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TECHNO-ECONOMIC ASSESSMENT OF A MICROBIAL POWER-TO-GAS PLANT – CASE STUDY IN BELGIUM

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ABSTRACT

A successful transition towards a cleaner and more sustainable energy management in 2050 requires the implementation of renewable energy sources on a large scale. Therefore, it is expected that the share of renewable energy will further increase. Due to the introduction of these intermittent energy sources, the need for flexibility in our energy system increases significantly. Power-to-gas (P2G) is one promising option for providing long term energy storage and for providing flexibility to the electricity system. An interesting, recent technological development is biological methanation. The latter utilizes microorganisms to catalyze the Sabatier reaction. This biological reaction can be achieved at lower temperatures and pressures than when a chemical catalyst is used and has a higher tolerance to contaminations from the CO_2 source, process upset or contamination by foreign organisms. We investigate the techno-economic potential of biological methanation (i.e. microbial power-to-gas concept) using a case study that revolves around anaerobic digestion using mainly municipal organic waste in Belgium. The most important parameters that influence the economic feasibility are the electricity consumption (44 %), operating hours of the electrolyser (14 %), and the investment cost of the electrolyser (14 %). Based on our findings we offer further routes of research that serve to strengthen the business case.

KEYWORDS

Anaerobic digester, Electrolyser, Demand response, Hydrogen, Biomethane, Biogas

HIGHLIGHTS

- The techno-economic feasibility of a microbial power-to-gas concept is analyzed.
- Energy use, operating hours and electrolysis investment are the main parameters.
- The business model needs to be further optimized for Belgium.
- Anaerobic digesters in Belgium need alternative flexible business models.

1. Introduction

A successful transition towards a cleaner and more sustainable energy management in 2050 requires the implementation of renewable energy sources on a large scale. Across European countries the proportion of renewable energy in total electricity production is currently very different. However, it is expected that the share of renewable energy will further increase. In these future scenarios a major role for wind and solar energy is expected [1]. These renewable energy sources are characterized by their intermittent nature, which will impact the supply security of electricity. Intermittent energy sources are energy sources that are not continuously available so that the produced renewable energy, which varies in time due to e.g. weather conditions, is not always in equilibrium with the consumers' power demand, causing an imbalance. As a consequence, on sunny, windy days, for example, electricity prices can be very low or even negative. During imbalance moments solutions need to be found by e.g. consuming more electricity, generating less electricity or storing the surplus electricity.

In markets with a large share of renewable energy, gas-fired electricity generation has already been used to maintain system supply and demand in balance [2]. As a consequence, power-to-gas (P2G) is gaining popularity as a solution to provide the needed flexibility to the energy system. The P2G concept is defined as the conversion of electric energy into hydrogen, i.e. using electricity in an electrolyser to split water into hydrogen and oxygen. The hydrogen can be deployed in four different ways: (i) (long term) electricity storage in case hydrogen is reconverted into electricity after buffering, (ii) the use of hydrogen as raw material in industry, (iii) the use of hydrogen as a fuel for transport, and (iv) storage of hydrogen in gas infrastructure, either by direct injection of hydrogen into the gas grid or by the conversion of hydrogen and CO_2 into methane. For example, Kötter et al. (2016) investigated the impact of P2G in the implementation of the Energiewende and concluded that P2G can have an important role to reduce the levelised cost of electricity of the energy system resulting from the option of long-term energy storage [3]. Also Qadrdan et al. (2015) analyzed the role of P2G assuming different allowable levels of hydrogen injection. They concluded that the production of hydrogen from electricity decreases the overall cost of operating the gas and electricity network in Great Britain given a high share of wind power generation [4]. Zoss et al. (2016) developed a mathematical model to evaluate if wind power generation in the Baltic States would meet the need of biogas plants for methanation. They concluded that an increase in the average CH_4 content of biogas is possible, however, that not in all cases the maximum possible quality could be achieved [5]. Grueger et al. (2017) analyzed the role of P2G and re-electrification in reducing wind farm forecast errors and the ability to provide a secondary control reserve in Germany. The authors conclude that both options can be economically viable depending on the system's configuration and their operating strategy [6]. Despite the recognition of the potential of P2G systems for our future energy system, the main drawbacks are still the relatively low efficiency and high investment cost for the electrolyser and operational costs due to the electricity price [7].

Hydrogen combined with CO_2 can be converted to methane and water, a process called methanation, which is based on the Sabatier reaction [8]. This reintegration of CO_2 into the power supply can contribute to CO_2 reduction [8]. There are several sources of CO_2 which can be considered such as biomass, flue gases from power plants and biogas or even from direct air capture, CO_2 from gas upgrading being the cheapest source [9]. Furthermore, Meylan et al. (2017) developed a methodology to assess the carbon balance of power-to-gas and concluded that biogenic and atmospheric CO_2 are most interesting because of their low greenhouse gas emissions. They indicate that using CO_2 from fossil resources might make sense during a transition period as emissions are saved [10]. Methane can be used in several applications. It can be stored, transported and can be converted back into electricity. In some countries, such as Germany, there are projects ongoing where hydrogen or methane formed from hydrogen are injected into the natural gas grid [7]. This conversion is mostly done by the (physico-chemical) Sabatier reaction in which high pressures, high temperatures and catalysts are required [11, 12].

Another interesting development in methanation methods is the so-called biological methanation. This approach utilizes microorganisms, more specifically hydrogenotrophic methanogenic archaea, to catalyze the Sabatier reaction [9]. This can be achieved at lower temperatures than when a chemical catalyst is used [13, 14]. It also has a higher tolerance to contaminations, such as organic acids and H_2S [15, 16]. The conversion of H_2 and CO_2 to CH_4 can be achieved in various types of reactor designs. In most of the reactors the reaction chamber is filled with liquid or moist solid particles. Other researchers used a trickle-bed reactor, in which the reaction chamber was not filled with liquid [15, 17], but instead they immobilized the microorganisms on the surface of a packed bed and sprinkled them with a limited amount of liquid, resulting in better material transport and higher efficiency of the system. Although there is a large interest in the methanation of CO_2, many questions about catalysts and biological methanation remain unresolved, but interest in the process has incited further research [15, 18, 19].

When developing innovative technologies, such as biological methanation, it is important to have a clear idea on the economic performance of the process. Therefore, in this study we performed a techno-economic assessment (TEA) to optimize the development of the process and to determine the most important parameters. Techno-economic studies have previously been performed for different P2G systems [20, 21]. For example, Parra et al. (2017) concluded that P2G systems in Switzerland generating hydrogen and synthetic natural gas (SNG) are not economically competitive with conventional gas production systems if only hydrogen and SNG are sold [21]. Collet et al. (2017) performed a techno-economic and life cycle assessment of methane production in France using a combination of anaerobic digestion of sewage sludge and power-to-gas technology. They concluded that the price of electricity influences to a large part the competitiveness of the system with injection of methane from biogas [20]. Schiebahn et al. (2015) indicated that the production cost of renewable hydrogen or methane in Germany is several times higher than the cost of natural gas. Therefore, they argue that the usage of renewable hydrogen is more interesting in the transport sector [1]. Kopp et al. (2017) concluded that hydrogen production in Germany using a Proton Exchange Membrane (PEM) electrolyser is most interesting when participating in the secondary control reserve market. Furthermore, they identified the capital costs, fixed costs and efficiency as important parameters to further improve the economic feasibility of the system [22]. Most of the existing studies focus on chemical P2G systems, but studies investigating the techno-economic feasibility of biological methanation are only limited. Here we report the results of a case-study for biological methanation (further called microbial P2G concept) in a Belgian context, aiming to identify the economic feasibility and the main influencing parameters of the microbial P2G concept. In Belgium several anaerobic digesters (mainly using agricultural waste and some using organic municipal solid waste (OMSW)) are installed. According to the yearly report of 2016 provided by Biogas E vzw (i.e. platform for anaerobic digestion in Flanders) 41 digesters were running in Belgium, by the end of 2015, with a total capacity of 2.6 million ton input material per year and an installed electrical capacity of 105 MWe. Only two installations used OMSW, the others being industrial or agricultural digesters. Recently, the number of industrial and agricultural digesters stagnated due to scarcity of input feedstock, although, for OMSW digesters, there is still some growing potential. In Belgium the state-of-the-art technology for processing OMSW is evolving from composting, to predigestion followed by composting. At the moment two installations have already implemented a predigester, two others are showing interest and are preparing predigestion. In the future three other installations might install a predigester. Currently many of the digesters face financial difficulties and are searching for alternative business models [23]. In Flanders, biogas upgrading systems have not been installed yet. This option will especially be interesting for OMSW digesters to improve the business case as these installations do not have a high local heat demand. Furthermore, we see an increased amount of renewable energy, with a yearly increase in the amount of energy produced by wind mills and solar panels [24]. Taking into account the number of digesters, the increasing interest in biogas upgrading, and the increase in renewable energy production, microbial P2G might be an interesting option for Belgium. We will identify the role of the microbial P2G concept to improve the financial viability of the anaerobic digesters. Simultaneously our results provide advice to technology suppliers on how to further improve their business, optimize their technology and reduce the time-to-market.

2. Material and methodology

2.1. Case study

In this paper we evaluate the techno-economic feasibility of a microbial P2G concept in Belgium. The concept under investigation consists of three separate steps, i.e. electrolysis, microbial methanation and biogas upgrading. Electrolysis is used in our case study to convert electricity into H_2 when the electricity prices are sufficiently low to operate the installation, e.g. in case of an oversupply of electricity. We analyzed the historical day-ahead and imbalance electricity prices in Belgium in 2016. Assuming that the market price of 1 MWh produced biomethane is 27 euro, and given the efficiency of the microbial P2G process, we concluded that if electricity is paid at the Belgian day-ahead prices, the electrolyser within the microbial P2G process would be running at approximately 10% of the time. Nevertheless, repeating the analysis with the Belgian imbalance prices, it was observed that the process would operate during 35% of the time. In the remainder of the paper, it is assumed that the electrolyser can operate during 35% of the time. A combination of anaerobic digestion (AD) and an additional external gas converter (i.e. microbial methanation) is used to transform the H_2 from electrolysis into CH_4 (Figure 1). In our case study 5% of the H_2 is sent to the AD and the remaining amount is processed in the external gas converter. The AD in this case study converts 51,400 ton OMSW on a yearly basis into biogas using an undefined microbial culture. This total amount of OMSW that is processed in the AD is within the range of the typical amount of OMSW that is processed by one intercommunal waste processor in Flanders. The biogas is composed on average of $55\%_{vol}$ CH_4 and $45\%_{vol}$ CO_2. Part of this CH_4 in the biogas is formed by the biological conversion of H_2 and CO_2 that is formed during the AD process. An additional dosage of H_2 in the AD, produced using the electrolyser, enriches the hydrogenotrophic microorganisms and stimulates an additional consumption of CO_2, resulting in a higher CH_4 content of the final biogas. The biogas is upgraded in the third step, after which it is injected in the natural gas grid. The CO_2 from the biogas upgrading is converted in combination with the remaining H_2 from electrolysis into an additional amount of methane using the external gas converter.

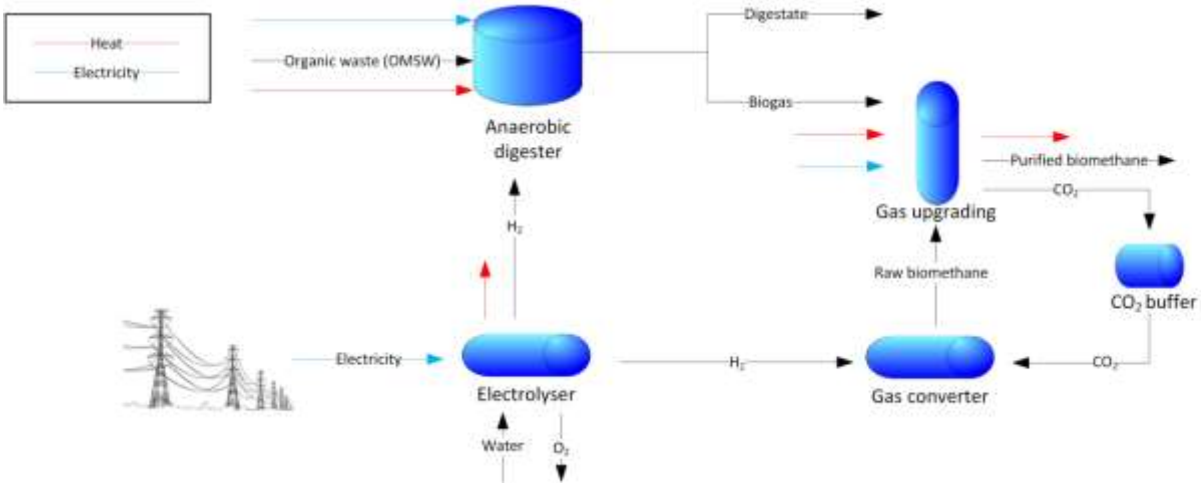

Figure 1. Microbial power-to-gas concept

2.2. Methodology

A TEA takes into account the entire value chain and can be applied during every technology readiness level (TRL). The methodology can be divided into four different phases. First, a market study is performed. Second, a process design is defined and translated into a simplified process flow diagram (PFD) and mass and energy balance, calculated using an Excel spreadsheet. Third, this information is directly integrated into a dynamic cost-benefit analysis (CBA) (i.e. economic evaluation). From this analysis, the profitability is identified. Due to the direct integration of the mass and energy balance and the cost-benefit analysis in one calculation tool and due to the dynamic modelling, it is possible to directly quantify the influence of changing one or more parameters (both technical and economic) on the mass and energy balance, as well as the economic feasibility of the process. The integrated calculation also allows to see how the result is influenced by the uncertainties of the assumptions made. This is evaluated in more detail in the fourth step, the uncertainty analysis, which identifies the potential barriers and gives advice on how to further develop the technologies. As information gathering is expensive, a TEA is performed in an iterative way with a go/no-go decision after every iteration [25] (Figure 2). When the technology seems promising, more data is added and more experiments are performed with a focus on the processes and parameters that have the highest influence on the feasibility. A detailed description of the methodology can be found in Van Dael et al. (2015) [26].

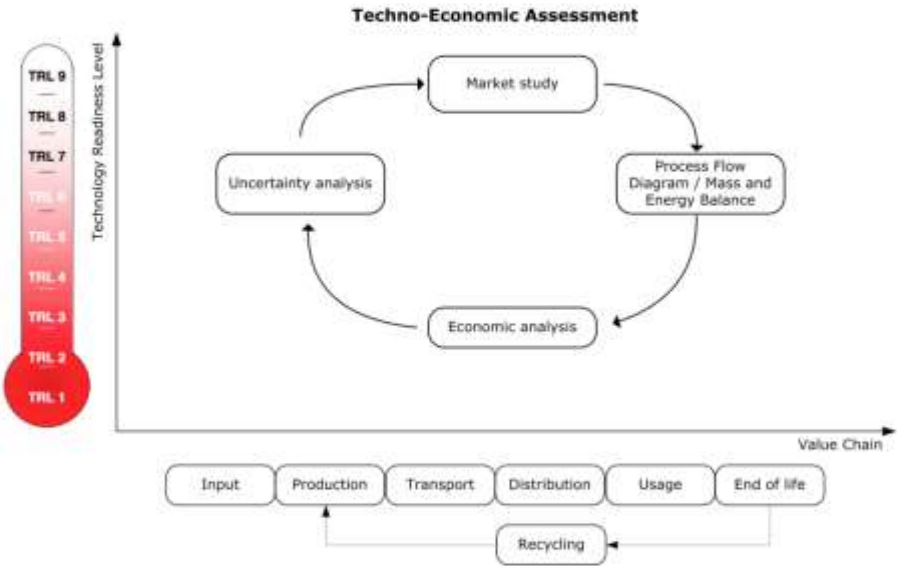

Figure 2. Techno-Economic Assessment

In this study the TEA is first applied to the three different steps of the microbial P2G concept as described in section 2.1, i.e. electrolysis, microbial methanation and the biogas upgrading. After the analysis of the different steps, the TEA is applied to the microbial P2G concept as a whole. This allows the identification of the economic feasibility of the different steps and the integrated concept and gives a better insight into the value chain, its opportunities and limitations. Data for the TEA were provided by technology suppliers in the region and were validated and completed using scientific peer-reviewed literature. The general economic assumptions are the same for the three separate steps and the microbial P2G concept as a whole. An overview of the general economic assumptions are provided in Table 1.

Parameter	Value	Unit
Debt/Equity ratio	80/20	-
WACC	5	%
Tax rate	33.99	%
Economic lifetime	10	year

WACC = weighted average cost of capital

Table 1. General economic assumptions

3. Results

3.1. Electrolysis

The first step of the microbial P2G concept is the electrolysis (scenario 1: electrolyser). In this study we used an alkaline electrolyser since this is at the moment the cheapest and most reliable technology [7]. However, for P2G systems a PEM reactor might be a better option because of the slightly higher efficiency and shorter startup time [27]. For the calculation of the size of the electrolyser in the first scenario we made the following assumptions: (1) the electrolyser is operating in 35% of the time (i.e. 3,066 hours per year), (2) the amount of OMSW that is processed in the AD is 51,400 ton per year, and (3) all the CO_2 from the biogas upgrading installation is converted using the external gas converter into additional methane with H_2 from the electrolyser. Using these assumptions we calculated that the electrolyser processes 55,350 MWh of electricity every year and has a size of 18 MWe. The total amount of tap water used, is 14,391 liter. This results in the production of 11,070,000 Nm^3 H_2 and 5,535,000 Nm^3 O_2 per year. The total amount of waste water that has to be disposed is 5,535 liter. The total residual heat that is produced in the electrolyser is 17,712 MWh per year. An overview of the assumptions used to calculate the mass and energy balance is provided in Table 2.

Parameter	Value	Unit	Source
Electricity use	5	kWh/Nm^3 H_2	[28, 29]
Tap water use	1.3	L/Nm^3 H_2	[29]
Waste water	0.5	L/Nm^3 H_2	
Hydrogen production	0.2	Nm^3/kWh	
Oxygen production	0.5	Nm^3/Nm^3 H_2	
Electrolyser size (40 ft container)	250	kWe	
Maximum number of modules combined	6	#	
Residual heat electrolyte and gas cooling	1.5	kWh/Nm^3 H_2	
Residual heat rectifier	0.1	kWh/Nm^3 H_2	

Table 2. Mass and energy balance assumptions alkaline electrolysis

For the economic analysis several assumptions were made (Table 3). For the alkaline electrolyser the total investment cost amounts to 21.6 million euro. The total yearly operational cost is 6 million euro and the total revenues are 3 million euro per year. For the electricity price we took the average of the lowest 35% Belpex prices of 2015. For the additional costs related to the electricity price, i.e. grid costs, taxes, and levies, we used data from Eurostat. Based on a cost breakdown of the operational costs of the electrolyser we can conclude that over 70% is due to electricity consumption, almost 18% is due to personnel costs and the remainder are insurance costs. The large share of electricity consumption in the total electrolysis costs is confirmed by Collet et al. (2017) that also found a share of 70% [20]. The largest revenues result from the sale of H_2. Selling O_2 only results in a small revenue compared to the revenue from selling H_2.

Parameter	Value	Unit	Source
Installed cost electrolyser	1,200	€/kWe	[7, 29]
Insurance cost	2.5	%I_0	
Electricity purchase price[a]	29.6	€/MWh	Belpex
Electricity price costs (grid, tax,…)[b]	49	€/MWh	Eurostat
Total electricity cost	78.6	€/MWh	
Wage rate personnel	35	€/hour	Eurostat
Personnel supervision	200	hour/year	
Personnel maintenance	5	%I_0	
Water purchase price	2.3	€/m^3	[29]
Water disposal cost	0.5	€/m^3	
Sale hydrogen	0.27	€/m^3	[29]
Sale oxygen	0.033	€/m^3	[21, 29]

[a] Average of the 35% lowest prices on the Belpex market (2015)

[b] Eurostat data for industrial consumers in the category 20,000-70,000 MWh/year

Table 3: Economic assumptions alkaline electrolysis

Based on the assumptions made, the resulting Net Present Value (NPV) is negative. Note that the economic lifetime is 10 year and the WACC 5%. A negative NPV implies that under the assumptions made, it is not economically interesting to invest in the electrolysis process. The total cost to produce the H_2 amounts to €0.8/m³ H_2 (or €8.9/kg H_2), whereas the selling price that is taken into account in the calculations amounts to only €0.27/m³ or €3/kg. However, for H_2 the current price ranges between €2-10/kg or €0.17-0.9/m³ and thus the process can be economically feasible under the current market conditions. In case the price of H_2 amounts to €0.9/m³, the NPV raises to 5.5 million euro, the Internal Rate of Return (IRR) amounts to 24% and the discounted payback period (DPBP) is less than 5 years. The sensitivity of the NPV for the first step to the electricity price without costs such as grid costs and taxes, and the H_2 price is provided in Figure 3.

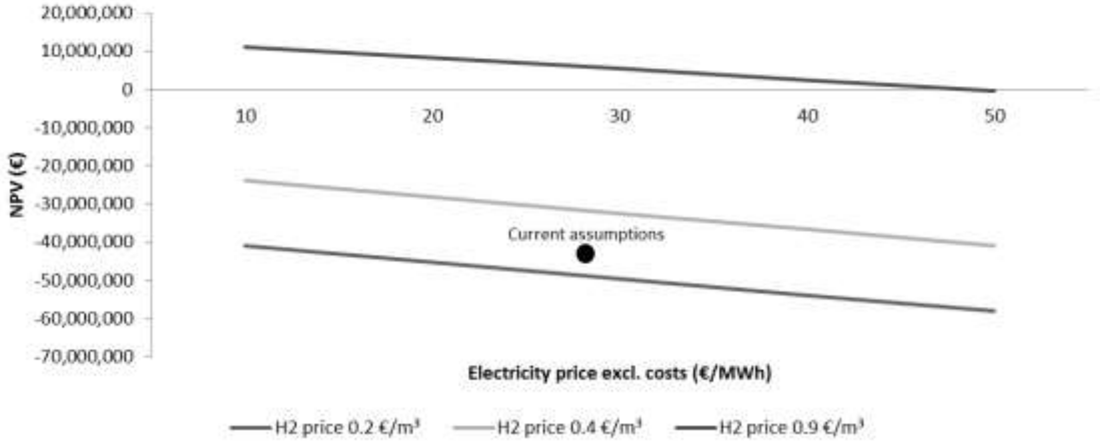

Figure 3. Sensitivity of NPV to changes in electricity and hydrogen price

As mentioned above, in our analysis we assumed the use of an alkaline installation. However, note that for an electrolyser with a size of 18 MWe the investment cost for a pressurized alkaline and Proton Exchange Membrane (PEM) installation are in the same range. Also the operational costs are the same for both types of installations. It is expected that the investment costs for both the pressurized alkaline and PEM electrolyser will lower over time to approximately €500-600/kWe [1, 29, 30].

To better understand the main influencing parameters, we performed a Monte Carlo analysis or sensitivity analysis in which we varied the technical and economic parameters 50,000 times with plus and minus 10% following a triangular distribution. The goal of this kind of analysis is to identify the parameters that have the highest impact on the variance in the NPV. Based on this sensitivity analysis we concluded that both the investment cost of the electrolyser and the electricity price have a high impact on the economic feasibility of the process. Using three sub-scenarios we further analyze the impact of changes in these parameters on the economic feasibility for the first step of the microbial P2G concept (Figure 4).

In the initial scenario, the size of the electrolyser is large in comparison to the amount of electricity that is processed due to the low operating hours per year. Therefore, we made an evaluation of a new scenario in which the electrolyser operates continuously (scenario 1a: continuous operation).

In case the installation processes the same amount of electricity, but operates continuously throughout the year, a size of only 6 MWe is required. This results in a lower total investment cost (i.e. 7.5 million euro instead of 21.5 million euro), however, the electricity price will be higher as the installation is not only operated when prices are lower due to e.g. an oversupply of electricity (i.e. €44.3/MWh instead of €29.6/MWh, the additional costs for taxes etc. remain the same). The resulting NPV remains negative under the assumptions made. An optimum should be found between the operating hours of the installation and the electricity price.

The electricity price consists for a large part of additional costs such as taxes. In case we do not take into account these additional costs (scenario 1b: no electricity costs), the production cost of hydrogen lowers from €0.8/m³ to €0.55/m³ H_2 or €6/kg H_2. An exemption from these fees could be provided by the government as a supportive measure. Furthermore, these costs also do not have to be paid in case an electricity source is available on the same site.

If we assume that no additional costs have to be paid for electricity and that the electrolyser operates continuously (scenario 1c: continuous operation and no electricity costs), the cost per m³ of H_2 further decreases to €0.37/m³ or €4/kg. Therefore, it is important that the electrolyser is used for multiple purposes, e.g. a combination of higher and lower added value products such as for energy, chemicals and transport fuel production, to increase the operating hours and as such reduce the operational costs.

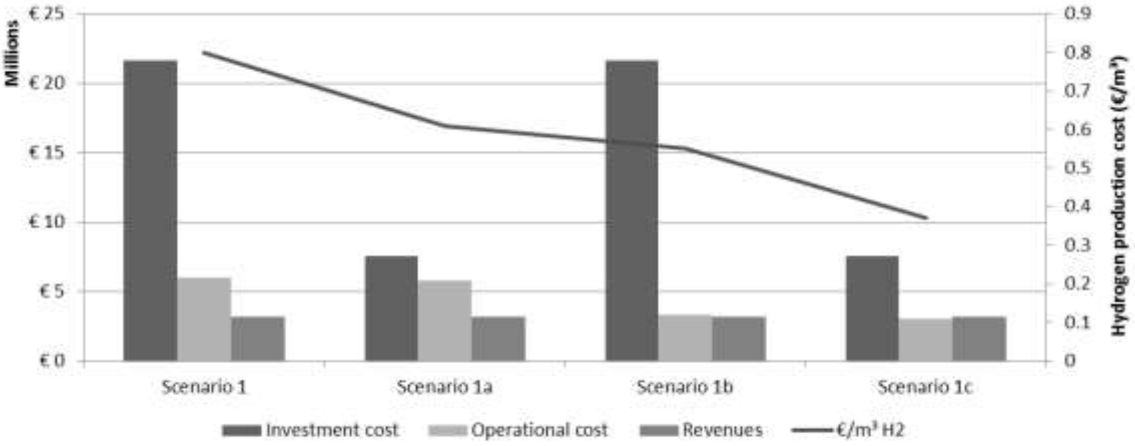

Figure 4. Graphical overview of the results of the different scenarios for the first step of the microbial P2G concept.

3.2. Microbial methanation

In the second step we perform a TEA for the microbial methanation (scenario 2: microbial methanation). For the size of the digester we assumed the conversion of 51,400 ton OMSW per year. To process this amount of OMSW we calculated that one digester with a size of ca. 3,500 m³ is needed. The output of the digester is the production of ca. 44,000 ton digestate and approximately 6.2 million m³ of biogas per year. By partly adding the H_2 produced by the electrolyser, the CH_4 content of the biogas rises from 55% to 57%. It is assumed that 5% of the H_2

production in the electrolyser is added in the AD. It is not possible to add more H_2 directly to the digester due to thermodynamic aspects. Therefore, the other 95% of the produced H_2 is converted in a separate gas converter. Next to the H_2, also the CO_2 from a gas upgrading step is added to this gas converter. We also foresee a 24h storage unit for the CO_2. In the gas converter, 3.3 million m³ of raw biomethane is produced. Under the assumption of a carbon conversion efficiency of 95% this raw biomethane has a methane content of 79%. The produced biogas and raw biomethane is sent to an upgrading installation in the third step of the microbial P2G concept. An overview of the mass and energy balance assumptions is provided in Table 4.

Parameter	Value	Unit	Source
Density OMSW	600	kg/m³	
Water content OMSW	60	%	[31]
Biogas production	119.65	m³/ton	[32]
Biogas methane content	55	%	[33]
Retention time digester	25	days	
Electricity use digester	0.12	kWh/m³ biogas	
Heat use digester	0.13	kWh/m³ biogas	
Efficiency gas converter	95	%	
Electricity use gas converter	100,000	kWh/year	
OMSW = organic municipal solid waste			

Table 4. Mass and energy balance assumptions microbial methanation

The assumptions for the economic analysis can be found in **Error! Reference source not found.**. For the investment cost of the digester we use formula (1) which is based on several offers we received from AD suppliers in the period 2006-2015:

$$\text{Investment cost AD } (€/m^3) = 7{,}711{,}627 \, (\text{capacity } (m^3))^{-1.03} \quad (1)$$

Parameter	Value	Unit	Source
Investment cost gas converter	2,000,000	€	
Investment cost H_2 buffer	600	€/kg H_2	
Investment cost compressor H_2 buffer	10,000	€/kg H_2 hour	
Investment cost CO_2 buffer	90	€/m³ CO_2	
Wage rate personnel	35	€/hour	Eurostat
Personnel maintenance digester	3	hours/day	
Personnel operation digester	1	hours/day	[34]
Purchase price electricity	139	€/MWh	Eurostat
Purchase price natural gas	30	€/MWh	Eurostat
Insurance cost	2.5	$\%I_0$	
Analysis cost input	1	€/ton	
Cleaning products	0.25	€/ton input	
Purchase price H_2	0.27	€/m³	
Maintenance gas converter	3	$\%I_0$	
Gate fee OMSW	60	€/ton	[34]
Selling price biogas and raw biomethane	0.2	€/m³	
OMSW = organic municipal solid waste			

Table 5. Economic assumptions microbial methanation

The total investment cost for the second step amounts to almost 9 million euro. The largest investment (i.e. 6 million euro) is for the AD itself. The largest operational cost, almost 3 million euro, comes from the H_2 that has to be bought in case the three steps are not considered as one integrated process. Other large costs are the personnel to run and maintain the AD. The revenues are mainly coming from the gate fee for OMSW and a smaller part, almost 40%, is the result of selling the biogas and raw biomethane to the upgrading facility. The total operational costs approximate 4.7 million euro and the revenues are almost 5 million euro per year. The operational costs are similar to the revenues and, for that reason, the investment will not be economically feasible in a reasonable time span. The NPV amounts to minus 4.8 million euro.

Also for microbial methanation we defined some sub-scenarios to better understand the impact of the assumptions made. A graphical overview of the total investment costs, operational costs and revenues in the different scenarios of the second step are provided in Figure 5. In a first sub-scenario we assumed that no H_2 has to be bought (scenario 2a: no H_2 cost), i.e. it can be added for free, and we find that the investment becomes economically feasible. Under the assumptions made, the NPV amounts to 10 million euro, the IRR to 85% and the discounted payback period is less than 2 years. However, this positive value mainly results from the gate fee that is received for processing the OMSW.

In a next sub-scenario we only took into account the extra costs and revenues compared to the current situation in Belgium in which OMSW is converted to biogas, without the addition of H_2 (scenario 2b: only additional costs). This means that only the investment costs for the gas converter and CO_2 storage are taken into account, i.e. ca. 2.7 million euro. For the operational costs we take into account the additional insurance costs and electricity use due to the addition of H_2. Furthermore we take into account the purchase costs of the H_2 and the maintenance costs for the gas converter. The total operational costs are approximately 3 million euro. The extra revenues exist of the sale of the raw biomethane that is produced in the gas converter and amount to 600,000 euro per year. This results in a negative NPV of minus 21 million euro. The main reason for this negative NPV is the purchase of H_2 and the lack of the revenues resulting from the gate fee of OMSW (note that the addition of a P2G concept does not alter the waste processing capacity of an AD plant). However, if we assume in a third sub-scenario that we can use waste H_2 and, as a consequence, that no price has to be paid for the H_2 (scenario 2c: only additional costs and no H_2 cost), the NPV is slightly positive. The IRR amounts to 26% and the DPBP is less than 5 years.

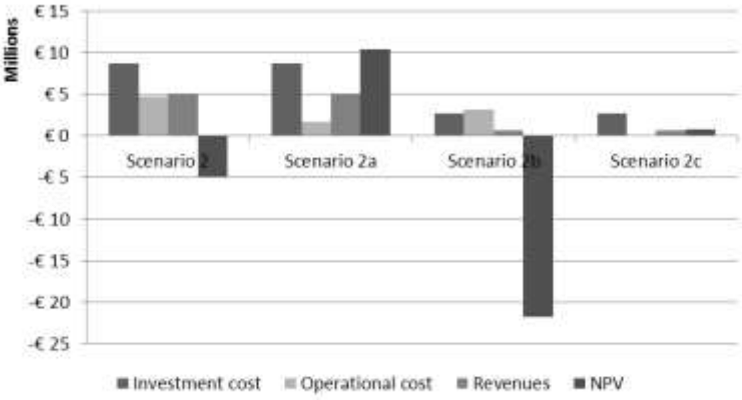

Figure 5. Graphical overview of the results of the different scenarios for the second step of the microbial P2G concept.

3.3. Biogas upgrading

The total amount of gas that is processed in the third step of the microbial P2G concept, i.e. the gas upgrading installation (scenario 3: biogas upgrading), amounts to circa 9 million m³ per year. The biogas consists of 66% of biogas originating from the AD installation and 34% raw biomethane from the gas converter. The resulting purified biomethane production amounts to circa 6 million m³ per year. Almost 2.8 million m³ of CO_2 that results from the upgrading is sent to a gas converter. Note that the costs associated with this gas converter are not taken into account in this step, but are part of the previous step (microbial methanation). The biogas upgrading installation uses approximately 2,200 MWh of electricity per year. The assumptions used to calculate the mass and energy balance are provided in Table 6.

Parameter	Value	Unit
Electricity use base mode	0.37	kWh/m³ biomethane
Electricity use when electrolyser operates	0.32	kWh/m³ biomethane
Heat use base mode	1.64	kWh/m³ biomethane
Heat use when electrolyser operates	1.21	kWh/m³ biomethane
Residual heat	0.27	kWh/m³ biomethane
Methane content biomethane	99.8	%

Table 6. Mass and energy balance assumptions biogas upgrading

Economic assumptions specifically for this step are provided in Table 7. For the investment cost of the upgrading installation we use formula (2) which is based on offers we received from several suppliers in 2013. This formula is based on an installation that converts biogas from AD into purified biomethane. In the microbial P2G concept that we investigate with a gas converter that uses the CO_2 from the upgrading to produce raw biomethane, an additional investment cost has to be taken into account as some steps have to be added to the upgrading installation to make sure that the resulting purified biomethane meets the grid requirements. In our model the total cost (i.e. capital and operational cost) for upgrading the biogas and raw biomethane to purified biomethane amounts to ca. €0.5/m³ of purified biomethane. This is higher than the range of costs that is suggested in literature, i.e. €0.11-0.25/m³ [35] but can be explained by the more complex installation that is needed in this concept.

$$\text{Investment cost } (\text{€/m}^3 \text{ biogas/h}) = 59{,}057\ (\text{capacity } (\text{m}^3 \text{ biogas/h}))^{-0.483} \quad (2)$$

Parameter	Value	Unit	Source
Wage rate personnel	35	€/hour	Eurostat
Insurance cost	2.5	$\%I_0$	
Personnel maintenance	0.2	FTE/year	
Personnel operation	0.5	FTE/year	
Purchase price electricity	139	€/MWh	
Purchase price biogas	0.2	€/m³	
Selling price biomethane	0.27	€/m³	
FTE = full-time equivalent			

Table 7. Economic assumptions biogas upgrading

The total investment cost for the upgrading installation amounts to almost 6 million euro. The total yearly operational costs are ca. 2 million euro. The main contributor to these operational costs is the purchase of biogas and raw biomethane (i.e. 1.8 million euro). The revenues from selling the purified biomethane amount to 1.7 million euro. Seeing that the operational costs are higher than the revenues, this step in itself is not economically feasible. Note that this step is normally integrated with the microbial methanation step in which case no price has to be paid for the gas itself. If we assume that the gas is delivered at a zero cost, the NPV amounts to 2 million euro and the discounted payback period is less than 4 years.

3.4. Microbial P2G concept

In this paragraph we describe the results of the TEA for the microbial P2G concept as a whole integrating electrolysis, microbial methanation, and biogas upgrading (scenario 4: microbial P2G concept), for which the analysis was made based on the assumptions for the mass and energy balance of the separate scenarios (Table 2, 4, 6). The assumptions for the economic calculations are provided in Tables 2, 5 and 7. A graphical overview of the resulting mass and energy balance is provided in Figure 6. The main inputs are OMSW, electricity and water and the resulting products are purified biomethane, O_2 and digestate.

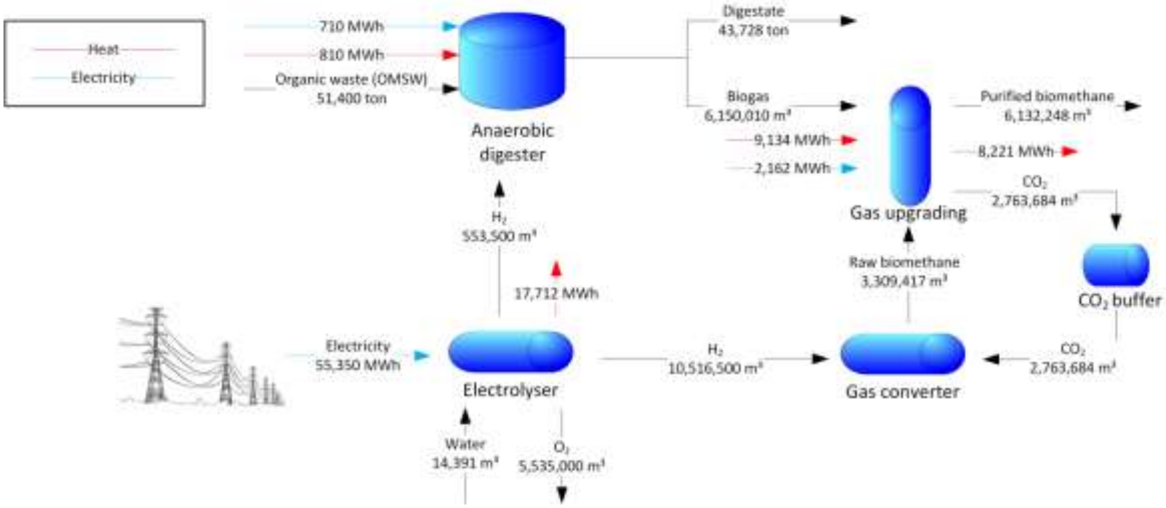

Figure 6. Mass and energy balance microbial power-to-gas concept

The total investment cost for the full concept is 36 million euro. The highest investment cost results from the electrolyser (i.e. 21 million euro). The operational costs amount to 8 million euro per year and the yearly revenues are approximately 5 million euro. Note that in this scenario we do not take purchase costs into account for the intermediate products, i.e. H_2 and biogas/raw biomethane. The purchase cost of electricity is the most important expense (59% of the total operational costs), followed by the personnel cost for the AD installation (28% of the total operational costs). For the revenues the main contributor is the gate fee of OMSW, followed by the sale of purified biomethane and finally the sale of O_2 with a share of 63%, 33% and 4%, respectively. Taking into account that the revenues are lower than the operational costs, the resulting NPV is negative.

To have a good understanding of the main influencing parameters, we performed a Monte Carlo analysis (Figure 7). We can conclude that the electricity use has the highest impact on the variance in the NPV, i.e. 44% of the variance in the NPV is explained by the variance in the electricity use. Also the operational hours of the electrolyser are important, combined with the investment cost of the electrolyser. Note that the operational hours have a positive impact because the longer the operational hours, the lower the investment cost and the higher the NPV. Next, the gate fee of OMSW is important, as well as the electricity price.

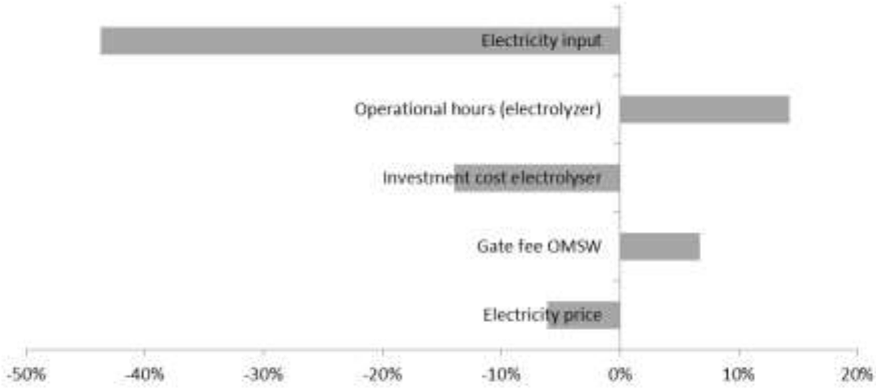

Figure 7. Sensitivity analysis NPV microbial power-to-gas concept

Using some sub-scenarios we investigate the impact of changes in assumptions on the economic feasibility in more detail (Figure 8). In case an exemption is provided for the electricity costs (i.e. grid, taxes,…) the operational costs and revenues are approximately the same (scenario 4a: no electricity costs). However, the concept is still not economically feasible.

If we additionally assume that learning effects will take place and that the investment cost of the electrolyser further drops to approximately €660/kW (i.e. expected by 2050 according to the P2G Roadmap study in Flanders [29]) (scenario 4b: no electricity costs and learning effects), the production cost of biomethane lowers to €1.62/m³, compared to €2.10/m³ with the initial assumptions. Note that this unit cost calculation takes into account the investment and operational costs and does not take into account revenues from the sale of O_2 and the gate fee for OMSW.

In a third sub-scenario we assume that waste H_2 from an external partner is used for free (i.e. no investment in an electrolyser). In this scenario the investment is economically feasible and the production cost of biomethane lowers to €0.66/m³. The resulting NPV amounts to almost 3 million euro. However, if we compare this sub-scenario with a scenario in which no H_2 is added to the AD (i.e. combination of an AD with gas upgrading) (scenario 4d: business as usual), we can conclude that, under the assumptions made, the business as usual scenario is more interesting from an economic point of view. For the business as usual scenario the NPV amounts to over 5 million euro. Note that the business as usual scenario is not yet implemented in Belgium. In Belgium the current situation is the combination of an AD with a CHP installation.

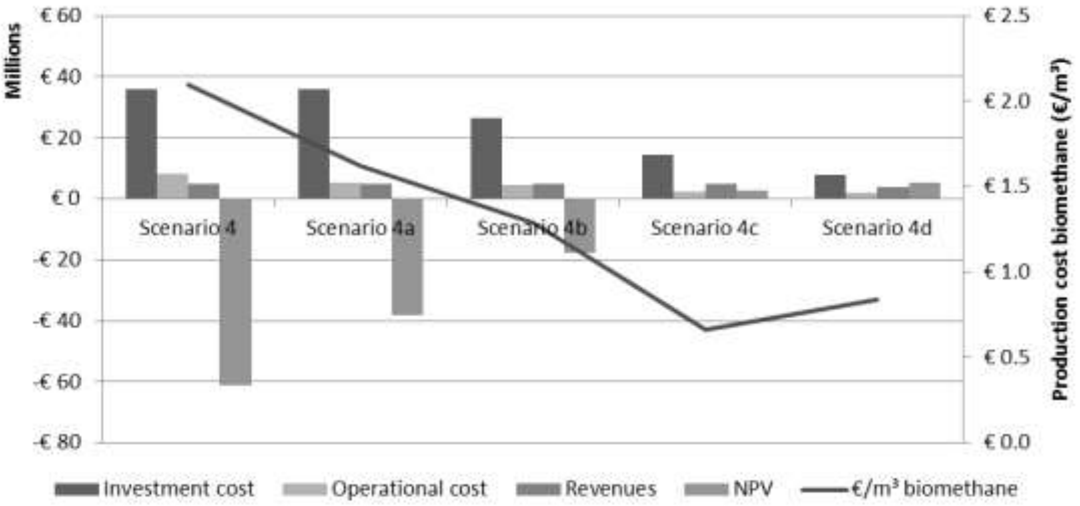

Figure 8. Graphical overview of the results of the different scenarios for the microbial P2G concept.

4. Discussion

Microbial P2G is still in an early development phase and using our iterative TEA methodology we provide advice on how to further improve this innovative technology. Based on the first iteration, we concluded that the cost of hydrogen is most important for the economic feasibility of the microbial P2G concept that we analyzed for Belgium and this cost is mainly determined by the price of electricity and the operating hours of the electrolyser. A similar conclusion was made by Atsonios et al. (2016), i.e. that large efforts have to be made for CO_2 derived fuels to be competitive in the global market [36]. However, if we look at the results for the hydrogen production only, i.e. electrolyser, it can be concluded that hydrogen production is economically feasible with an increased number of operating hours and investment costs for the electrolyser that lower to the estimated level of 2050 [29]. The business case for the electrolyser can even be further improved if we look for additional products such as added-value chemicals or liquid biofuels that can be produced with the H_2. In a future iteration of the TEA it should be analyzed how a combination of producing high-added value products and the production of biomethane when electricity prices are low, increases the economic feasibility. This concept has several advantages such as increasing the operating hours of the electrolyser and decarbonization of the gas network by producing biomethane.

Several studies showed that, when looking at the microbial P2G concept from an environmental point of view, biogas upgrading from biogas without hydrogen addition, is more interesting than a continuous microbial P2G system [20]. Important for assuring a low environmental impact is the use of renewable electricity, since the results of the environmental analysis are dominated by the electricity consumption of the process [21]. Uusitalo et al. (2017) show that greenhouse gas emissions are reduced with the production of methane. However, even more greenhouse gas emissions are reduced when hydrogen or methanol are produced [27]. Therefore, also from an environmental point of view we would advise future research to focus on the production of several end-products (e.g. hydrogen, added-value chemicals, liquid biofuels and biomethane) and as such strive for the highest societal benefits. Also Götz et al. (2016) conclude that for the economic feasibility different business cases such as mobility, balancing services and CO_2 certificates need to be taken into account valorizing the potential of the P2G system in the transition of the energy system [7].

Looking at the business case for the anaerobic digester, the results show that assuming we do not need to invest in the electrolyser, but have some residual H_2 available and compare it with the business as usual scenario (i.e. AD with upgrading installation), the business as usual scenario is more interesting from an economic point of view. Considering these results, we advise to analyze whether a microbial P2G concept on a smaller scale (i.e. smaller electrolyser) can improve the economic feasibility in a second iteration of the TEA. In our case study we took into account an electrolyser to process all the CO_2 resulting from the biogas upgrading resulting in a large electrolyser with a low number of operating hours. However, using a smaller electrolyser that produces H_2 that is fed into the digester when the electricity price is low, can help to decarbonize the gas grid and to balance the electricity grid. The remaining operating hours can be used to produce other products as mentioned above.

Furthermore, for AD other aspects need to be analyzed in more detail to improve the business model for installations in Belgium that face difficulties nowadays. Aspects that should be further analyzed, next to the above mentioned grid balancing service, are for example the role of AD in the day-ahead electricity market. Researchers already investigated the potential of flexible biogas production and/or biogas storage using flexible feeding patterns of the feedstock for the AD. For example the potential of a two-phase digestion of grass silage to be used as a demand-driven system is investigated and it is concluded that it might offer advantages [37]. Recently, Zealand et al. (2017) analyzed the effect of feeding frequency and organic loading rate on biomethane production [38]. In these cases additional combined heat and power (CHP) capacity is needed. These flexible business cases can mainly be used to counterbalance a shortage of electricity on the grid. By combining the CHP overcapacity with the suggested smaller electrolyser, also positive imbalances (i.e. excess of electricity on the grid) can be counterbalanced. However, these ideas need to be further investigated to identify their economic feasibility. In a recent study, Willeghems (2017) looked at the role of AD in the day-ahead electricity market in Belgium. She concluded that the current policy framework in Belgium does not stimulate such flexible business models. Therefore, she argues that for flexible business models also policy makers need to be involved in the discussion [39].

5. Conclusions

A successful transition towards a more sustainable energy system implies the increased implementation of renewable energy sources and as a consequence the need for technologies that can provide the necessary flexibility to balance the electricity grid. Power-to-gas is one of the technologies that gains popularity as it can have the potential to decrease the overall operating cost of the grid. However, the main drawback is still the high cost and relatively low efficiency. We add in this paper to literature by performing a techno-economic analysis for a microbial power-to-gas system in a Belgian context. From our study we conclude that the high investment cost is mainly due to the investment cost of the electrolyser and the low number of operating hours we assumed. Furthermore, the costs to operate the system are high due to the electricity price, which for a large part exists of additional costs such as grid costs, taxes, etc. With an increased amount of renewable energy, the concept can become more interesting as this would influence the operating hours and as a consequence the investment cost of the electrolyser. To improve the business case of microbial P2G the following aspects are important and should be taken into account in future research: (1) renewable electricity should be used to minimize the environmental impact and reduce the electricity costs, (2) the operating hours of the electrolyser should be as high as possible, and (3) multiple products should be produced, e.g. H_2, added-value chemicals, and liquid biofuels. Therefore, we would like to stress the importance of an in-depth analysis of the possible P2G role in decarbonization of our energy systems and accordingly the need to involve policy makers in future discussions concerning P2G.

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