D.T. 4.3.5 ADDITIONAL 3 FEASIBILITY STUDIES ON BEHALF OF THREE NEW PA

Project Title: REEF2W Increased renewable energy and energy efficiency by integrating, combining and empowering urban wastewater and organic waste management systems

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1. Introduction

1.1. The REEF2W Project

In the wake of the energy transition ("Energiewende"), an increased focus is concentrating on the yet unexploited energy-saving potential of the wastewater sector. Wastewater treatment plants are large consumers of energy and often have key shares in the carbon footprint of municipalities and urban governments. Their energy consumption usually accounts for the bulk of operational costs of wastewater utilities, sometimes up to 60 per cent. However, despite being a large source of electricity and heat, sewage is generally overlooked. In fact, the amount of energy it contains can be 10 times bigger than that is required to treat it. Lately an increasing number of wastewater operators have deployed energy-efficiency measures and novel technologies to better harness the energy of sewage. Evaluations of pioneering projects show that utilities are not only capable of becoming energy self-sufficient, but also suppliers of energy thereby diversifying the local mix.

The project REEF2 Water recognizes that wastewater is an integral part of the water-energy nexus. The project is funded by the European Development Bank's Interreg Central Europe Programme and is carried out through 11 research institutes and wastewater utilities from Italy, Czech Republic, Germany, Croatia, and Austria. The projects main objective is to drive up energy efficiency and renewable energy production of wastewater treatment plants. It provides an innovative approach in integrating organic waste and wastewater streams and infrastructures. Where beneficial, bio-waste will be used to enrich sewage sludge, helping to elevate outputs of heat and electricity in a process called co-fermentation. To prove that the new technologies can be technically feasible and make economic viable, project partners will develop a comprehensive assessment tool in close collaboration with utility operators in- a series of workshops. Another key task of Reef2 Water is to investigate the legal and policy framework conditions and to advocate for policy alternatives that spur the large-scale use of wastewater-to-energy solutions.

1.2. Scope of the deliverable

The purpose of this deliverable is to analyse the energy efficiency and the potential to produce renewable energy in the project's five pilots. These form the first two steps of the Integrated Sustainability Assessment (ISA). Implementing the first part of the feasibility will allow to understand how much energy the WTTPs currently use, and at what level of efficiency. Furthermore, it will provide a quantitative understanding about the potential to increase energy outputs. In the (fictive) technological upgrades defined for each pilot, these include measures to optimise existing processes and to install new technologies that produce renewable energy (See Figure below).

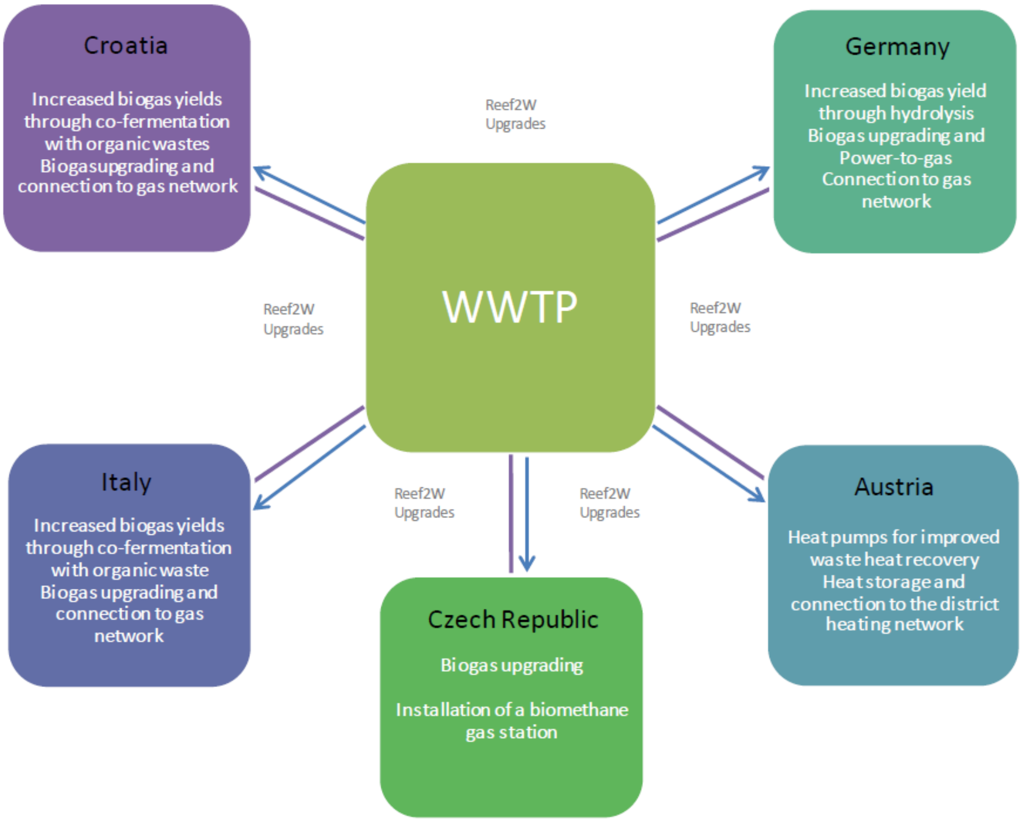

Figure 1: Presentation of the REEF 2W upgrades in the five European pilot plants

How is it relating to previous deliverables?

The ISA methodology was developed in the REEF 2W project and has been tested during the training courses. While the feedback gathered from the participants is being integrated, this is the first organized attempt to test the ISA tool. The results for applying these first two tools will provide the data required to conduct the second part of the Feasibility Study (in Work Package 3). The results will also be important for other communicational purposes. For example, they provide evidence of the potential of wastewater-to-energy solutions, which is demonstrated in the Regional Strategies (DT2.5.1) and the MOUs (DT.2.5.2).

2. Background

2.1. The Integrated Sustainability Assessment

The Integrated Sustainability Assessment (ISA) tool is used to systematically assess technical innovations for energy optimisation of wastewater treatment plants (WWTPs) on different sustainability criteria. The instrument allows for making predictions about potentials to improve energy performance, the technical feasibility or the environmental sustainability of the REEF 2W solutions. For more detailed information, please check DT.1.4.1-3.

The ISA instrument, which was developed as an Excel spreadsheet and online tool, comprises five core steps:

I: Energy efficiency is determined through a comparative analysis that measures current energy consumption against recognized efficiency standards. This benchmarking shows the optimization potential for heat and electricity savings.

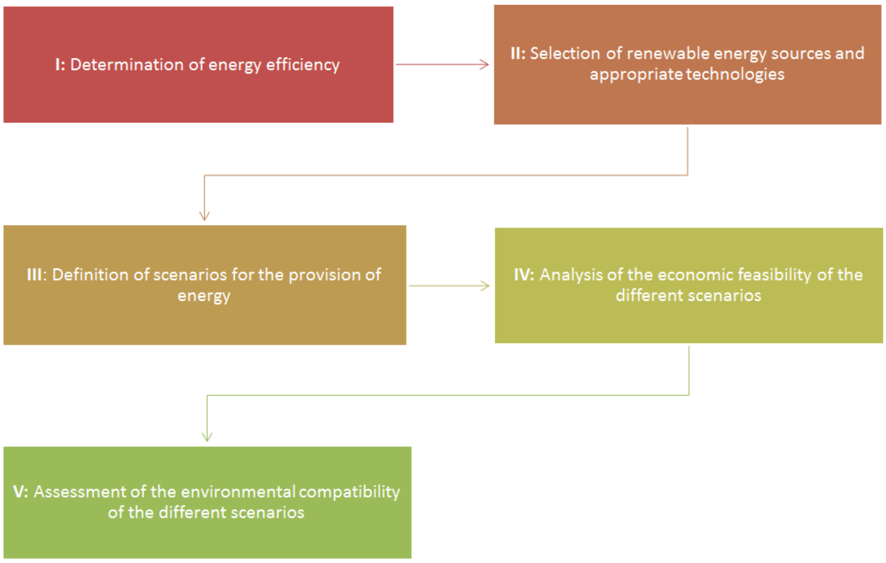

Figure 2: The five steps of the ISA method

II: Suitable technologies are selected through a potential analysis that compares different renewable energy sources. Emphasis in the project is set on improving heat and biogas yields while increasing the efficiency of subsequent uses such as biogas upgrading.

III: Different scenarios demonstrate how excess energy can be used for self-supply of the WWTP and feed-in into the gas, electricity and heat grid. These consider the amount of available surplus energy, energy consumption and energy demand of neighbouring settlements as well as existing grid infrastructures.

IV: The economic feasibility assessment of planned measures will be carried out through a life-cycle cost analysis incorporating generated revenues from energy savings and sales, and investment and maintenance costs.

V: To assess the environmental impacts, a Life Cycle Assessment (LCA) focusing on CO_2-reduction potentials is carried out for each scenario.

2.2. The Expected Benefits

The implementation of REEF2W technologies entails several advantages from an energetic, economic and environmental point of view.

Table 1: Energetic, economic and environmental benefits of the REEF 2W technological solutions

Energy optimization	Economic feasibility	Environmental sustainability
Additional process steps such as thermal hydrolysis or co-fermentation with organic substances increase biogas yields. **Additional heat production is achieved by heat pumps in the sewer.** **A more efficient utilization of biogas is achieved by Combined Heat and Power or biogas upgrading.** **More efficient energy consumption, increased energy yields and the production of storable biomethane increase system security and flexibility.**	Energy savings and self-supply of energy and heat lead to a **reduction in operating costs**. Sales of excess heat, electricity and biomethane allows for **additional revenues**. Reduced sewage sludge volumes **reduce disposal cost**s, especially where cost-intensive waste incineration is the only option. Optimized economics of wastewater treatment plants lead to **financial savings for municipalities.**	Energy savings and reduced use of fossil fuels result in a **lower CO2-footprint** of WWTPs. Biogas obtained from sewage is a **more environmentally friendly biogas** compared to crop-based feedstocks. Recycling of organic waste in sewage treatment plants **replaces the CO2-intensive disposal on landfills.** The wastewater sector increases its **contributions to a sustainable energy transition** and **climate protection.**

3. Description of pilot site (status quo)

3.1. Characteristics of the WWTP Braunschweig

The wastewater of the city of Braunschweig and surrounding communities is delivered by pumping stations to the WWTP Steinhof (figure 3). Here, the wastewater is treated for the removal of suspended solids, organic matter, and nutrients N and P in a conventional activated sludge process with nutrient removal. The status quo of wastewater treatment consists of mechanical treatment, primary sedimentation, activated sludge process and final clarifier, infiltration fields, the irrigation system for delivery of effluent and sludge (in summer) to farmland, anaerobic sludge stabilisation in digestors, biogas electrification in combined heat and power (CHP) plants and seasonal sludge dewatering and storage on-site. In addition to the wastewater-derived sludge, a small amount of external co-substrate (grease) is converted to biogas, using free digestor capacity for the disposal of food waste to improve biogas production. Part of the purified effluent from the process is then spread on historic infiltration fields (220 ha, in operation for more than 100a) for polishing prior to its discharge to surface waters via the Aue-Oker canal. The remaining part of the effluent is pumped to a dedicated agricultural area where it is spread on agricultural fields. (Remy, 2012)

On average, it is calculated that the WWTP Braunschweig receives a wastewater load of 350000 PECOD per year (SE/BS 2010).

The CHP system receives digester gas from the WWTP, biogas from ALBA Niedersachsen-Anhalt GmbH’s bio-waste fermentation facility, and gas from the waste disposal site in Watenbüttel and the biogas plant in Hillerse (in total 7.3 million m^3 biogas). Therefore, the CHP unit generates electricity and heat in excess. The excess electricity is injected into the public grid. The waste heat from the engines and the exhaust heat are used for heating purposes in the WWTP itself as well as at the ALBA Niedersachsen-Anhalt GmbH’s bio-waste fermentation facility. (Abwasserverband Braunschweig, 2020)

Figure 3: Braunschweig WWTP (source: google maps)

3.2. Technology upgrade of the pilot

The integrated approach envisioned in REEF 2W encompasses a wide range of technological steps and processes. Except biogas upgrading and power to gas, many of them have already been realized at WWTP Braunschweig. For example, co-digestion of external substrates in the digestor is practiced since many years, and recently a thermal-hydrolysis stage has been implemented in the Braunschweig WWTP. Therefore, the feasibility study will focus on the remaining REEF 2W technologies and their potential to be implemented at this plant:

Biogas Upgrading

A biogas upgrading unit will receive the biogas produced during anaerobic digestion as well as externally supplied biogas and upgrade them into bio-methane, eliminating the carbon dioxide and any other impurities to achieve grid gas quality. For this process, only a small footprint is needed even in the case of upgrading the full biogas stream.

Electrolysis Unit

The electrolysis unit will use electrical energy from the grid during low demand times or during surplus of renewable energies and produces a stream of hydrogen. The inevitably simultaneously formed oxygen stream will be fed into the biological treatment stage for increased oxygen supply of the activated sludge, or may even be used for a prospective ozonisation step as one option for a tertiary treatment stage in the future.

Biomethanation and grid injection

Hydrogen produced in the electrolysis stage and the extracted carbon dioxide stream from biogas upgrading will be injected into a biological methanation unit, producing high quality bio-methane from the two feed gases. The related reactor vessel and its accessories only have a small footprint.

Additionally, a grid injection site and required pipelines will be installed. This site will be owned and operated by the grid owner who will also be responsible for calorific adjustment, odoration, compression and pressure control.

3.3. Data availability and quality

For the evaluation of the tool, it is important to use high-quality and real data measured at the WWTP. It should be noted that certain errors and inaccuracies in the data cannot be avoided for various reasons such as data imperfections, the use of averages and the neglect of peak loads during a year. Therefore, a deviation between the results of the tool and the actual data is to be expected. Usually, the information requested in the tool can be provided by the WWTP operator. For this purpose, a questionnaire in form of an Excel file listing all required input data is available to the tool user, comprising:

- Plant and equipment data
- Operating data in annual average

However, detailed information on individual process steps and equipment such as pumps, motors and screens were not provided by the operator of the WWTP Braunschweig. For a plant operator, this data is often difficult to collect. Furthermore, some data for processes such as biogas production, heat demand as well as electricity generation are confidential and are kept secret by utilities. This also applies to the WWTP Braunschweig.

Generally, the user is allowed to enter data from any WWTP of choice or to use the default value collected during the tool development (offered in pop-up windows). The data used for this feasibility study refer to the annual average value of Braunschweig WWTP. Both parts of the REEF 2W tools (energy efficiency (EE) of WWTP and generation of renewable energy (RE)) were evaluated and the results are described in the next section.

4. Energy performance of pilot WWTP

4.1. Evaluation of energy efficiency

The evaluation of the energy performance in the tool can be divided into two categories: EE of WWTP and generation of RE. The first part of the tool can provide a simple and rapid performance analysis without requiring detailed input information. The EE tool indicates that a WWTP consumes between 20 and 50 kWh of electrical energy per year and per PE120. PE120 is equivalent to the population, assuming 120 g chemical oxygen demand per PE per day. Specific thermal energy consumption of state-of-the-art WWTPs should be between 0 and 30 kWh/PE120/a. These ranges refer to power consumption and do not consider on-site power generation.

The energy consumption is about 12.2 GWh of electricity and 7.9 GWh of heat per year. Due to the high amount of external gas available, the degree of energy self-sufficiency of this system is higher than 100%.

After entering the data in the tool, the average electricity demand of the WWTP Braunschweig is 33 kWh/PE/a, which is within the standard range of energy efficiency. The result of this analysis was compared to the benchmark published by the German water association (DWA) 2015. Figure 4 shows the specific electricity demand in kWh/PE/a of size class 5 (GK5: > 100.000 PE) in Germany on the abscissa. The ordinate shows the percentage of WWTPs that have a certain electricity demand.

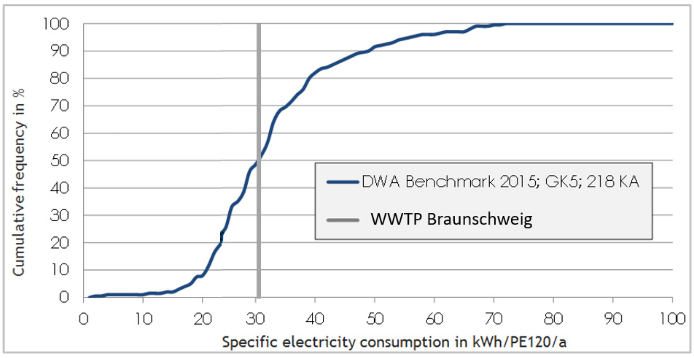

Figure 4: Specific electricity consumption of WWTP Braunschweig compared to DWA benchmark (DWA, 2015)

As shown in the figure above, the specific electricity consumption of WWTP Braunschweig is comparable to the 50% of plants analysed in the DWA benchmark.

The result of thermal energy efficiency shows that the selected treatment plant is also within the standard range of thermal energy efficiency. This WWTP consumes 20 kWh/PE120/a of heat. As mentioned, heat is produced in excess at this WWTP, and the excess is sold to the ALBA Niedersachsen-Anhalt GmbH's bio-waste fermentation facility which is not far away from the WWTP.

Considering the EE results, the Braunschweig WWTP is energetically a well-performing WWTP. However, the energy costs of this plant can still be reduced by improving the energy efficiency of wastewater facilities' equipment and operations and by capturing more of the energy in wastewater to generate electricity and heat.

4.2. Analysis of the WWTP spatial context

As already mentioned, the wastewater treatment plant and bio-waste plant are supplied with the heat produced in the CHP units. Therefore, there is no excess heat on site and a spatial analysis is not necessary.

5. Application of renewable energies and associated energy output improvements

In the REEF 2W tool, the following technologies were implemented:

- Renewable energy technologies such as photovoltaic power plant, solar thermal power plant, hydropower plant and hybrid collectors
- Thermal hydrolysis
- Power-to-gas
- Biogas upgrading
- Co-fermentation
- Heat pump

The use of these technologies enables WWTPs to generate substantial amounts of energy they can use on site, to the extent that they become self-sufficient and feed surplus energy into the grid. Both the co-digestion and thermal-hydrolysis were already implemented in the Braunschweig WWTP. From a technical point of view, it is possible to integrate all considered renewable energies in the Braunschweig WWTP. However, the plant operator is highly interested in two of these options: biogas upgrading and power to gas technology for his plant. Therefore, these two technologies were evaluated in the second feasibility study. In the following, the selected technologies are briefly described.

5.1. Selected technologies

5.1.1. Biogas upgrading

A complete upgrading of the digester gas and feeding into the public gas grid make it possible to use the biomethane regardless of location and time. The produced biomethane during biogas upgrading is a gas from renewable resources with the same quality as natural gas and can replace it by providing a carbon-neutral form of energy. The following figure (Figure 5) shows the main available technical processes for biogas upgrading.

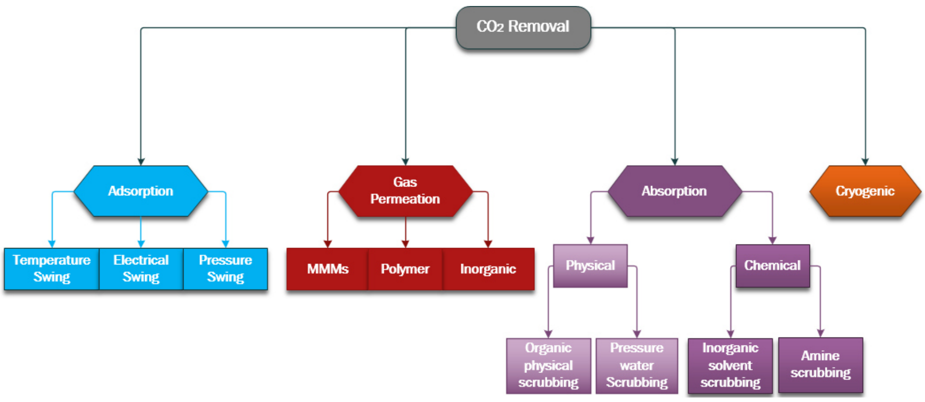

Figure 5: Various gas upgrading technologies

From this selection, the following technologies were implemented in the REEF 2W tool:

- Pressure Swing Adsorption (PSA)
- Pressure Water Adsorption (PWA)
- Membrane
- Cryogenic

5.2. Power to Gas

The power-to-gas (PtG) process in general means the transformation of electrical energy into hydrogen through electrolysis. This is an energy intensive process which can only be economical when using cheap excess electricity from the electrical grid and transforming this electricity into a storable form of energy. Hydrogen produced in the electrolysis stage and the carbon dioxide stream from biogas upgrading can be injected into a separate reactor (methanation unit) to produce high quality biomethane. Therefore, the power to methane technology typically covers the process of methanation of H_2 with carbon containing gases such as CO_2.

For this first part of the process to produce hydrogen, there are several electrolysis technologies on the market. The PEME and AEC technologies are currently available; however, the SOEC system is still at the research stage. The typical characteristics of all three technologies are summarized in the following table.

Table 1: Typical characteristics of different electrolysis technologies (Jannasch, et al., 2016) (Lehner, et al., 2014)

Criteria	AEC	PEM	SOE
Type of electrolyte	20-30% KOH in H_2O (l)	Polymer, e.g. NAFION®	Ceramic of Yttria-stabilized zirconia
Type of electrodes	Ni-based	Pt/C-based	Ni-based, Perovskite
Type of membrane	Asbestos or asbestos free polymer	Same as the electrolyte	Same as the electrolyte
Operation temperature, °C	60-90	50-80	600-1000
Operation pressure, bars	< 30-40	< 200	Up to 30
Power density, W/cm^2	≤ 1	≤ 4	> 1
Part load range, %	15-100	0-100	0-100
Efficiency (based on LHV), %	60-80	60-80	90-95
Life-time (hours)	100000	10000 - 80000	10000
Power consumption kWh/Nm^3 H_2	4-7	4-7	3-4
Start-up time (cold/hot condition)	From 10 minutes to 1 hour	seconds	hours
Products	H_2, O_2	H_2, O_2	H_2, O_2
Maturity	commercial	commercial	Pre-commercial

Only the PEM electrolyser was implemented in the REEF 2W tool.

6. Evaluation of techologies using REEF 2W tool

6.1. Biogas Upgrading

In this scenario, the entire biogas is upgraded and around 3.7 Mio. m^3 of biomethane is generated annually, which can be fed into the local gas grid. The internal electricity consumption of four upgrading technologies is calculated in the tool and the results are shown in figure 6.

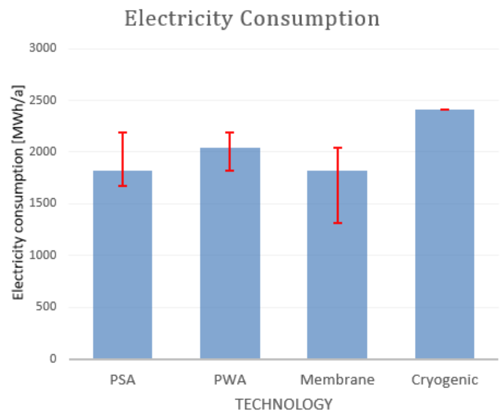

Figure 6: Comparison of electricity consumption of all four technologies

As shown in the figure above, both PSA and membrane technologies consume approx. 1.8 GWh electricity per year to upgrade the entire amount of biogas in the Braunschweig WWTP. In general, the choice of a suitable technology depends on various factors such as the mode of operation, amount of biogas and legal requirements as well as investment costs. A simplified economic calculation was carried out for a membrane plant (see appendix). The investment costs for this system (input capacity: 850 m^3 biogas/h) are estimated at around one and a half million euros. Regarding the CAPEX it is apparent that a biomethane upgrading plant is the least expensive option for biogas usage. It is even cheaper than CHPs which need to be regularly maintained and replaced roughly every 10 years.

In view of the environmental assessment, the carbon footprint of this WWTP is already negative due to the large amount of biogas available at the site. Implementing a biogas upgrading instead of a CHP unit, increase the carbon credits of the WWTP from -3000 to -250 tonnes of carbon dioxide equivalents, since the WWTP has to cover its annual electricity and heat demand from the public grid. The global warming potential is heavily influenced by the electrical grid energy consumption and its substitution for the used energy mix. Therefore, electrical energy generated by biogas in the CHP unit is more worth than the biomethane credits generable from the same amount.

6.2. Power-to-Gas

As a first estimate of capacity, a 2 MW electrolyser or PtG plant was selected in the second scenario. This PtG plant can produce around 3 Mio. m^3 of hydrogen per year and consumes 16 GWh of electricity (full load operation assumed). The hydrogen generated in this process can be used in a subsequent methanation process to produce biomethane. With this amount of hydrogen, about 750,000 m^3 CO_2 (about 20% of total CO_2 in biogas) can be captured and converted into biomethane (750,000 m^3). A simplified economic calculation was carried out for a 2 MW PtG plant (see appendix).
The investment costs for the electrolyser with a biological methanation process amount to four million euros. Obtaining this investment cost poses a major challenge for an operator. Based on all economic assumptions, at the moment, this system cannot be operated economically. However, the role of this technology for the energy system is emphasized, since other benchmark technologies to store energy have limited expansion capacity (e.g. pumped storage hydro power stations).
Nevertheless, the economy of power-to-gas also depends on the available electricity and related electricity price as well as the related legal and economic regulations. Government incentives such as direct and indirect subsidies could make this technology economically interesting in the future.
Regarding the environmental assessment, the carbon footprint of this WWTP can be decreased per m^3 of biomethane production (assumption: excess electricity with low carbon footprint is used for PtG), since the generated biomethane replaces the natural gas in the gas grid. The CO_2 credits generated with 750,000 m^3 of biomethane amounts to 1800 tonnes of carbon dioxide equivalents. In addition, 20% of CO_2 in biogas is captured in the methanation process.

6.3. Discussion and Conclusion

The first part of the tool (EE) can provide an easy and rapid performance analysis. For the evaluation of this part, it is important to use high-quality and real data from a WWTP. However, detailed information regarding individual process steps and equipment such as pumps, motors and screens were not available for comparison. The result of the first part of this analysis shows that the Braunschweig WWTP is energetically within the defined energy efficiency range in the EE tool. However, the energy costs of the selected plant can still be reduced by improving the energy efficiency of wastewater facilities' equipment and operations and by capturing the energy in wastewater to generate electricity and heat. The second part of this analysis compared and evaluated the combination of different technologies in the selected WWTP. Upgrading of biogas into biomethane and injection into natural gas grid allow the highest efficiency levels to be achieved, both in the generation of electricity and in direct heat utilization. This practice is mature enough and commercially available. The second technology evaluated in this analysis was power-to-gas. This technology can be used to increase the biomethane production and to use the excess power from renewable energy technologies. At the moment, finances are the key barrier and appear to impede the implementation of this technology due to prohibitive investment costs and high prices for electricity.

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Appendix

Table 2: Assumption for economic calculation

Parameters	Value	Unit	Sources
Electricity buying price	210	€/MWh	Braunschweig
Electricity selling price	85	€/MWh	Braunschweig
Electricity for PtG	0 / 40	€/MWh	Assumption
Natural gas	10	€/MWh	Braunschweig
Thermal energy selling price	6	€/MWh	Braunschweig
Biomethane selling price + avoided grid charge	53 + 7	€/MWh	Stadtwerke Berlin
Oxygen	0.14	€/m³	Stadtwerke Berlin
Lifetime of plant	8	year	Assumption
Period under consideration	8	year	Assumption

Table 3: Economic comparison of different technologies for biogas utilisation per process (without considering the energy demand of the WWTP)

Parameter	CHP (2.8 MW)	Upgrading (850 m3/h)	PtG* (2 MW)	PtG* (2 MW)	Unit
Investment cost:					
Plant	5320	1500	4000	4000	T€
Operational cost:					
Maintenance	330	120	320 (8% of CAPEX)	320 (8% of CAPEX)	T€/a
Electricity	-	378	0	640	T€/a
Linear depreciation of invest	671	188	500	500	T€/a
Sum	1001	686	820	1460	T€/a
Income:					
Biomethane	-	2220	450	450	T€/a
Oxygen	-	-	210	210	T€/a
Electricity	2720	-	-	-	T€/a
Thermal energy	102	-	-	-	T€/a
Sum	2822	2220	660	660	T€/a
Economic Check:					

Profit	1821	1535	-160	-800	T€/a
Payback period	2.2	0.9	11.8	-	Year
Return on Invest	3	8	0	-2	-

*Electrolyser works under full load and consumes 16 GWh of electricity

Formula:

Payback period (Year) = $\frac{Investment}{Profit-depriciation}$

Return on Invest = $\frac{Total\ profit\ during\ the\ lifetime\ of\ \ plant}{Investment}$

Table 4: Economic comparison of different technologies for biogas utilisation per process, including the costs for energy demand of WWTP

Parameter	CHP (2.8 MW)	Upgrading (850 m3/h)	PtG* (2 MW)	PtG* (2 MW)	Unit
Investment cost:					
Plant	5320	1500	4000	4000	T€
Operational cost:					
Plant	330	120	320 (8% of CAPEX)	320 (8% of CAPEX)	T€/a
Electricity	-	378	0	640	T€/a
Linear depreciation of invest	671	188	500	500	T€/a
Sum	1001	686	820	1460	T€/a
Demand WWTP:					
Electricity	2520	2520	2520	2520	T€/a
Thermal Energy	79	79	79	79	T€/a
Sum	2599	2599	2599	2599	
Income:					
Biomethane	-	2220	450	450	T€/a
Oxygen	-	-	210	210	T€/a
Electricity	2720	-	-	-	T€/a

Thermal energy	102	-	-	-	T€/a
Sum	2822	2220	660	660	T€/a
Economic Check:					
Profit	-778	-1065	-2759	-3399	T€/a

*Electrolyser works under full load and consumes 16 GWh of electricity

Lemen, 09.09.20

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