WP3 – Biogas valorization and efficient energy management

D 3.2: Technical and economic analysis of biological methanation

The project "Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration" (POWERSTEP) has received funding under the European Union HORIZON 2020 – Innovation Actions - Grant agreement° 641661

Deliverable 3.2	***Technical and economic analysis of biological methanation***
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Abstract	Results from bio-methanation integrated in WWTP highlighted that using this technology contributes that WWTPs reach a positive energy balance. As the integration of the P2G plant to the rest of the WWTP allows reducing aeration and heating costs and offers an additional flexibility on the use and storage of power, a bio-methanation plant would allow a WWTP to become an energy producer and an energy storage operator able to interconnect the electrical, heat and gas grids.

Dissemination level of this document

X	PU	Public
	PP	Restricted to other programme participants (including the Commission Services)
	RE	Restricted to a group specified by the consortium (including the European Commission Services)
	CO	Confidential, only for members of the consortium (including the European Commission Services)

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Glossary

Methanation: Reaction of Carbon Dioxide (CO_2) and Hydrogen (H_2) to produce methane (CH_4).

Power-to-gas: Process of converting electrical power to gas, allowing easier storage and transport of energy.

Archaea: Single-cell organism, first identified in extreme environments (geyser, salt lakes…) but are commonly found on earth in various ecosystems. Electrochaea is using a unique strain of a methanogenic archaea

WWTP: wastewater treatment plant

Executive Summary

Electrochaea.dk, as partner of the H2020 project POWERSTEP has conducted an experimental and engineering study to evaluate the benefits of coupling its technology of power-to-gas via bio-methanation to a wastewater treatment plant (WWTP).

This report details the demonstration of the concept and assesses several ways to optimize an integrated system where a power-to-gas plant is coupled to the biogas production of a WWTP. The technology was demonstrated and studied in the POWERSTEP case study 3 in collaboration with the Wastewater Treatment plant of Avedøre (Denmark, Copenhagen area) operated by Biofos.

After more than 2 years of operation and improvements of the Biocat plant, the smart goal of producing a high-quality gas stream has been reached. The Biocat plant has produced for a continuous period a high-quality gas containing more than 97%-CH4 and less than 2% H2.

The technical and economic study has also shown there is a clear symbiosis between a power-to-gas plant by bio-methanation and a wastewater treatment plant. Different tracks of integration have been assessed in this document for a reference case defined by:

- A WWTP of 350 000 PE, equipped with biogas digester and an upgrading plant
- A methanation plant able to process the corresponding CO_2 flow-rate (240 Nm^3/h), with an electrolyzer power of 4.8 MW

The different points of integration have shown a positive outcome for all of them, as they allow providing a direct outlet with a high level of availability for the by-products of the power-to-gas plant:

- The **oxygen** produced by electrolysis of water can be used to support the operation of the activated sludge ponds. As shown by both 15 years of operation at the WWTP of Lynette (Copenhagen, DK) and during a lab trial conducted during the project, pure oxygen is not toxic for the activated sludge and results in similar oxygen uptake rates as air used from the blowers. As the oxygen produced by the electrolyzer is already pressurized, it totally displaces the corresponding operation of the air blowers normally used to aerate the ponds. Additionally, the instantaneous oxygen demand of the aerated ponds has a similar order of magnitude as the oxygen production resulting of the operation of a methanation plant matching the CO_2 production of the biogas reactors of the WWTP. The avoided aeration costs represent a gain of profitability for the P2Gas plant of 18 %.
- The **heat** produced by both the electrolyzer and the methanation reactor can be integrally re-covered for fulfilling the heat demand of the biogas digesters and the building heating. The avoided heating costs represent a gain of profitability for the P2Gas plant of 35%. However, integrating flexible and intermittent sources of heat in the heating loop of the WWTP, where several sources and consumers are present, may require adapting its design and controls.

- **Storage of CO_2** during the hours of non-operation of the reactor is feasible at a limited cost and without large challenge on site safety. It allows reaching a higher annual production of methane and therefore defining a plant configuration with a better economy. Depending on its size, the CO_2 storage allows improving the plant profitability by 7 to 1%.
- **The use of the by-water** produced by the methanation reactor as a source of substrate for the biogas digesters allows a small additional production of methane. The direct coupling between the methanation water outlet and the sludge pit of the biogas digester represents the cheapest and most efficient way of handling a flow which otherwise would be considered as a waste

Higher integration of controls and real-time data exchange between the different interfaces (Power supply, electrolysis, CO2 supply, heat up-taker, oxygen up-taker) are necessary to maximise the operability of the methanation plant, to offer grid-balancing services and to achieve a high level of valorisation of the co-products.

It results from these assessments that a power-to-gas plant by bio-methanation can be an important contributor to the effort of WWTP to reach positive energy balance. As the integration of the plant to the rest of the WWTP allows reducing aeration and heating costs, and offers an additional flexibility on the use and storage of power, a bio-methanation plant would allow a WWTP to become an actor in the electrical grid balancing not only as possible electricity producer (with the gas engines) but also as an energy storage operator able to interconnect the electrical, heat and gas grids. To maximise the profitability of the power-to-gas plant, a high level of integration needs to be achieved to reach a high-level of valorisation of the co-products.

1. Introduction

1.1. Methanation

Methanation is the reaction of CO_2 and H_2 into CH_4.

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O$$

The thermo-chemical methanation, discovered at the beginning of 20th Century by the French chemist Paul Sabatier, Nobel Prize in Chemistry in 1912, consists of converting carbon monoxide (CO) or carbon dioxide (CO_2) in the presence of hydrogen in presence of metallic catalysers (Nickel and Cobalt) to methane (CH_4) and water.

The reactions of methanation are known to be highly exothermic reactions with decrease in the number of moles.

Biological methanation differs from the thermo-chemical methanation by using a living micro-organism to catalyse the reactions. Species of the Archaea kingdom have specialized in the processing of H_2 and CO_2 to produce their own energy and fix the carbon necessary to their growth. Such micro-organisms can be found in the natural environment such as hot springs where extreme conditions of pressure and temperature are present, and both the source of energy and carbon can be found, but also as part of a typical anaerobic ecosystem present in biogas reactors.

Electrochaea, drawing from academic work carried out at University of Chicago, has developed a reactor design and operation procedures to build a bio-reactor hosting a pure culture of a specific Archæ presenting a high level of performance for the methanation reaction. The strain has been selected to meet the constraints and requirement of an industrial scaled system able to quickly transform high amounts of volatile energy (such as hydrogen, or indirectly electricity) into a storable form of energy, methane.

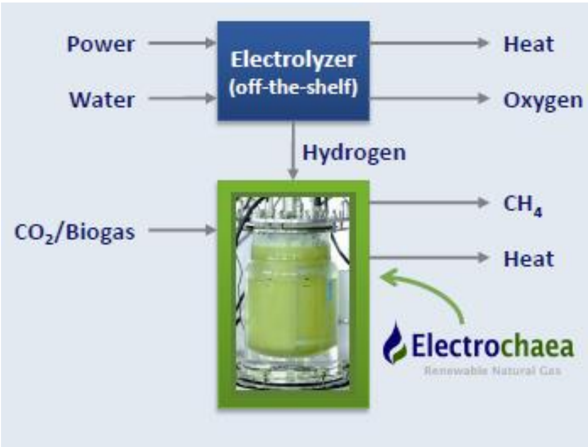

Figure 1 - Electrochaea methanation technology

1.2. The Biocat project and the biocat reactor

As part of the development of its bio-methanation technology, Electrochaea.dk has conducted a Research and Development project, the Biocat project, supported by a

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Danish research grant, Forksel. The overall objective of the 2 years project, (see Figure 2 and Figure 3), was to design, engineer, construct, and operate a 1-MW Power-to-Gas facility to produce and inject grid-quality methane under intermittent operations. The plant built for this project was using hydrogen from alkaline electrolysis and a methanation reactor based on biological catalysis.

Figure 2 - The P2G BioCat Plant on BIOFOS site in Avedøre, Kanalhommen 28

Figure 3 - Construction of the biogas upgrading (grey building and the two columns on the left) and the Biocat plant (background).

The system, called the BioCat plant, operated for 8 months during the project, including commissioning. During the project, the system used 42 193 Nm³ biogas, 170 m³ water and 708 215 kWh electricity for system operations and to produce 129 290 Nm³ hydrogen for methanation of ~16 000 Nm³ CO_2 from the biogas and making available ~15 000 Nm³ of renewable methane and 85 000 kWh heat for use at Avedøre's facility. The system operated at variable loads and was used intermittently through 3 seasons until December 22, 2016. At the end of the project, plant operation had been controlled enough to produce a gas with a methane content of more than 90% before purification.

The process of siteselection to build the plant identified the Wastewater Treatment plant of Biofos A/S, at Avedøre, Denmark, as a potential site for its availability of bio-genic CO_2 under the form of biogas. At this point of the technological development, the emphasis of the project was on the demonstration of the core technology and the optimization of its design and operation rather than the integration of the methantion plant with its interfaces (heat exchange, water discharge,). It was however clear that wastewater treatment plant had a strong potential to be relevant sites for a bio-methanation plant as:

- The biogas digesters at a WWTP offer a punctual source of concentrated CO_2, either as raw biogas or as separated CO_2. In addition, there is a growing interest

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for biogas upgrading plants rather than the installation of combined heat and power.

- The oxygen produced during the electrolysis is a by-product of the methanation plant which is often hard to valorize, but it could be used at the treatment plant in replacement or addition to the existing aeration system used for the activated sludge process.
- The moderate temperature of the heat source can be a challenge for an efficient and straight-forward export of the heat produced by the methanation plant
- The by-water produced by the reactor contains anaerobic biomass which could represent a source of organic matter and/or an interesting microbial complement to the existing ecosystem present in the biogas reactors.

To investigate and demonstrate these *a priori* statements, the operation of the Biocat plant installed at Biofos A/S has been extended and further tests have been conducted through the POWERSTEP project.

1.3. Plant description

The BioCat plant was erected on the BIOFOS wastewater treatment site in Avedøre between November 2015 and March of 2016. The system includes the 9 m tall BioCat reactor in a 12 m tall frame, a balance of plant skid, one electrolyser with a Power of 600 kW, several containers for the utilities (water softening, power panels, instrument air, control-room and gas analyzer).

The plant has been designed to treat up to 50 Nm^3-CO_2/h. It can use as a carbon source either the raw biogas produced by anaerobic digestion of urban sludge, or the off-gas produced by the biogas upgrading plant purifying the raw biogas before injection. The second gas stream used for the reaction is hydrogen. It is produced on-site by one electrolyser with a maximal production capacity of 110 Nm^3-H_2/h. The gas leaving the biological reactor is subjected to several post-treatments to remove dust, contaminants and water and to remove excess H_2 and/or non-reacted CO_2 from the gas stream. The tail-gas generated during the post-treatment stages is recycled to the reactor, whereas the main stream is meant to be injected in the natural gas grid. Therefore, the pilot plant is connected to an injection container, owned and operated by HMN, where the gas quality is controlled and the gas can be injected to the natural gas grid.

At the beginning of the project, only the metabolic heat generated by the reactor was exported by a water-loop to Biofos, to support the heat demand of the biogas digesters. The water collected from condensates traps and from the continuous draining of the metabolic water produced in the reactor is collected through a gas-liquid separator at atmospheric pressure, and then exported to the internal sewer system of Biofos.

A general layout of the process and its integration to other parts is illustrated on Figure 4 and a view of the reactor and the surrounding site is shown on Figure 5.

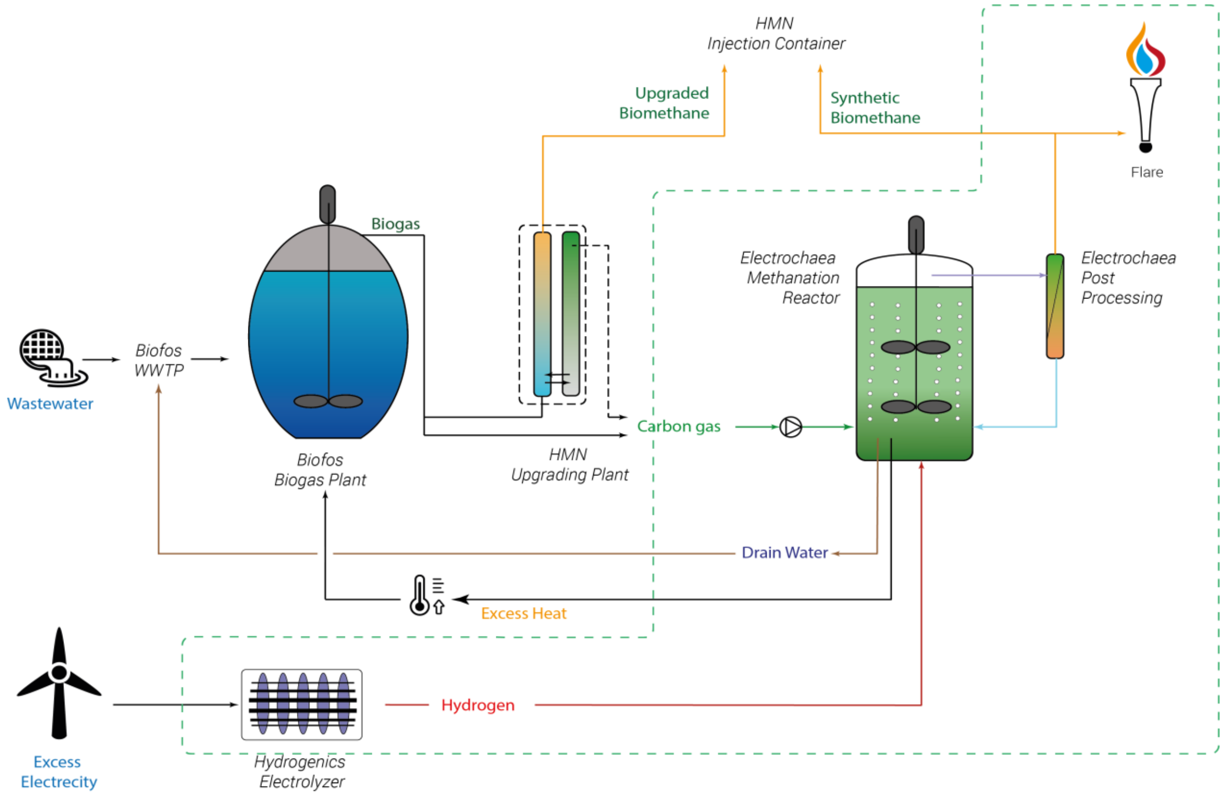

Figure 4 - General layout and integration of the BioCat reactor. Electrochaea perimeter is delimited by the green dashed line, future upgrading plant in black-dashed line.

Figure 5 - View of the BioCat plant showing the reactor (left), balance of plant (center) and the biogas plant (background)

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2. Campaign runs

The BioCat plant has been operated for the objectives of the POWERSTEP project mostly through two campaigns of 5 weeks, in March and June 2017. As the upgrading plant treating the biogas and supposed to deliver the pure CO_2 to the methanation plant was not achieved at this time, the two campaigns have been carried out with raw biogas as a source of CO_2. Two short tests in December 2017 and March 2018 have demonstrated similar performance and operability when using pure CO_2 as a carbon source.

The campaigns have demonstrated:

- The mechanical and biological stability of the plant, with 98% process availability during the last test, and more than 2 500 hours of operation since the first inoculation in April 2016.
- The ability of the BioCat plant to produce a gas with more than 97% methane, compatible with specifications of the Danish gas grid (see Figure 6 and Table 1).
- The ability of the Biocat plant to quickly modulate its loading-rate and to achieve rapid stop/start without impacting the quality of the product gas.

An example of flexible operation with high quality gas is illustrated by Figure 6, with a methane content varying between 97 and 98% regardless of the variations of the process loading rate.

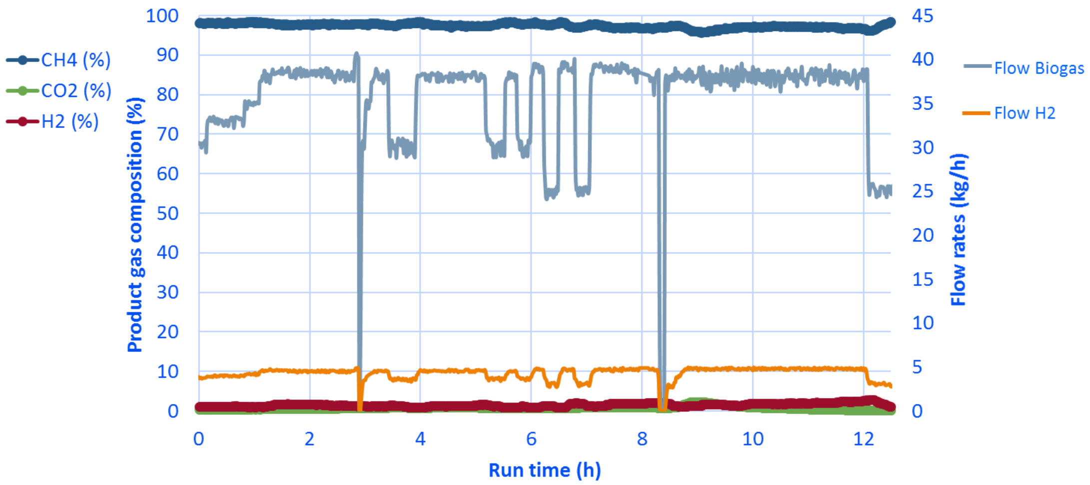

Figure 6 - Response of the BioCat process to sudden changes load changes.

Table 1 - Specifications of the Bio-methane quality for injection into the Danish Gas grid

Parameter	Unit	Limit	BioCat
Wobbe index	MJ/m3	50.76 – 55.8	52
CH4	% of dry gas	> 97%	97%
CO_2	% of dry gas	< 3%	1%
H_2	% of dry gas	< 2%	2%
O_2		< 0.5	N-D

The sections below describe the mass and energy balance of the plant when operating with CO_2 or biogas as primary source of carbon. In order to have a clear distinction between the methane produced by anaerobic digestion of organic matter and the methane produced by methanation of CO_2, the term of neo-methane has been introduced, in opposition to the bio-methane. Neo-methane refers to methane produced by methanation of CO_2 and the bio-methane refers to the methane produced by purification of biogas.

2.1. Mass and energy balance (CO_2)

When operating with CO_2 as a source of carbon, the two gas streams, H_2 and CO_2, are supplied to the reactor with a stoichiometry allowing the full conversion of the CO_2 into CH_4. The fine control of the initial ratio between H_2 and CO2 results in a product gas with very low content of non-reacted CO_2 and low content of excess Hydrogen. The production of hydrogen represents the main consumption of energy, with a much lower consumption for the other utilities on site and gas compression.

As shown in Figure 7, under nominal operation 52% of the consumed electricity is exported as methane and 31% as heat, which represents an overall energetic yield of 83%.

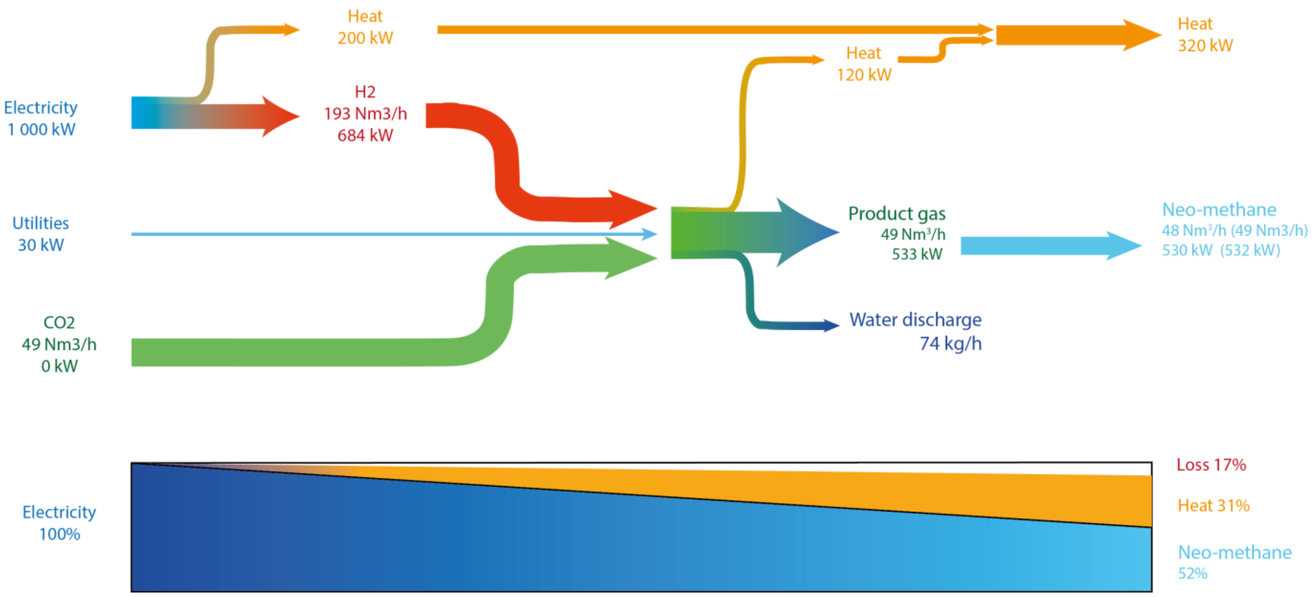

Figure 7 - Mass and Energy balance with CO2 as primary carbon source

2.2. Mass and energy balance (biogas)

When operating with raw biogas as carbon source, the methane carried over with the biogas does not affect the specific efficiency of the micro-organism and does not create any inhibition. However, it mechanically reduces the partial pressure of hydrogen in the first part of the reactor, and therefore slightly reduces its volumetric efficiency. This effect is not detrimental to the operation of the system and an operation where a single methanation plant is used both to purify the bio-methane and to convert the CO_2 into neo-methane is possible.

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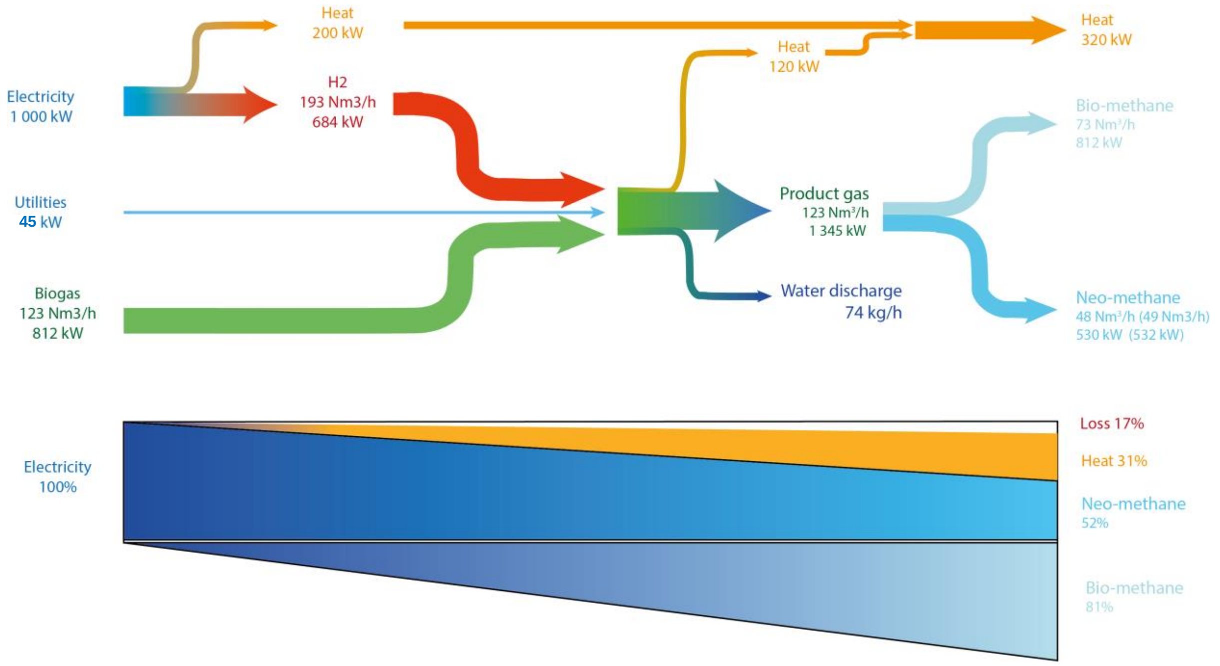

Figure 8 – Mass and Energy balance with biogas as primary carbon source

3. Reference design of a power-2-gas plant integrated to a WWTP

The BioCat system is a demonstrator, and even though it is the largest bio-methanation reactor ever built, it is still a pilot-scale system. Therefore, the technical and economic analysis of the different improvements of the integration of a bio-methanation system to a wastewater treatment plant has been assessed for a commercial-scale plant matching the CO_2 availability and constraints of a wastewater treatment plant.

The reference case corresponds to the maximal load of the Avedøre WWTP, with a theoretical capacity of 350 000 PE (population equivalents; 21.9 kg BOD/year). The plant includes a biogas reactor treating mostly the sludge generated by the wastewater treatment, and marginally additional sources of organic matter and a biogas upgrading facility. The biogas production resulting from anaerobic digestion of sewage sludge is estimated at 600 Nm^3/h, with a standard composition of 60% methane-40% CO_2, which corresponds to a flow of 240 Nm^3-CO_2/h. Main figures of the WWTP of this reference case are listed in Table 2.

Table 2 - Main parameters describing the WWTP of the reference case.

		per hour	per day	per year
COD	ton	2.2	53	19 345
Primary sludge	ton-SS	1.1	26	9 490
Secondary sludge	ton-SS	0.5	13	4 792
Methane production	Nm3	364	8 728	3 185 720
Biogas production	Nm3	606	14 547	5 309 533
CO2 production	Nm3	242	5 819	2 123 813
BOD in aerated ponds	Ton	0.7	16	5 840
Oxygen demand		1.0	22.9	8 367

The bio-methanation plant is sized to match the peak flow of CO_2. The performance level for the bio-methanation plant, drawing from the one demonstrated at the pilot scale system, assume 99% conversion of the CO_2 to the product gas and a limited excess of H_2, leading to a gas quality meeting the specifications of the Danish gas grid (Table 1).

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Table 3 - Reference case - Peak flows

Parameter	Unit	Value	Comment
Biogas flow	Nm^3/h	600	
CO_2 flow-rate	Nm^3/h	240	CO2 content of the biogas 40%
H_2 demand	Nm^3/h	965	
Electrolyser Power	kW	4 824	Default yield of 5 kW/Nm3-H2
Product Methane flow	Nm^3/h	238	
Oxygen production	Kg/h	689	
Heat production	kW	1 580	Metabolic heat and electrolyser heat
By-water production	Kg/h	375	

A key parameter to assess technical-economic performance of a power-to-gas system is the annual hours of operation. Such a plant is designed to operate intermittently, according to the availability and cost of renewable electricity, and/or to comply with the up- or down-regulating demands from the electrical grid operator. Figure 9 shows the annual distribution of the power price on the spot market in 2016[1].

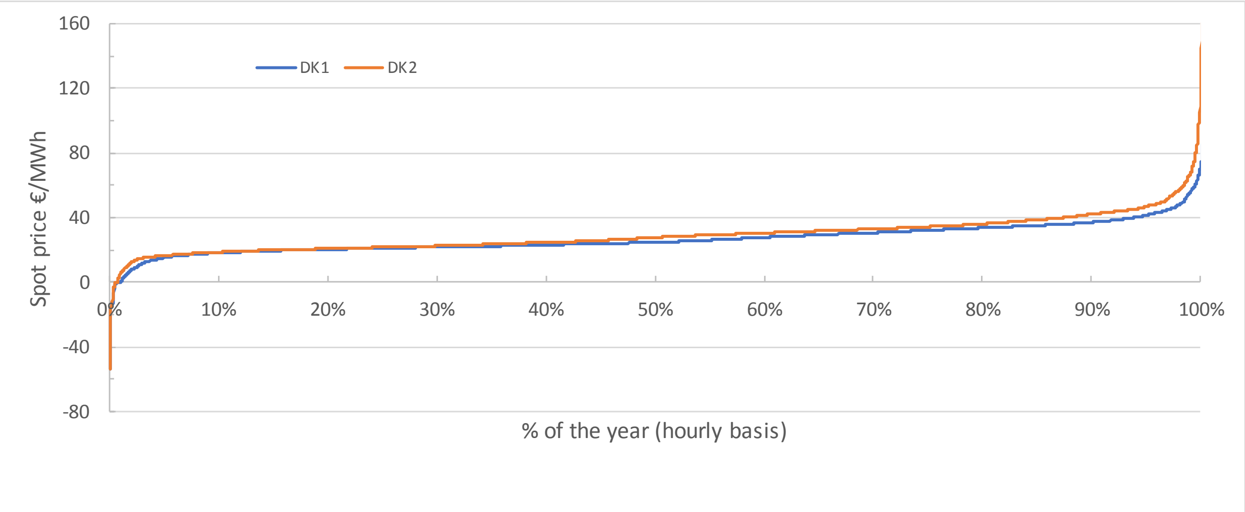

Figure 9 - Distribution of electricity price over the year (2016) in DK1 (West) and DK2 (East) (*Source www.nordpoolgroup.com*).

The average price was 26.52 and 29.03 €/MWh respectively for DK1 (Western Denmark) and DK2 (Easter Denmark, Capital region), with a peak price higher than respectively 37.10 and 42.03 €/MWh for the 10% most expensive hours (see Table 4). The actual number of hours of operation is an economic decision which will depend on the exact conditions. Two cases have been compared -, with a plant operation of either 40% or 60% of the year.

[1] Downloaded from https://www.nordpoolgroup.com in January 2018

Table 4 - Distribution of the spot-price of electricity in DK1 (Wester Denmark) and DK2 (Easter Denmark).

	DK1		DK2	
€/MWh	**Price**	**Average price**	**Price**	**Average price**
Cheapest 40% hours	23.10	18.65	24.69	19.67
Cheapest 50% hours	24.75	19.72	27.77	20.96
Cheapest 60% hours	27.87	20.78	30.49	22.32
Cheapest 80% hours	33.64	23.27	36.08	25.02
Cheapest 90% hours	37.10	24.61	42.03	26.56
Annual average		26.52		29.03

Figure 10 shows how the spot electricity price varies over the day. The average hourly price shows unsurprisingly lower prices over night between 20:00 and 06:00, and a relatively lower price in the afternoon (12:00 to 16:00). Rare events of negative prices (less 0.6% of the year) happen during these periods, corresponding to a low demand and a high production from the renewable energy sources (mostly wind turbines in Denmark).

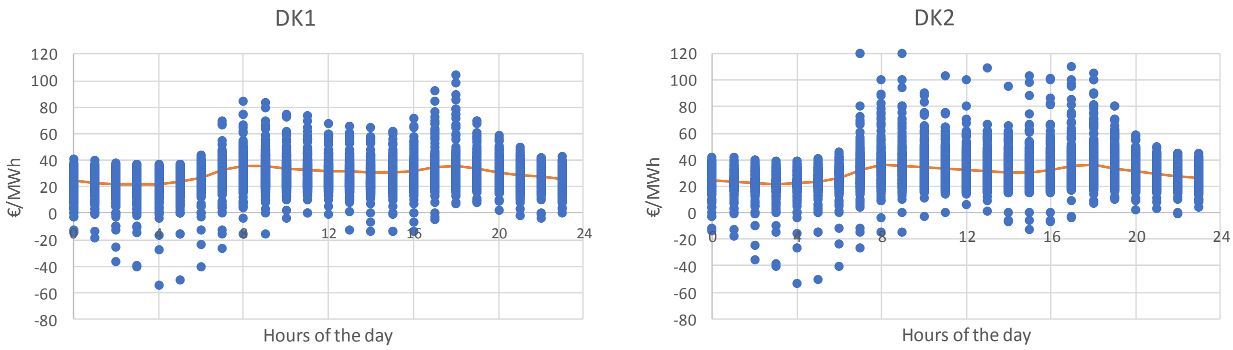

Figure 10 - Hourly distribution of the power price over the day (2016) for DK1 (on the left) and DK2 (on the right). The blue dots show the distribution of the price over the year for this hour of the day, the orange line the annual overage.

The basic operation pattern for the reference case is then defined as:

- 40% of operation, from approximatively 20:00 to 06:30
- 60% of operation, from approximatively 20:00 to 06:30 and from 12:00 to 16:00

The typical duty cycle of the first pattern implies a stand-by of 13.5 hours and 10.5 hours of consecutive operation, whereas the second type of duty cycle alternates a long operation period followed by a succession of three short stop and start periods (5.5 hours stop, 4 hours operation 4 hours stop).

These duty-cycles are just prototypes used to simplify the technical dimensioning and the economic assessment. In practice, the exact length of the different periods would be adjusted depending on the current price and the request from the grid operator.

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3.1. Costing elements

The reference case described in this section assumes that only the production of methane represents a source of revenue, and that the other co-products (heat, O_2) are not valorised.

Additionally, the price for electricity does not include transport and distribution fees. The current taxation of electricity in Denmark, but also in most of European countries, makes any form of energy storage non-profitable. Stakeholders generally agree that the structure of electricity price needs to be adapted for energy storage plants, but no decision or clear orientation has been defined so far. In order to pursue this analysis, and assuming that such plant will eventually exist, implying the regulatory framework has been adapted, it has been assumed that the totality of the transport and distribution taxes for electricity had been removed. The value of the methane produced by methanation has been adjusted to match the value of the bio-methane, which means it is assumed that subsidies for the bio-methane have been generalized to the neo-methane.

Numeric figures about costs and rentability are presented in the rest of the document in relative numbers compared to the reference case, defined as 60% of operation, without valorisation of the co-products. The different indicators used to assess a process configuration are the investment (CAPEX), the operation costs (OPEX), the production cost of methane and the rentability at 20 years of the plant (including reinvestments). The CAPEX, OPEX, incomes and methane costs are expressed relatively to the reference case, the rentability is described in difference compared to the reference. For example a income of 0.7 means that the income of this case is equal to 70% of the income of the reference case, and a rentability difference of -10% means that the rentability is lower by 10% than the reference case.

The comparison of the three scenarios shows that it is clear that increasing the number of operating hours improve the profitability, as the average higher cost of electricity is more than compensated by the higher turn-over.

Table 5 - Relative effect of reducing the hours of operation (relatively to the base case 60%)

	40%	60%	80%
Electrolyser size (MW)	4.8	4.8	4.8
Methanation size (Nm3-CO2/h)	240	240	240
CAPEX (relative to case 60%)	1.0	1.0	1.0
OPEX (relative to case 60%)	0.7	1.0	1.5
Income (relative to case 60%)	0.7	1.0	1.3
Rentability difference	-10%	-	+1.5%
Cost MWh-CH4 (relative to case 60%)	1.16	1.00	0.98
Economic figures are expressed relatively to the reference case (60%, no valorisation of the co-products).			

4. Improvements of the system integration

In order to improve the economical balance of the plant, several improvements have been assessed:

- The utilization of the oxygen in the aerated ponds to replace or complement the existing blowers for the aerated ponds.
- The recovery of the heat produced by the electrolyzer and the methanation reactor to substitute the heat generation for the biogas plants.
- The storage of intermediate gases allows increasing the size of the plant and focusing its operation on more profitable hours.

The two first improvements, as they increase the sources of income for each kWh of methane produced will increase the marginal profitability of the plant operation. The last one will allow optimizing the operation hours within the more profitable hours without reducing the annual production. The technical and economic assessment of these different improvements are detailed in the sections below.

4.1. Utilisation of the oxygen produced by the electrolysers

4.1.1. Background

The operation of the power-to-gas plant implies the production of hydrogen by electrolysis. This reaction produces oxygen, which often is not valorised and just vented in the atmosphere. However, aeration is the most important part of the activated sludge technology, the reference technology used for the biological wastewater treatment.

In an activated sludge aeration tank, oxygen is normally supplied for the degrading bacteria by injecting atmospheric air in into the tanks for instance via blowers (compressors) and diffusors. The oxygen can also be supplied by injecting pure oxygen into the activated sludge.

The old BIOFOS wastewater treatment plant (WWTP) Lynetten used to have such a dosing of pure oxygen for the high loaded activated sludge plant. This was in the period from 1980 to 1993. The oxygen was produced by distillation of air and the design of the activated sludge plant was with a short sludge age (3-5 days) as compared to 15-20 days in the current configuration of the activated sludge plant of Lynetten and Avedøre. The relative expensive plant for the production of oxygen was chosen because the use of pure oxygen enables a very high Oxygen Supply Rate (OSR) for a relative compact process volume.

Drawing from the experience of the full-scale operation during 13 years at Lynetten, the oxygen produced by the electrolyzer of the power-to-gas plant could in theory be useful for the biological treatment of wastewater. It would allow making the process tanks more compact with a possibility to increase capacity or construct new plants at a lower cost.

The oxygen that is produced by the 600 kW electrolyzer of the BioCat plant is currently not utilized at WWTP Avedøre, but an evaluation of the feasibility of using the pure oxygen in the activated sludge has been investigated within the POWERSTEP project.

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This section reports an investigation into the efficiency and economy of the two oxygen sources.

The investigation and comparison has been done at two levels.

1. Experiments in laboratory scale to compare the efficiency of air to pure oxygen in the actual activated sludge from a BIOFOS treatment plant with a long sludge age of 20 days.
2. A design exercise to evaluate the economy of a full-scale installation

4.1.2. **Laboratory experiment**

Appendix 1 contains a detailed report on the laboratory experiment with oxygen and air. The results basically show that there is no difference between the use of air and oxygen with respect to process kinetics. Once the oxygen is dissolved in the sludge, the microorganisms can't "tell" whether the oxygen comes from air or pure oxygen.

The difference is mainly in the efficiency of dissolving. Since there is a 5 times higher driving force from the pure oxygen (concentration 100% as compared to 21%) the transfer rate of oxygen between the gas bubbles and the sludge is higher in the case of pure oxygen. This is significant since the 'process time' and thereby the total turnover rate is improved in plants with intermittent aeration like the alternating ones.

4.1.3. **Evaluation of a full-scale application**

Design case

The aeration needs have been calculated for the WWTP defined for the reference case using figures of BOD flows and aeration currently observed at Avedøre.

In the Figure 11, an example of OUR measurements from the actual Avedøre WWTP is shown. The figure shows that the oxygen demand at Avedøre WWTP is currently varying between 320-640 kg O_2/h (night and day) for a BOD load of 14 tons per day and an energy consumption of 10.96 MWh/day. This boils down to the oxygen uptake of 0.9 kg-O_2 per kg-BOD received, and a corresponding energy consumption of 0.87 kWh/kg-O_2 uptaken. Considering a power purchase cost of 0.7 DKK/kWh (94 €/MWh), it means a value of the oxygen of 0.0818 € per kg of O_2 actually used.

When substituting oxygen to air for the aeration, the dynamic of the bubbling will be affected. It is generally accepted that because of the poor mass-transfer of oxygen in air bubbles, a relative small amount, only 5-10%, of the oxygen content in air, depending on basin depth (among other things), is absorbed in the water phase. As pointed before, the transfer-rates of O_2 will be increased by a factor 5 by bubbling pure oxygen. We assumed in the following analysis that 100% of the oxygen will be dissolved, which may be somewhat optimistic.

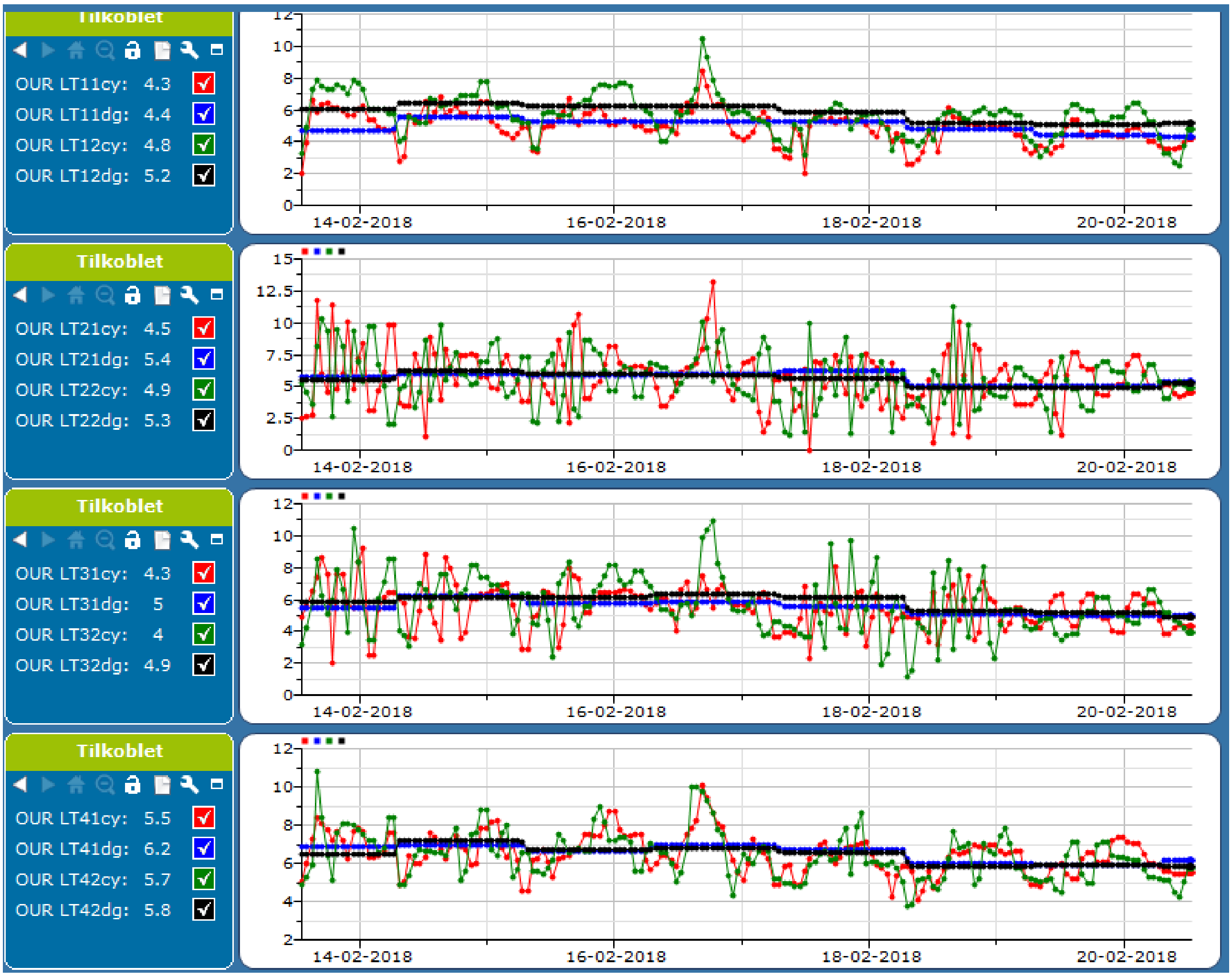

Figure 11 - OUR Oxygen Uptake Rate calculated in 8 aeration tanks (g O_2/m^3/hour). The graph is from the STARpro control system and shows two curves for each aeration tank. The ones with much variation (..cy) is based on cycles calculations (nitrification+ denitrification) whereas the more stable curves (..dg) is based on diurnal averages.

The design for the reference case is based on a 100% load of the biological plant, which corresponds to a BOD load of 21 ton/day and a theoretical OUR in the range of 600 to 1 200 kg O_2/h. As shown in Table 6, the corresponding oxygen production from the electrolyzer of the power-to-gas plant would be in the same order of magnitude but slightly lower than the average demand of the activated sludge ponds.

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Table 6 - Aeration needs

		per hour	per day	per year
COD	ton	2.2	53	19 345
Primary sludge	ton-SS	1.1	26	9 490
Secondary sludge	ton-SS	0.5	13	4 792
Methane production	Nm3	364	8 728	3 185 720
Biogas production	Nm3	606	14 547	5 309 533
CO2 production	Nm3	242	5 819	2 123 813
BOD in aerated ponds	ton	0.9	21	7 665
Aeration needs	ton-O2 transferred	0.48 – 0.96	19	6 898
Aeration costs	€	64	1 546	564 516
O2 production	ton-O2	0 - 0.70	16.7	6 098
O2 exchanged	Ton-O2		11.6	4 227
Saving	€		947 €	345 878 €

It is however important to notice that the maximum demand of oxygen of the WWTP is between 6:00 and 24:00, and a lower aeration is required between 0:00 and 6:00. These daily variations have been included in the calculations above and averaged for the daily and annual consumption. It shows that between 00:00 and 6:00 where the power-to-gas is likely to be operating, only 68% of the O_2 production from the electrolyzer can be used in the aerated ponds. At the scale of the day, still 90% of the O_2 produced will be valorized in the WWTP.

4.1.4. Capital costs for oxygen utilization

The present layout at Avedøre WWTP is shown in Figure 12. The red line represents the pipeline necessary to convey the pure oxygen from the electrolyzer to the closest connection point of the aeration system.

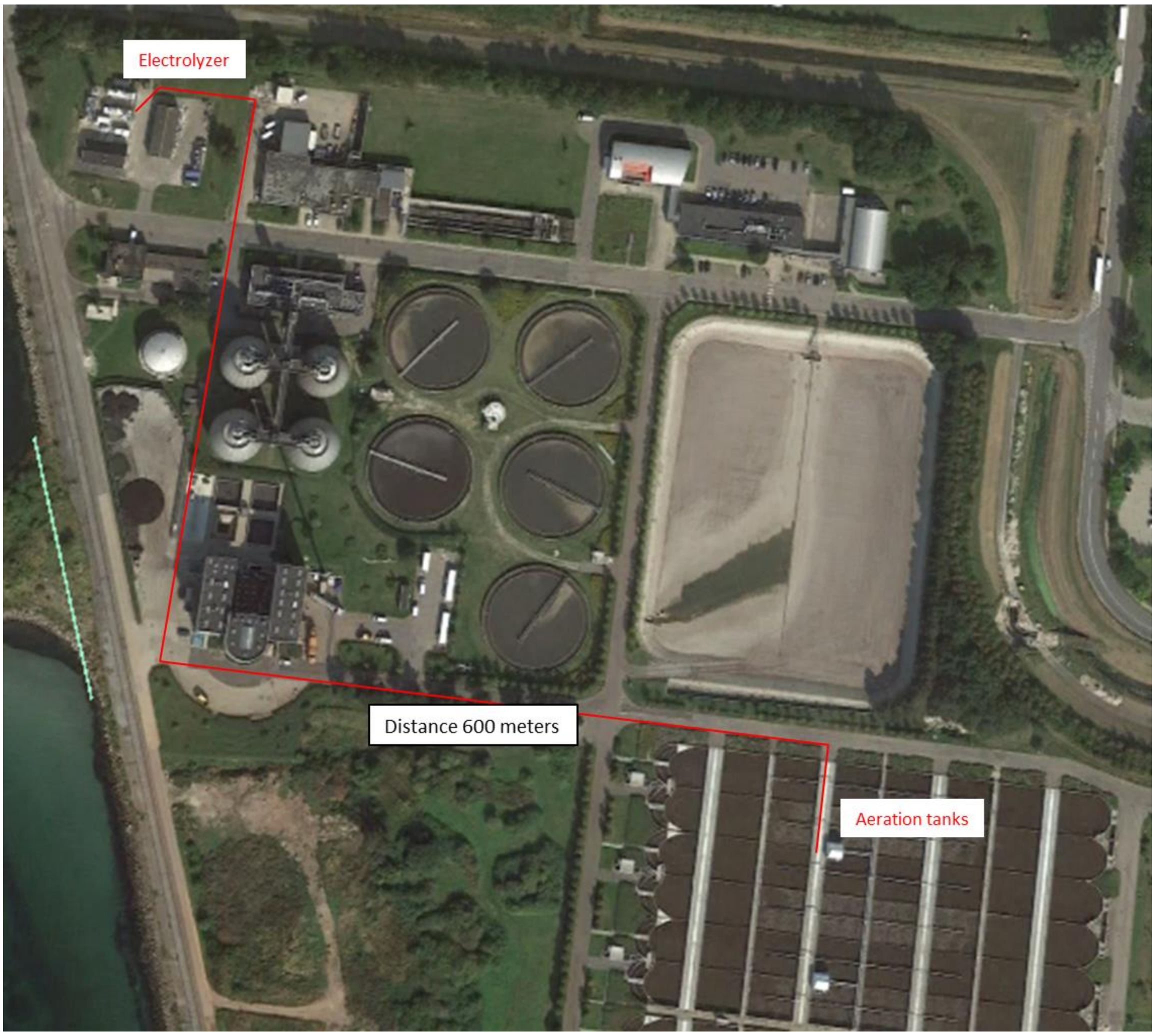

Figure 12 - Avedøre WWTP. Possible layout of an oxygen pipe for the aeration system.

The design and civil works to install a pipe with valves and control etc. is estimated to cost 2 mill. DKK (269 k€). Considering the pilot-scale of the current plant and assuming 3 000 hours of operation per year, it would have requested an investment of 269 k€ to save 17 k€ of aeration costs, which is why it was not possible within the economy of POWERSTEP to realize this installation.

On the other hand, a full-scale installation such as the scenarios calculated above generates a saving of 345 000€ per year for an investment of 269 000€. Table 7 details the effect of adding oxygen valorization on the economy of a full-scale power-to-gas plant, in comparison to the reference case. The effect on the CAPEX is marginal (increase by 4%) but it allows an increase of 30% of the annual income. It results in an improvement by +18 %of the profitability.

Table 7 - Effect of O_2 exchange on system economy

	60% ref	60%+O2
Electrolyser size (MW)	4.8	4.8
Methanation size (Nm3-CO2/h)	240	240
CAPEX (rel. to case 60%)	1.0	1.04
OPEX rel (rel. to case 60%)	1.0	1.0
Income (rel. to case 60%)	1.0	1.3
Rentability diff.	0.00	0.18
Cost MWh-CH4 (rel. to case 60%)	1.00	0.99

In the case of a CO_2 storage is in place allowing a larger size of the power-to-gas plant and therefore a higher flow of O_2, a larger part of the oxygen demand from the WWTP could be covered, but a larger fraction of the produced O_2 would have to be vented (77% of the produced O_2 valorised against 90% before). Still, the income generated by the valorisation of O_2 increases from 345 000 to 444 000 €.

4.2. Integration with heat recovery systems

A bio-methanation plant generates heat, through the water electrolysis and through the methanation reaction. Both systems will require cooling at the same time, and with similar temperatures for heat source and cooling fluid. Table 8 details the heat exchange parameters for the BioCat plant and for the reference case, corresponding to an electrolyzer with 4.8 MW_e power plate and a methanation plant with a treatment capacity of 240 Nm^3-CO_2/h.

Table 8 - Heat production from a bio-methanation plant

Parameter	Unit	Value	Comment
Electrolyser			
Heat production	kW	120	BioCat system
Heat production	kW	965	Reference case (4.8 MW electrolyzer)
Heat production	MWh/year	5 072	Reference case (60%)
Temperature Heat source	C	65	
Temperature return	C	55	Real-time controlled to control electrolyte temperature
Bio-Methanation			
Heat production	kW	77	BioCat system (designed: 120 kW)
Heat production	kW	615	Reference case (240 Nm3/h CO2)
Heat production	MWh/year	3 232	Reference case (60%)
Temperature Heat source	C	60	
Temperature return	C	50	Real-time controlled to control reactor temperature
Coolant flow-rate	m3/h	5 - 20	Real-time controlled to control reactor temperature

At the beginning of the POWERSTEP project the bio-methanation reactor had a heat exchange in place with the Biofos water loop. This loop is used to recover the heat from different heat sources over the WWTP to cover the needs of the biogas reactors (~1 MW_{th}) and heating the buildings (see Figure 13). This heat exchange had been designed to recover the heat of the maximal load of the BioCat reactor during the BioCat project (1 MW_e of electrolysis, 50 Nm^3-CO_2/h).

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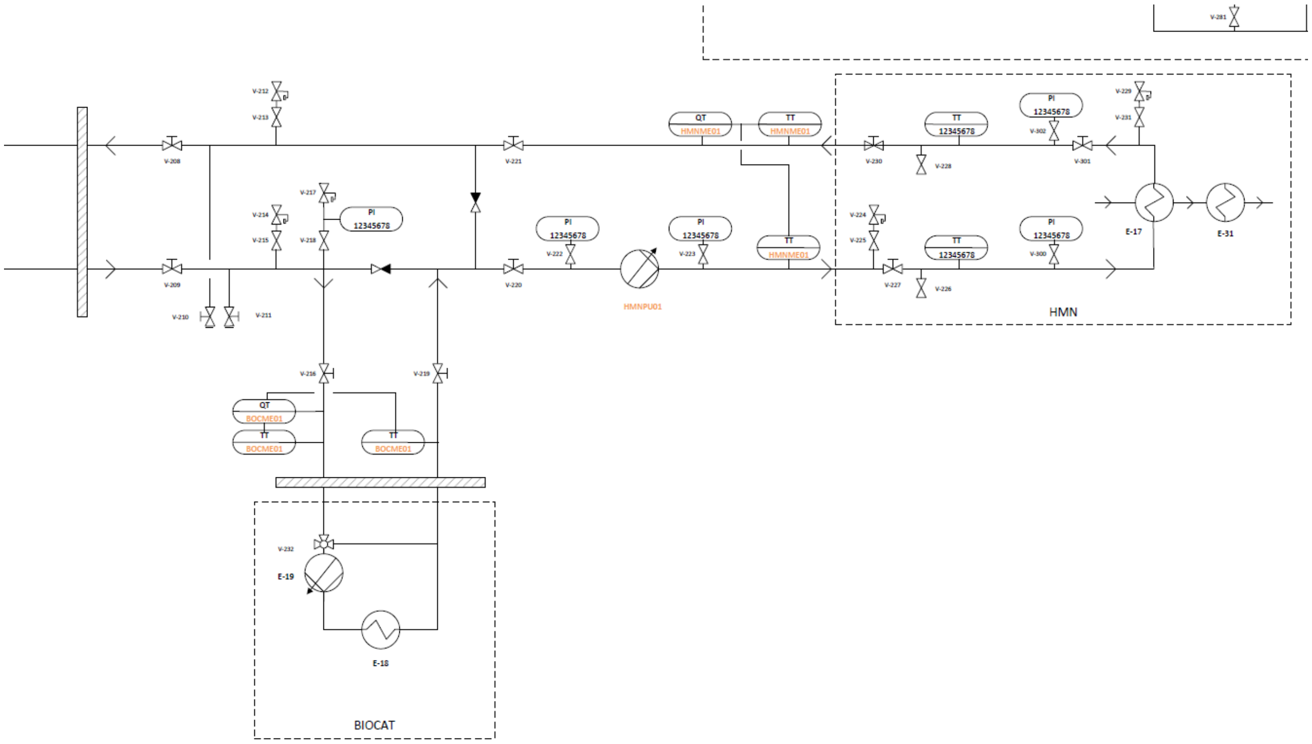

Figure 13 - Process Flow and Instrumentation diagram of the heating/cooling system for gas engine, the bio-methanation plant and the biogas upgrading plant.

During the POWERSTEP project, the architecture of the heating/cooling system of Biofos had to be modified to accommodate several changes:

- Improved heat recovery from the discharge of the biogas plants
- Maximization of the export of the high temperature heat produced by the sludge incinerator
- Integration of the heat exchange with the electrolyzer
- Flexibilization of the heat recovery with the possibility of recovering simultaneously heat from the gas engine already installed, from the biogas upgrading plant under construction, from the methanation plant and finally from the electrolyzer.

Achieving a high level of robustness and flexibility for the heating cooling required:

- To change the architecture of the heating/cooling, with additional pumps and control valves, to prevent the apparition of back-flows or short-cuts
- To install additional instrumentation to measure the heat exchanged by the methanation plant, the electrolyzer and the biogas upgrading plant
- To develop additional controls to guaranty the cooling capacity to the sub-systems.

The modifications to integrate the heat from the electrolyzer are detailed on Figure 14.

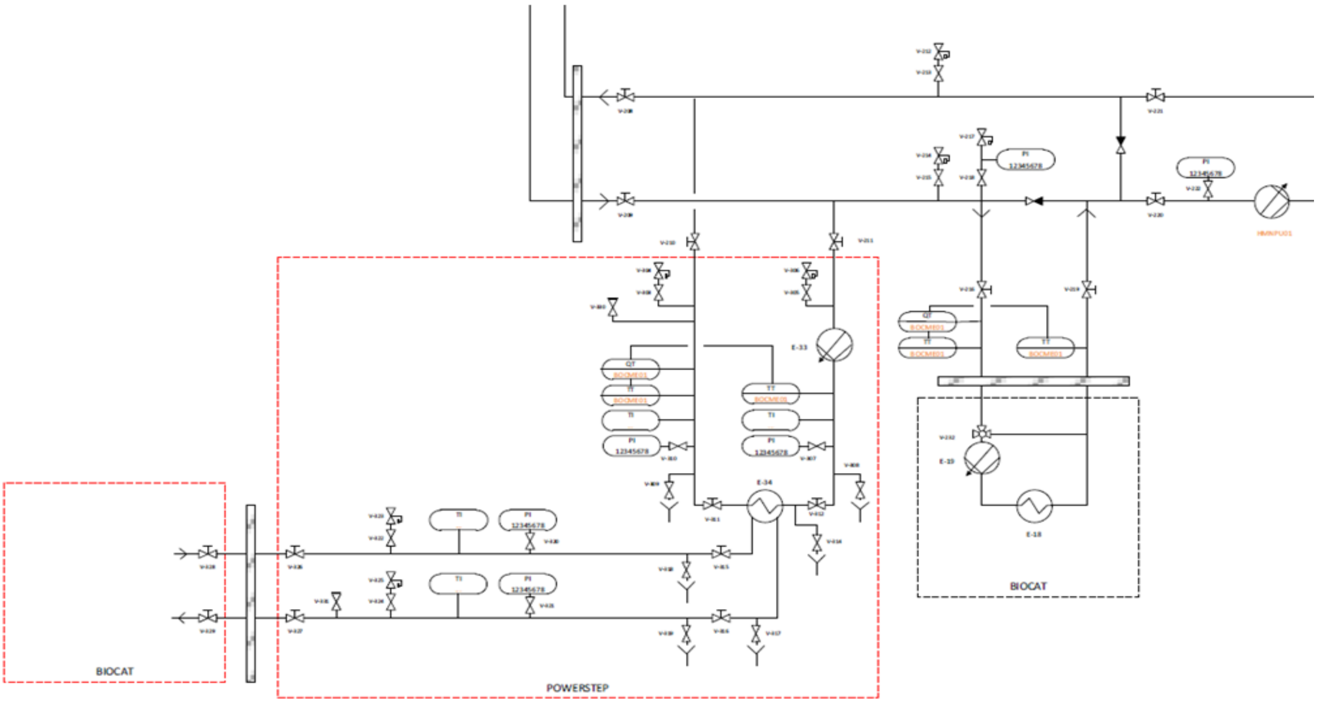

Figure 14- Modification of the heating/cooling system to recover heat from the electrolyzer.

The modifications of the heating/cooling architecture and controls allowed achieving a robust and flexible operation with for instance the biogas upgrading and the methanation plant operating in parallel. Figure 15 and Figure 16 show the heat exchanged (in kW) for the two plants. The heat exchange from the methanation plant show the ramp-up of the system until nominal operation at half-load where stable heat exchange is achieved (30 to 40 kW).

The heat exchange for the electrolyzer has been installed in April 2018 and will be tested during a continuous operation test in May 2018.

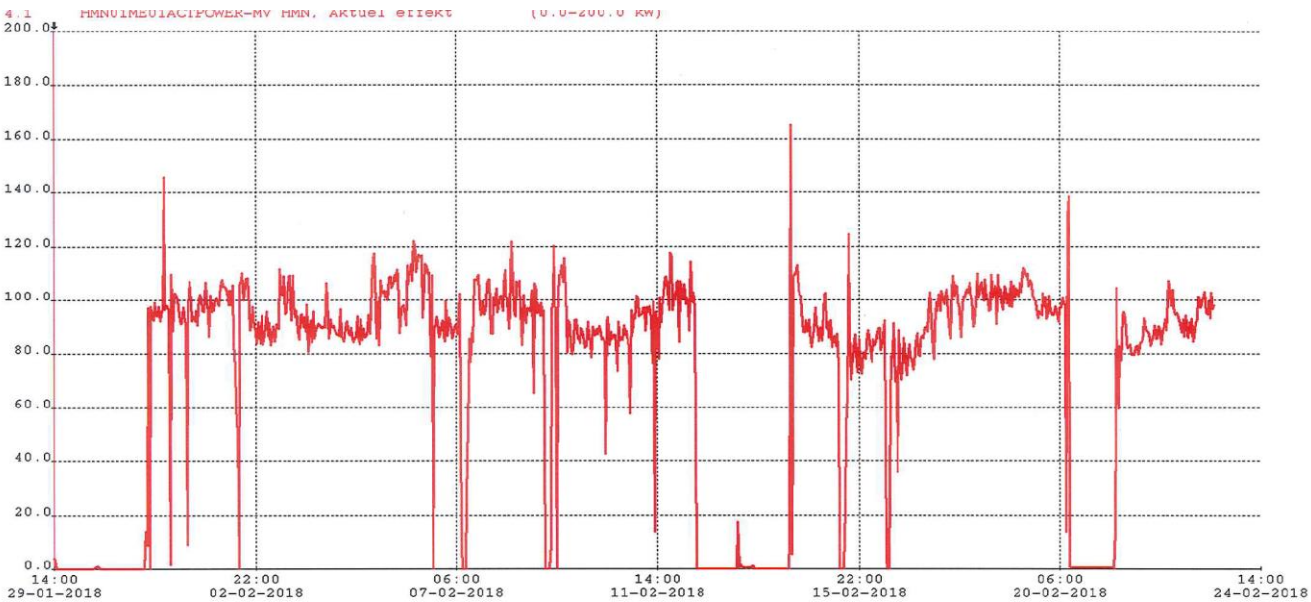

Figure 15 - Heat exchange from the biogas upgrading plant (January to February 2018)

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Figure 16 - Heat exchange from the bio-methanation reactor (December 2017)

Contrary to the exchange of oxygen, the cooling if the electrolyzer and the bio-methanation reactor is a critical function, low performance or failure of the cooling will create a process stop within 15 minutes. Therefore, the equipment for heat exchange is basically already included in the initial CAPEX. The added value of the heat exchange has been calculated based on the avoided costs. In the case of the Avedore WWTP, heat would need to be purchased at a cost of 47 €/MWh. It generates a maximal income (or avoided cost) of 380 888 €/year.

Table 9 - Income from the heat exchange

Parameter	Unit	Value	Comment
Electrolyser Heat production	MWh/year	5 072	Reference case (60%)
Methanation Heat production	MWh/year	3 232	Reference case (60%)
Total	MWh/year	8 104	Reference case (4.8 MW electrolyzer)
Maximal Heat exchange	kW	1 580	Reference case (4.8 MW electrolyzer)
Heat value	€/MWh	47	
Maximal Heat income	€	380 888	Assuming 100% heat recovery

However, achieving 100% heat exchange will require the right distribution of temperature between the cold source and the heat source and might require additional control to accommodate with the intermittency of operation of power-to-gas plants. The maximal heat exchange of the power-to-gas can indeed be higher than the instantaneous heat consumption of the WWTP during the summer season. However, the biogas plant can be used as heat storage, and the excess heat produced during night operation can be stored by allowing a temporary increased set-point of the temperature control of the digesters. It is worth noticing, that as for the oxygen valorisation, there is a good match between the heat and temperature demand of WWTP and what a power-to-gas plant with similar size can provide. It means that this kind of exchange should always be integrated in the design phase, but also that the WWTP cannot be considered as an infinite heat sink (or oxygen sink) and that the match between offer and demand needs to be assessed in detail and dynamically to include diurnal or seasonal variations.

The effect of the heat recovery alone, and combined with the oxygen utilization, is detailed in Table 10. As stated before, no additional CAPEX has been included. However, considering the criticality of the heat exchange, a fall-back option could be added in situations with limited availability of low heat demand of the cooling system. In the favourable case where the cooling system is able to absorb all the heat produced and then to avoid heating costs, the additional income for the power-to-gas plant (+ 50%) makes a significant impact on the profitability (+35 %). Combined to the oxygen utilization, it will increase the annual income by 80%.

Table 10 - Effect of Heat exchange and O2 recovery on system economy

	Ref (60%)	60%+Heat	Ref+Heat+O2
Electrolyser size (MW)	4.8	4.8	4.8
Methanation size (Nm3-CO2/h)	240	240	240
CAPEX (rel. to case 60%)	1.0	1.04	1.04
OPEX rel (rel. to case 60%)	1.0	1.0	1.0
Income (rel. to case 60%)	1.0	1.5	1.8
Rentability diff.	0.00	0.35	0.54
Cost MWh-CH4 (rel. to case 60%)	1.00	0.98	0.97

4.3. Storage of intermediate gases

Contrary to most of heavy industry plants, a power-to-gas plant needs to be able to implement flexible duty cycles to follow the dynamic of power pricing and up- or down-regulation requirement from the electrical grid operator. As seen in section 3, a typical duty cycle would be an average operation time of 60 to 80%, with daily process stops of 5 to 10 hours. Consequently, only a fraction of the CO_2 generated by the biogas upgrading plant could be processed. This section assesses the opportunity of storing intermediate gases to increase the annual amount of CO_2 processed into methane, and therefore to maximize the turn-over of the plant. Several scenarios have been defined, relying on the storage of intermediate gases to be used when energy price makes process operation more profitable:

- The reference case corresponds to a plant designed for the maximal CO_2 instantaneous flow-rate (240 Nm^3/h) available, and an average operation of 60% of the time (14.4 hours/day).
- Case 1 adds a CO_2 low pressure storage able to store the equivalent of 7 hours of production from the upgrading plant. The additional CO_2 is processed during the same periods of the day than the reference case, implying that a larger production capacity for Hydrogen.
- Case 2 is similar to case 1 but with a larger storage, allowing to capture all the CO_2 produced.

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- Case 3 explores the opposite approach where a high-pressure storage stores the hydrogen produced during the 40% cheapest hours of the day to allow processing the CO_2 produced during 60% of the day.
- The storage on-site of CH4 has not been considered, as in Denmark, the grid operator guaranties the off-take of the gas, regardless of the consumption of gas in the local grid.

Table 11 - Storage scenarios

	Ref Case	Case 1 CO_2, 7 hrs	Case 2 CO_2, 10 hrs	Case 3 H_2, 5 hrs
Methanation reactor				
CO2 flow-rate	240	357	400	240
	60%	60%	60%	60%
Hours of operation / year	5 256	5 256	5 256	5 256
Hours of operation / day	14.4	14.4	14.4	14.4
Electrolyser				
H2 max production (m3/h)	965	1434	1608	1447
	60%	60%	60%	40%
Hours of operation / day	14.4	14.4	14.4	9.6
Hours of operation / year	5 256	5 256	5 256	3 504
CO2 storage (hours)		7	9.6	
CO2 storage (m3)		1 680	2 304	
H2 storage (hours)				4.8
H2 storage (Nm3)				4 631

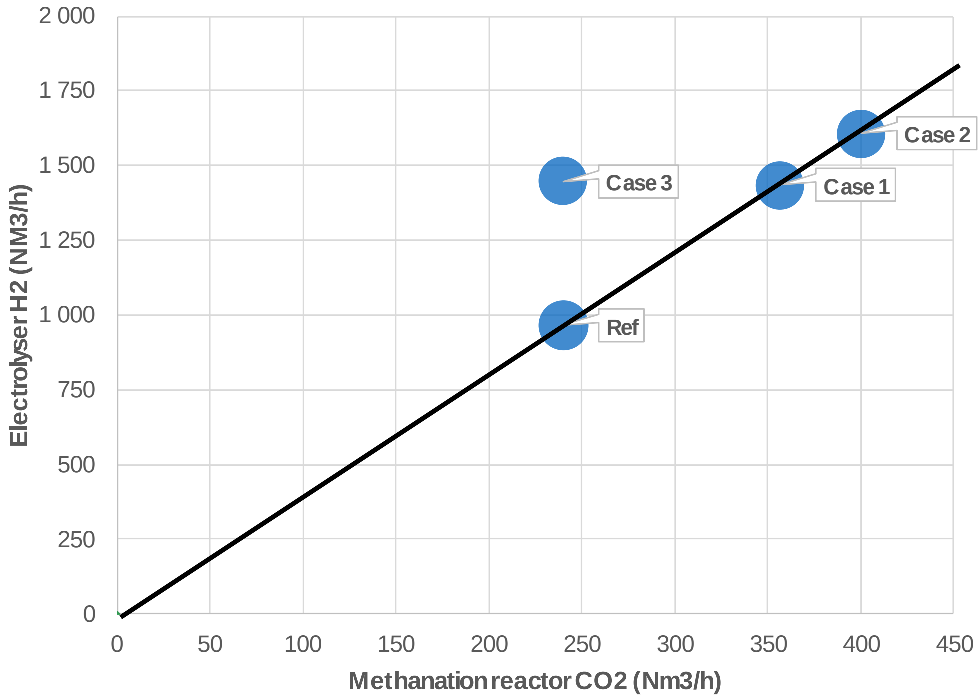

Figure 17 - Maximal flow of treated CO2 vs. maximal Hydrogen production inNm3/h for the four cases.

The cases 1 and 2 require a storage of respectively 1 680 and 2 300 Nm^3. Such storage is typically provided with a low-pressure gas balloon, made of high-tensile fabric (see Figure 18). As CO_2 is an inert gas, storing large volumes will not present a high risk and therefore can be easily imagined for a WWTP.

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Figure 18 - Example of gas balloon used for temporary storage

On the other hand, the H_2 storage would require high pressure vessels (~30 bar) and imply the storage of large quantities of explosive gas (9 000 Nm^3 – 30 MWh), which would require special authorization, not necessarily matching the daily operation of a WWTP.

Table 12 - Effect of storage on the economy of the power-to-gas plant.

	Ref (60%)	Ref +Heat+O2	Case 1 CO_2, 7 hrs	Case 2 CO_2, 10 hrs	Case 3 H_2, 5 hrs
Electrolyser size	4.8	4.8	7.2	8	7.2
Methanation size	240	240	360	400	240
CAPEX rel	1.0	1.0	1.4	1.5	1.9
OPEX rel	1.0	1.0	1.5	1.6	1.0
Income rel	1.0	1.9	2.8	3.2	2.1
Rentability rel.	0.00	0.62	0.69	0.71	0.48
Cost MWh-CH4 rel.	1.00	0.97	0.92	0.92	1.19

As detailed on Table 12, the integration of CO_2 storage tanks improves the profitability of the installation. However, as they will concentrate the treatment of higher quantities of CO_2 within the same period of time, the production of O_2 and heat might exceed the demand of the WWTP, requiring additional equipment to dissipate the heat and decreasing the actual profitability.

4.4. Metabolic by-water use

The bio-methanation reaction produces water which needs to be discharged to avoid reactor overflow. This waste stream contains not only the metabolic water but also methanogen micro-organisms. The possible synergy of the BioCat biomass with the existing anaerobic ecosystem present in the anaerobic digesters has been assessed and judged to be likely null and, in any case, non-measurable considered the site constraints:

- The discharge of the by-water implies an abrupt depressurization from 9 to 1 bar, which would compromise the cellular integrity of a large fraction of the methanogen biomass.
- The biomass used in the BioCat reactor has an optimal activity above 60°C but the biogas digesters are operated in a mesophilic range (35-40°C), which means that the BioCat cells having survived the flash depressurization will have anyway a very small activity and therefore will not be able to compete with the indigenous methanogens.
- A full-scale power-to-gas reactor represents a liquid flow of 5.4 m^3/day to compare to the 40 000 m^3 of digesters. Such level of dilution of the low-activity biomass within an already acclimated ecosystem would result in the absence of any significant effect.

Therefore, it has been concluded that the main benefit of the BioCat by-water was to provide a source of biomass. The flash-depressurization would represent a pre-treatment comparable to some pre-treatments used to improve the biodegradability of urban sludge. Chemical analysis of the BioCat by-water have shown a COD content of 36 g/L, which corresponds to a theoretical methane potential of 12.6L of methane per kg of by-water. In the case of a full-scale plant, that would represent an additional source of methane of 68 Nm^3/day to compare to the daily methane production of the methanation reactor of the reference case, 3 456 Nm^3/day, which means less than 0.3%.

As the BioCat plant was initially connected to the sewer system, the water discharge was treated as any other sewage water, and the biomass produced by the reactor was oxidized during the activated sludge treatment. After this assessment, the sludge produced by the BioCat reactor has been transferred on a daily basis to the sludge pit of the biogas digesters, where all additional sources of substrate for the biogas reactors are collected.

Among the items to document for the Case Study 3, the recycling of the water discharge in the AD reactors has been replaced by the optimization of the nutrient feeding and the study of recovery systems in order to reduce the amount of nutrients and micro-elements wasted by the discharge of the metabolic water and to meet disposal standards at WWTP and within local municipal regulations.

This change has been justified by current research indicating that microorganisms from the methanation reactor will not appreciably benefit WWTP digester or its efficiency, and not in the small quantities provided by BioCat. Devitalized biomass from the methanation bioreactor could be digested in anaerobic digester and would provide a small amount of additional digestible biomass. This task has been already started with analysis and lab work with alternative composition of the nutrient feed and the testing of several filtration technologies.

The re-use of the by-water does not create a quantifiable additional source of income for the plant but is anyway a simple and positive way of handling this by-product which would be a waste otherwise.

5. Controls for an improved operation and integration

Because of the dynamic and intermittent nature of the operation of Power-to-gas system, and the multiple interfaces (CO2 supply, power supply, heat exchange, oxygen exchange), on-line control and data exchanges are key for maximising the operability and the actual valorisation of all the co-products.

As the BioCat plant had been designed and built first to study and optimise the design and operation of the bioreactor, data exchange and control with the interfaces were only partially implemented at the beginning of the Powerstep project. During the project, the communication between all the interfaces have been implemented and real-time controls for the heat exchange and partially for the grid balancing have been implemented. Figure 19 gives an overview of the different communications and cascading controls necessary for a full integration with heat and oxygen recovery.

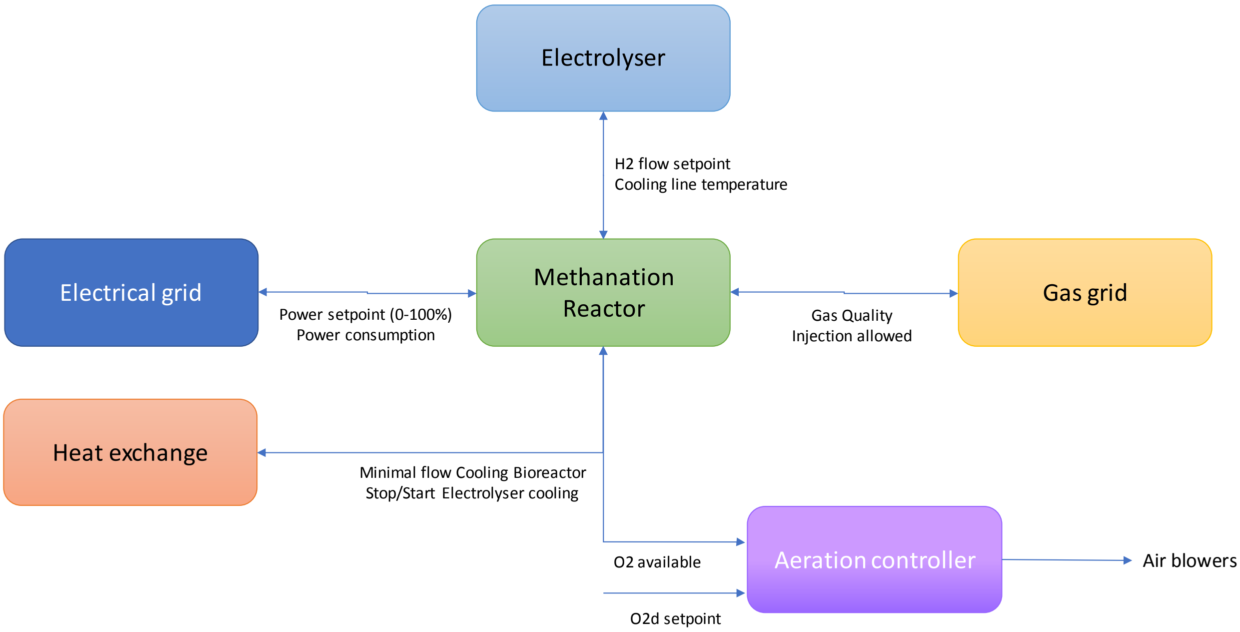

Figure 19 - Overviwe of the dommunication interfaces necessary for a full integration of the bio-methanation plant to the Wastewater Treatment plant.

5.1. Heat exchange

The heat produced during operation of the methanation plant is meant to be exported to the internal heating/cooling loop of the WWTP to provide heating to the biogas digesters and the buildings.

The integration of the heat exchange implied to modify the heating/loop to be able to accept intermittent heat sources without impacting the overall operation of the heat loop. In practice the gas engine, the methanation plant and the upgrading plant need to be able to operate independently, but the combination of parallel flows (between the gas engine and the methanation and upgrading plants, between these heat sources and the by-pass directly to the district heating) was creating undesired temperature drops or counter flows. As part of the project, the piping and modes of

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operation have been modified to allow reliable heat exchange. Figure 20 illustrates the Process Flows and Instrumentation after the modifications:

- **The pump of the gas engine** is controlled to extract the heat from the gas-engine, a feed-back controller modulates the flow based on the temperature at the outlet of the heat exchange. If the temperature is too low, the flow is decreased. A three-ways valve allows a partial recirculation of the water loop in the gas engine to avoid too low temperature in the engine cooling.
- **The pump of the cooling line of the methanation plant** modulates its flow in function of the temperature in the methanation reactor. As the methanation plant needs to be pre-heated for start-up until the exothermic reaction takes place, the cooling line can be by-passed, and an electrical pre-heater heats the cooling line.
- **The upgrading plant** is the third heat source in the system. The flow of its cooling pump is modulated to keep a temperature constant at the outlet of the heat exchange: if more heat is produced, the flow of cooling water needs to be increased to counter an elevation of the outlet temperature.
- To allow the cooling water flow to leave the perimeter of the methanation plant, another control is surimposed to the pump of the upgrading plant, guarantying a minimal flow through the two systems connected in series (methanation and upgrading plants); when the methanation plant has finished its start-up and switches from pre-heating to active cooling, a signal is sent by the PLC of the methanation plant to define the minimal flow.
- **The heat source of the electrolyser** has a similar temperature as the methanation reactor. Therefore, its heat exchange had to be implemented in parallel to the one of the methanation reactor. The cooling pump starts once the temperature in the electrolyser cooling loop is above the one of the general cooling loop (usually one hour after start-up) and then modulate its flow to keep constant the temperature at the outlet of the heat exchanger.
- After the three local and intermittent heat sources, a larger pump guaranties that no back-flow is happening between the three heat sources by applying a minimal flow if at least one of the three heat sources is enabled. Additionally, the pump controls the pressure difference in the heat consumption loop to guaranty that enough flow is supplied to the heat consumers.

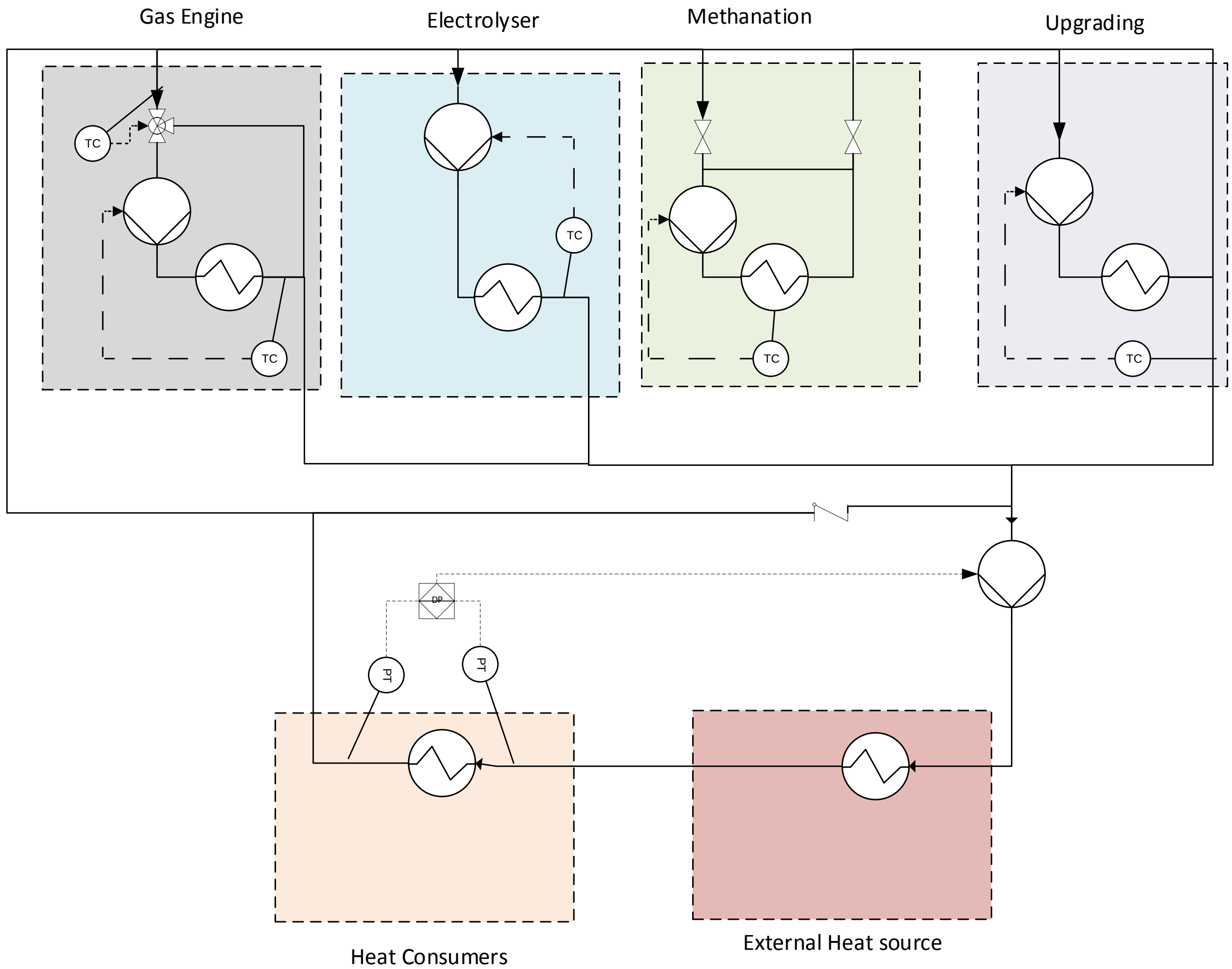

Figure 20 - Simplified PFID of the heat exchange between Biofos heat consumers and the three intermittent heat sources (gas engine, methanation reactor and electrolyzer, the biogas upgrading plant)

5.2. Oxygen export

A setpoint of the oxygen concentration in the activated ponds ca be defined and modified according to the biological parameters characterising the nitrification/denitrification. In absence of oxygen source, a controller modulates the operation of the air compressors to follow this setpoint.

In presence of an intermittent oxygen source, the controller needs to be modified to prioritize the oxygen stream over the air compressors until the pressure in the oxygen line is too low and does not allow a positive flow of oxygen anymore. At this point both the air compressor can be activated to supply the additional amount of oxygen.

5.3. Grid-balancing

The methanation plant is designed to provide an energy storage to the electrical grid. Therefore, its operation follows signals from the electricity supplier to modulate its activity:

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- **Down regulation:** A start signal can be sent by the grid operator to require a start-up of the methanation reactor when excess electricity is produced.
- **Up regulation:** A stop signal can be sent to require that the methanation plant disappears from the electrical grid.
- **Frequency regulation:** the methanation plant will modulate its power consumption to keep the frequency of the electrical grid constant.

To make the BioCat reactor compatible with these regulations, several controls and communications have been implemented:

- A box supplied by the electricity supplier sends a setpoint of power consumption and measure the current consumption of the plant.
- A procedure for instantaneous shutdown has been defined and implemented, able to stop the plant immediately after reception of the stop signal.
- A procedure for automatic start-up has been defined based on the analysis of hundreds of manual start-ups.
- A controller able to modulate the loading rate of the methanation reactor has been implemented and a controller allowing the electrolyser to modulate its production according to the H2 demand over the entire range of supply flow has been implemented.

6. Conclusion

After more than 2 years of operation of a 1 MWe Power-to-gas via bio-methanation, the smart goal of producing a gas with a methane content of more than 90% has been reached, as the BioCat demonstrator has produced repeatedly and in a stable way a gas with a methane content above 97%, qualifying for gas grid injection.

Data and experience from a 2 year´s operation of the demonstrator, additionally to the technical and economic assessment of the integration of the Power-to-gas plant with the WWTP show there is a clear symbiosis between a power-to-gas plant by bio-methanation and a wastewater treatment plant.

Different tracks of integration have been assessed in this document for a reference case defined by:

- A WWTP of 350 000 PE, equipped with biogas digester and an upgrading plant.
- A methanation plant able to process the corresponding CO_2 flow-rate (240 Nm^3/h), with an electrolyzer power of 4.8 MW

The different points of integration have shown a positive outcome for all of them, as they allow providing a direct outlet with a high level of availability for the by-products of the power-to-gas plant:

- The **oxygen** produced by electrolysis of water can be used to support the operation of the activated sludge ponds. As shown by both 15 years of operation at the WWTP of Lynette (Copenhagen, Dk) and during a lab trial conducted during the project, pure oxygen is not toxic for the activated sludge and results in similar Oxygen Uptake rates. The oxygen produced by the electrolyzer being already pressurized, the oxygen totally displaces the corresponding operation of the air blowers used normally to aerate the ponds. Additionally, the instantaneous oxygen demand of the aerated ponds has a similar order of magnitude than the oxygen production resulting of the operation of a methanation plant matching the CO_2 production of the biogas reactors of the WWTP. The avoided aeration costs represent a gain of profitability for the P2Gas plant of 18 %.
- The **heat** produced by both the electrolyzer and the methanation reactor can be integrally re-covered for fulfilling the heat demand of the biogas digesters and the building heating. The avoided heating costs represent a gain of profitability for the P2Gas plant of 35 %. Integrating flexible and intermittent sources of heat in the heating loop of the WWTP, where several sources and consumers are present, requires adapting its design and controls.
- **Storage of CO_2** during the hours of non-operation of the reactor is feasible at a limited cost and without large challenge on site safety. It allows reaching a higher annual production of methane and therefore defining a plant configuration with a better economy. Depending on its size, the CO_2 storage allows improving the plant profitability by 7 to 11 %. Storage of H_2 is economically not interesting and will require additional safety constraints. Storage of CH_4 is not necessary as the grid usually guaranties the off-take of the product gas.

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- **The use of the by-water** produced by the methanation reactor as a source of substrate for the biogas digesters allows a small additional production of methane but above the additional methane production, the recycling of the by-water to the biogas digesters is the simplest, cost- and energy-effective way of treating the by-water.
- **Real-time controls and communications** between different parties (methanation reactor, electricity supply, CO2 supply, H2 supply, gas up-taker, heat up-taker, oxygen up-taker) are necessary to maximise the operability of the methanation plant, to provide grid-balancing services and to achieve actual valorisation of the co-products (heat and oxygen).

It results from these assessments that a power-to-gas plant by bio-methanation can be an important contributor to the effort of WWTP to reach positive energy balance. As the integration of the plant to the rest of the WWTP allows reducing aeration and heating costs and offers an additional flexibility on the use and storage of power, a bio-methanation plant would allow a WWTP to become an actor in the electrical grid balancing not only as possible electricity producer (with the gas engines) but also as an energy storage operator able to interconnect the electrical, heat and gas grids.