ biological methanation remains an intricate process requiring sufficient balancing to allow for levels of hydrogen where adequate volatile fatty acids and biogas are produced whilst further conversions of carbon dioxide to methane are also feasible. CO_2 is a product of aceticlastic archeae and as such there are challenges in elevating the CH_4 content to levels approaching biomethane. For gas to grid or for use as a transport fuel in-situ biomethanation may need to be followed by an upgrading process. This is a disadvantage when compared to ex-situ biomethanation.

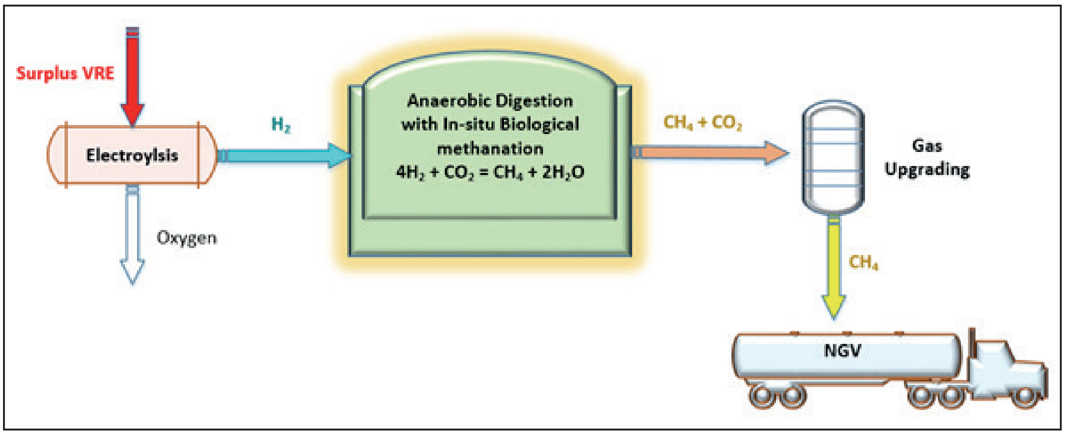

Figure 15: In-situ biological methanation system

3.3.2 Ex-situ biological methanation

In ex-situ biological methanation, the hydrogen and carbon dioxide (from biogas) are added to an external biomethanation reactor which can be located adjacent to the biogas system. This is illustrated in Figure 16. The methane content leaving the ex-situ reactor is significantly higher than the in-situ process (Voelklein et al., 2019). Limited upgrading of the biogas may be required for the substitution for natural gas (again in Figure 16 the system is illustrated as fuelling a NGV). The methanation reactor is typically designed to provide a more controlled environment. The feedstock for the ex-situ biomethantion process does not include for solid or liquid biomass but purely gases.

The only reaction encouraged is that of hydrogen with carbon dioxide to produce methane. The reactor should as such be dominated by hydrogenotrophic methanogenic archaea to the exclusion of aceticlastic methanogenic archeae and acidogenic and acetogenic bacteria. Nutrient supply to the ex-situ reactor is important for the microbial population to thrive. For example Methanothermobacter wolfeii was found to be the dominant microbial species in thermophilic ex-situ biological methanation and the addition of tungsten has been deemed beneficial (Guneratnam et al., 2017; Winter et al., 1984).

Since ex-situ methanation takes place externally to the biogas system, this approach is generally favoured since the risk of digester failure due to elevated hydrogen partial pressure and inhibition of VFAs is eliminated. For natural gas substitution or for use as an advanced transport fuel ex-situ biomethanation has a significant advantage over in-situ biomethanation as the need for a conventional physio-chemical gas upgrading system is minimized. Currently ex-situ systems operate at demonstration scale but are still not at commercial technology readiness.

A perceived barrier to the technology is the dissolution of hydrogen within the reactor and the contact between hydrogenotrophic methanogenic archeae and the dissolved hydrogen (Voelklein et al., 2019). Future research to optimise the technology will concern improving methane evolution rates (MER; measured in L CH_4 per L reactor per day) through maximising the gas to liquid mass transfer rates of hydrogen.

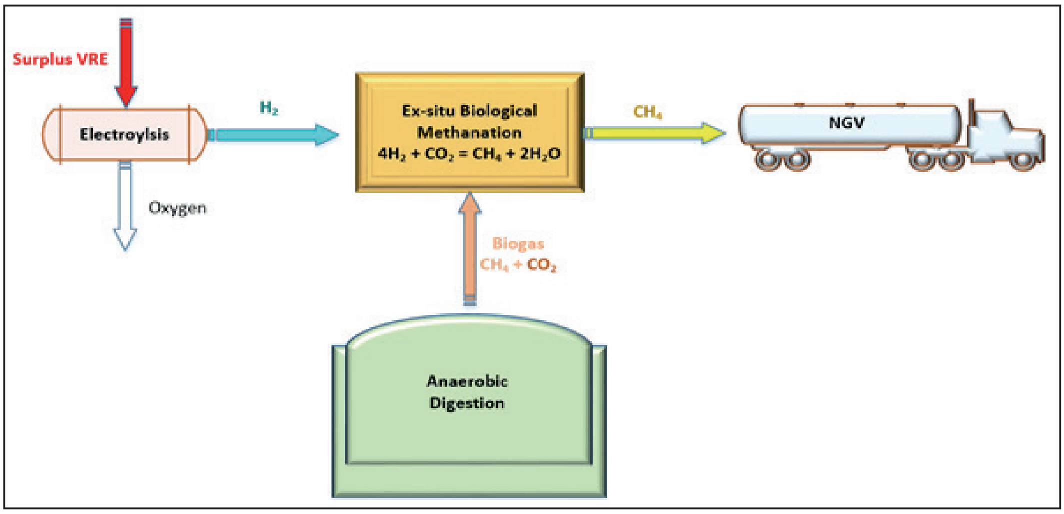

Figure 16: Ex-situ biological methanation system

3.3.3 Biological methanation system development

The dissolution of hydrogen is vital for efficient methanation and thriving microbial communities. The solubility of hydrogen in water is 0.7 mmol H_2/ L, 24 times less than carbon dioxide at 55 °C. This presents a limitation to the methanation process (Voelklein et al., 2019). Characteristics of methanation such as temperature and pressure along with elements such as the reactor configuration, mixing speed, and methods of gas diffusion, all influence the solubility of hydrogen. Few studies have reported hydrogen solubility as the governing influence in methanation; the volumetric gas-liquid transfer coefficient (typically denoted KLa) is a difficult parameter to measure accurately and subsequently has been often overlooked.

Much of the existing work on biological methanation has been carried out at laboratory scale. Numerous reactor configurations have been designed to be tested for process performance. The most common reactor type for biological methanation has been the continuously stirred tank reactor (CSTR), owing to its existing use in biogas systems. Three critical parameters have been established in assessing the performance of biological methanation: methane evolution rate (MER) measured in litres of methane per litre volume of reactor per day (L CH_4/Lvr/day); retention time, the length of time the hydrogen and carbon dioxide remain in the reactor; and gas purity, the percentage methane (%CH_4) measured exiting the methanation reactor.

Table 4 shows a range of values for these important parameters as reported in previous biological methanation studies in which CSTR systems were utilised (adapted from Rusmanis et al. 2019). The dataset for in-situ processes was attained from just one study and as such can be considered much less robust than the data presented for ex-situ systems. Data is also reported for one demonstration facility which is at a much larger scale (approximately 3,750L) as compared to the in-situ (1L) and ex-situ (1 – 16L) reactors. Some form of agitation is used in all methanation systems reported as a means of improving hydrogen dissolution. In essence, for any methanation system, high MER, high purity and low retention time would be favourable.

Table 4: Reported values for key parameters of biological methanation (Adapted from Rusmanis et al. 2019)

Biological Methanation System	Pressure (barg)	Temperature (°C)	MER (L CH_4/L_{vr}/day)	Retention time (hours)	Purity on exit (%CH_4)
Lab In-situ	1.5	55	0.5 - 3.2	1 - 8	90 - 95*
Lab Ex-situ	0 - 5	60 - 65	9.9 - 688.1	0.004 - 0.76	2 - 97
Demonstration scale Ex-situ	8.5	62.5	800	0.05	99

* CSTR data only available for one in-situ methanation study at small scale (<1L). Other in-situ methanation studies based on diffusion reactors report %CH_4 values in the range 6-75%.

The variation in MER, retention time and purity can be considered a result of the early development stage of the biomethanation technology. However, progression in reactor performance can be noted with the use of certain microbial strains (Methanobacter) and lower retention times which indicate a high efficiency of gas conversion (i.e. higher resulting purity). Of interest, pure cultures are used in the demonstration scale ex-situ reactor and may explain the enhanced performance. Higher pressure is also employed to maximise the solubility of hydrogen and availability to hydrogenotrophs within the reactor system.

For both types of biomethanation system the solubilisation of hydrogen is a key parameter. This can be considered a potential barrier to technology uptake and much research in the future will examine hydrogen gas to liquid transfer to optimise biomethanation processes. Furthermore, parameters such as hydrogen injection rate and corresponding MER must be tested to ensure a more robust technology.

3.3.4 Variation in process design and energy use

Alternative layouts to biological methanation exist to the two basic process designs outlined above; this is particularly the case for ex-situ systems. For instance, separation of the carbon dioxide from biogas may occur initially via a conventional physio-chemical process and thus only purified streams of carbon dioxide and hydrogen would be sent to the ex-situ reactor, potentially enhancing the process efficiency. This could limit the perceived advantages of the ex-situ system in that it does not remove (or reduce the scale of) conventional upgrading. Gas storage also becomes of significant importance, whether it is for intermediate storage of hydrogen, biogas or pure carbon dioxide prior to biomethanation, depending on the plant configuration.

Hybrid systems have also been explored as a concept. A model was developed based on laboratory experiments for the sequential use of both in-situ and ex-situ processes in a $1MW_{el}$ biogas plant by Voelklein et al., (2019). The model included for a grass silage digester in which hydrogen would be injected to provide an in-situ biomethanation process, using the carbon dioxide in biogas as the carbon source. The exit gas purity was modelled (based on lab experiments) at 70 % methane; this methane enhanced biogas was forwarded to an ex-situ biomethanation reactor for further upgrading. The gas was recirculated in the ex-situ system until the model suggested a final purity of 84 % methane. It was noted that elevating the biogas to natural gas grid quality may require a more optimised ex-situ reactor with higher pressures.

The end uses of the methane are also numerous. Upgrading biogas to biomethane (typically > 98 % methane) may be sufficient for injection of the gas to the natural gas grid. This is often considered to be a superior pathway for deployment in biogas systems as compared with CHP units that just produce electricity and may (or may not) avail of a seasonal market for heat. Biomethane offers more value in its availability for off site use at a node of high energy availing of scale. It could for example be used at a large combined cycle gas turbine with high electrical efficiency (upto 60 % electrical efficiency) or at a source of demand for industrial heat or at a public transport facility. Biomethane in the gas grid offers great flexibility and potential for improved revenues in energy utilisation. Thus the gas, if of sufficient quality when leaving biological methanation, may be injected into the gas grid and avail of a large maket with a variety of enhanced end uses and economic returns.

Using biogas systems, surplus renewable electrical energy can also be transformed to produce advanced fuel for natural gas vehicles (termed gaseous fuel from non-biological origin in the recast EC Renewable Energy Directive (EC, 2018)), increasing energy security in the transport sector.

3.4 PTG - BENEFITS OF TECHNOLOGY AND SECTOR COUPLING IN A FUTURE ENERGY SYSTEM

The benefits of integrating biogas systems with PtG are significant. Not only can such technology coupling significantly increase the volume of methane produced from biogas systems by converting the carbon dioxide but it can also provide a means for bioenergy with carbon capture and utilisation. Future implementation of PtG systems should be readily matched by investment in biogas systems to amplify and integrate the benefits of both technologies. Furthermore, biogas acting as the carbon source for PtG is seen as a most favourable source of carbon dioxide, with minimal cost and potential to generate savings if conventional biogas upgrading can be substituted by ex-situ biomethanation. Utilising the by-product stream of carbon dioxide to generate additional methane (by up to 70 % according to Voelklein at al., 2019) exemplifies a circular economy approach providing for carbon capture in biogas systems. Expansion of the biogas industry will also result in growth of the bioenergy sector, identified as critical in order to align with the 2°C Scenario under the Paris Agreement (IEA ETP, 2017).

As demonstrated, biogas systems can act as a flexible technology in allowing for further uptake of surplus VRE as a gas. This can be considered of substantial importance in the future since it is reported that gas infrastructure delivers between 50 and 100 % more energy to end consumers than electricity in Europe and the US (IEA WEO, 2019). In essence, the development of PtG with biological methanation has the ability to absorb surplus VRE and avoid potential curtailment and/or constraint of electrical systems. This is of significant merit in a future energy system, transitioning from fossil fuels through the production of green gas and ultimately facilitating higher proportions of wind, wave and solar energy. This, in effect, provides a mechanism for sector coupling of the electricity and gas networks, which as a result, could allow both sectors to work in synergy.

Ultimately, through integration with PtG systems, biogas can play a role in the supply of renewable energy to the wider energy system. The energy can also be considered flexible with the option of injecting to the gas grid for customers, using for heat in large industry or as an advanced transport fuel in sectors which are hard to decarbonize (such as haulage and intercity buses). Curtailment of surplus electricity can be lessened and the requirement for expensive hydrogen infrastructure avoided in the short term. Such processes can be installed as stand alone solutions in areas with unstable grids.

Furthermore, biogas systems have the capability to act as a potential "source and sink" by combining CHP with PtG (as mentioned in section 1.2) – adding further flexibility. Thus, whether electricity supply exceeds demand, or demand exceeds supply, biogas can act as a facilitator in a more flexible, controlled energy system.

3.5 EXEMPLARS OF BIOLOGICAL METHANATION

Electrochaea have developed a grid-scale energy storage solution. The proprietary power to gas process converts renewable energy and biogenic carbon dioxide into grid-quality renewable methane for storage and distribution. Demonstration plants successfully injected renewable methane into commercial gas grids in Switzerland and Denmark.

The company's technology based on biological methanation makes it possible to store renewable energy and recycle CO_2 in a cost-effective way. This technology eliminates the temporal link between energy supply and demand, allowing efficient energy and CO_2 storage as renewable methane. When renewable power is available but not immediately used, renewable methane can be generated "on demand" and stored in the gas grid. This enables the growing market for renewable electric power and provides an expanding source of renewable gas. The more intermittent renewable electricity generated, the more valuable this technology becomes as a storage mechanism.

The core of the power to gas system is a selectively evolved microorganism – a methanogenic archaea – that has displayed excellent catalytic ability and industrial robustness. The technical advantages of this biocatalyst enable the "BioCat" methanation technology to operate at lower capital and operating costs and with greater flexibility than conventional thermochemical methanation processes.

Electrochaea is a growth-stage company with headquarters, engineering and development teams in Munich, Germany, and commercial scale demonstration facilities in Denmark and Switzerland, and a research reactor in Golden, Colorado at the National Renewable Energy Laboratory (NREL). The Electrochaea story started in the year 2006 with basic research and four years of proof-of-concept work in Prof. Laurens Mets' laboratory at the University of Chicago. Derisking of the process for commercialization began in 2011, using raw biogas to produce methane at a brewery digester in St. Louis, Missouri, and continued with field trials in Foulum, Denmark.

In 2016, an industrial scale plant was commissioned in Avedøre, Denmark. The Electrochaea-BioCat plant, located at the BIOFOS wastewater treatment facility demonstrated a power to gas technology (in this case power to methane via biomethanation) at a commercial scale (1 MW of electrical power at the electrolyser). The system is comprised of a biomethanation reactor utilising a unique 'biocatalyst' in the form of hydrogenotrophic methanogenic archaea that convert carbon dioxide and hydrogen to methane. The BioCat plant operated from April 2016 until October 2019 and ran for more than 4500 hours. The overall objective of the project was to design, engineer, and construct a commercial-scale power to methane facility to demonstrate the commercial feasibility of the technology and effectively store energy and carbon dioxide.

The design of the BioCat plant was such that the carbon dioxide required for the biomethanation reactor was sourced from a local biogas plant. Biogas was added to the biomethanation reactor at a rate of 125 m^3/hour (STP) with a biogas composition of approximately 37 % CO_2 and 63 % CH_4. Electrochaea demonstrated the application of the technology with raw biogas by "upgrading" the existing methane in the biogas and converting the CO_2 into methane. Pure streams of CO_2, separated from biogas through gas upgrading, have also been added to the biomethanation unit in separate trials without changing the gas output quality of the plant.

The hydrogen was produced from an onsite electrolyser (Hydrogenics' S1000 alkaline electrolyser) which was run in conjunction with the local power grid. Simulations were also performed for operations at times of low electricity demand in an automated process. The selected electrolyser had a quick response time to deal with the varying loads of electricity consumption.

The hydrogen from electrolysis was delivered to the biomethanation reactor at a stoichiometric ratio of 4:1 ($H_2:CO_2$) which was equivalent to a rate of up to 200 m^3/hour (STP) for further conversion to methane.

Implementing a circular bioeconomy approach, the heat from the exothermic reaction both from methanation and electrolyser were recycled to dry sludge in the wastewater treatment plant. The biomethanation reactor operated at a pressure of 8.5 bar and a temperature of 62°C. The unique biocatalyst (hydrogenoptrophic methanogenic archaea) could achieve CO_2 conversion efficiencies of 97–98.6%. The methane generated in methanation (which is of 97–98.6% purity) was injected to the local gas distribution grid operating at 3 bar pressure. A process flow diagram is illustrated in the Figure 17.

A second-generation plant, with automated remote operation, was commissioned in 2019 in Switzerland, under the STORE&GO project, "Horizon 2020 research and innovation programme" funded by the European Union and was injecting high quality methane onto the gas grid within 96 hours of startup. The plant produced methane for more than 1300 hours from July 2019 until February 2020.

Both plants have demonstrated flexible operation with immediate recovery after different periods of shut-down. This flexibility is important to accept intermittent renewable power, when it is available. Load factor tests have shown that the Electrochaea power to gas system can be operated at 0–100% capacity. The Electrochaea power to gas technology captures would-be curtailed electricity and converts it into methane for immediate use or for storage and use at a later time. Currently Electrochaea is working on deploying commercial PtG plants in excess of 10MW_{el} scale.

For more information, please visit the following websites:

http://www.electrochaea.com/
http://biocat-project.com/
https://www.storeandgo.info/

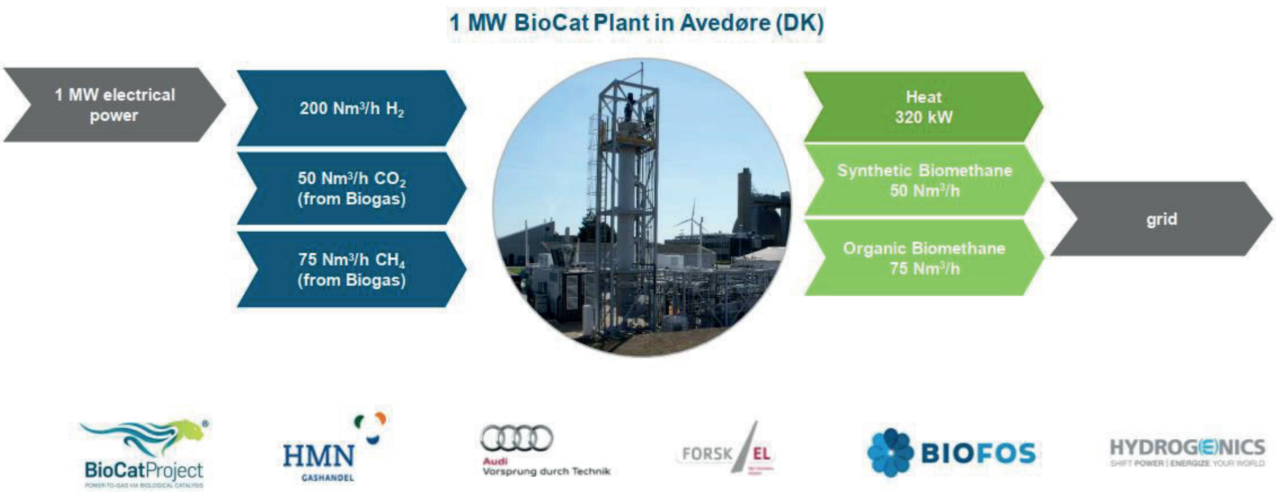

Figure 17: Methanation of raw biogas via Electrochaea system

4. Discussion and Conclusion

The perception of the role of biogas has changed over the years. Biogas was traditionally seen as a means of treatment of a range of wet organic wastes (from municipal, industrial and agricultural sources), more recently as a source of renewable energy (as exemplified by digestion of Maize in the German biogas industry). The end use of biogas was initiallty dominated with production of combined heat and power; more recently upgrading to renewable gas in the form of biomethane either injected to the gas grid or utilized as a transport fuel has increased.

The authors believe the **next stage of the biogas industry** will be associated with a fundamental change in future renewable smart energy systems. The structure and characteristics of energy provision as well as energy consumption will evolve with the transition to a more sustainable and decarbonized economy with significantly larger proportions of variable renewable electricity in the energy mix. Consequently producers and consumers will face significant changes in the energy market, particulary associated with times of production of energy and times of use of energy. The increasing relevance of CO_2 emission reduction will alter economics and demand for different energy vectors with different levels of decarbonization at different times. The integration of energy vectors will be essential in facilitating PV during daylight hours, wind power on windy days and renewable sources of dispatchable energy such as from bioenergy.

The biogas plant operation itself can be controlled extensively and with this control comes high levels of flexibility. This is a huge advantage over other renewable energy provision systems. Biogas systems:

- have a very positive attribute of being dispatchable but furthermore can be ramped up and down to match the vagaries of temporal mismatch between variable renewable energy supply with the demand for a variety of energy vectors.
- can be a node of integration between electrical and natural gas grids in providing a sink for electricity (through power to gas systems) that would otherwise be curtailed or constrained and an enhanced producer of green gas for injection to the natural gas grid for use as a source of electricity, heat or advanced transport fuel.

The flexibility of biogas systems can facilitate energy delivery: to the electricity grid as close as possible to the electricity demand profile facilitating voltage and grid stability; to provide heat to consumers facilitating the seasonal demand profile of heat; to the gas grid to decarbonize gaseous fuels such as for industrial heat; directly to local consumers such as for transport biofuel for haulage and buses. Biogas can play an essential role (together with PV) as part of a virtual power plant in local distribution energy grids. Biogas can couple the electricity and gas grids when serving as a biological battery. Biogas systems have a role to play in the future electro-fuel market using hydrogen from electricity (preferable curtailed or constrained) to react with CO_2 in biogas producing biomethane (replacing the role of physio-chemial upgrading techniques) and increasing the output of biomethane (typically by 70 %).

The future of biogas will be influenced by the future of gaseous energy carriers. Within Europe and the United States between 50 and 100 % more energy is delivered to the end consumer as gas as compared to electricity (IEA, 2019). Biogas offers significant advantages where it can be used to displace fossil natural gas in existing infrastructure such as the food and beverage industry (Kang et al, 2020) and in high temperature applications for material production (such as cement and glass). Biogas plants can provide a myriad of solutions to the many challenges of future agricultural and waste treatment infrastructures and to the circular economy approaches to production of transport biofuel. The flexibility and system integration described in this report will be a significant driver for biogas systems to be integrated to future energy systems as a means to facilitate intermittent renewable electricity.

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