D.T 3.3.4 – PA5: FEASIBILITY STUDY ON GENERATING A MIX OF ENERGY OUTPUTS BERLIN

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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Content

List of Figures

List of Tables

1. Introduction

The purpose of the deliverable is to finalize the feasibility study by combining of the D.T 2.3.4 Feasibility Study (step 1&2)_Czech Republic and second part described in D.T 3.1.2 Feasibility Study (step 3&4)_Berlin.

The aim of D.T 2.3.4 was to analyse the energy efficiency and the potential to produce renewable energy in the project's pilots. This was done using REEF 2W tool. Implementing the first part of the feasibility study allows to understand how much energy the WTTPs currently use, and at what level of efficiency.

In the D.T 3.1.2. Integrated Sustainability Assessment (ISA) was applied to compare status quo and proposed REEF 2W solution. Based on the ISA evaluation a decision maker can evaluate the strong or weak points of proposed innovative solutions in following contexts: environmental, economical, social, technical.

2. Background

2.1. The feasibility study methodology

The REEF 2W 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 REEF 2W tool, which was developed as an Excel spreadsheet and online tool, comprises five core steps:

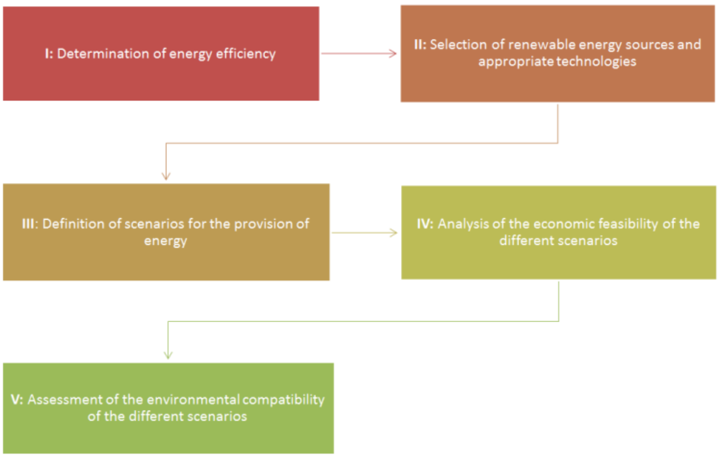


Figure 1: The five steps of the ISA method

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.

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 take into account 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 CO_2-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 CO_2-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 WTTP

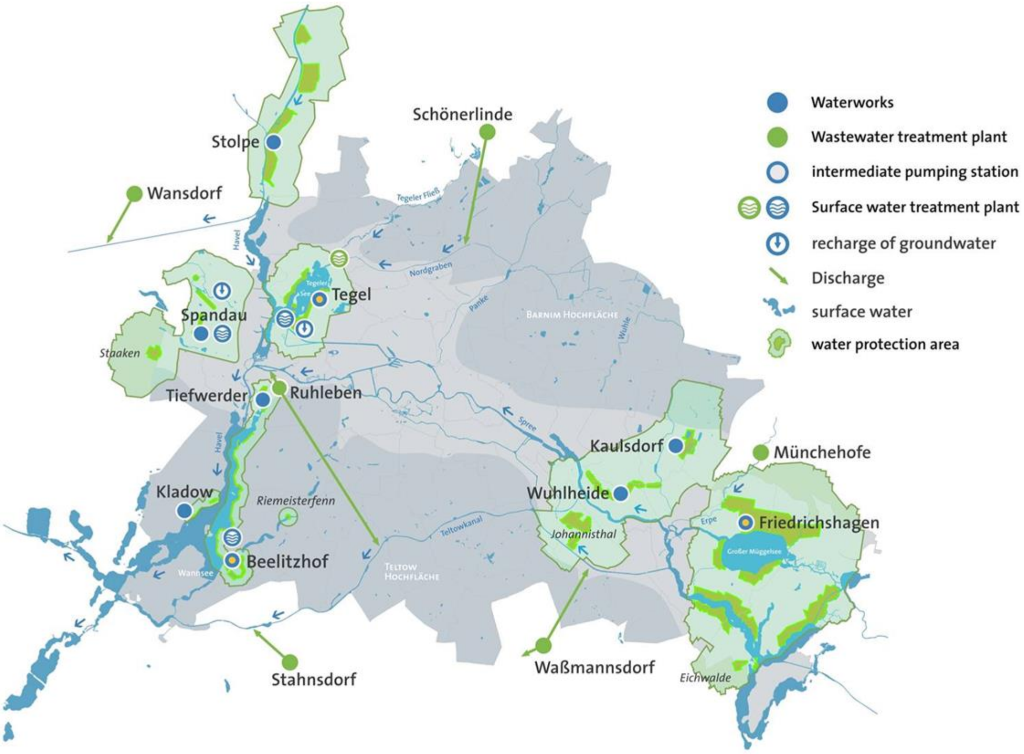


Figure 2: The location of Schönerlinde sewage treatment plant in Berlin (Source: BWB)

The WWTP Schönerlinde is a part of Berlin's Water Works (Berliner Wasserbetriebe – BWB), which provides 3.7 million people in Berlin and Brandenburg with drinking water, as well as collection and advanced biological wastewater treatment. The wastewater in Schönerlinde is treated by mechanical and biological processes with biological phosphate elimination in combination with nitrification and denitrification. The sewage sludge is digested in digesters with mesophilic digesting at approx. 35°C and subsequently drained in centrifuges. Figure 3 gives an overview of the treatment process at Schönerlinde sewage treatment plant. The following technical dates are from the information sheet of BWB (BWB, 2019).

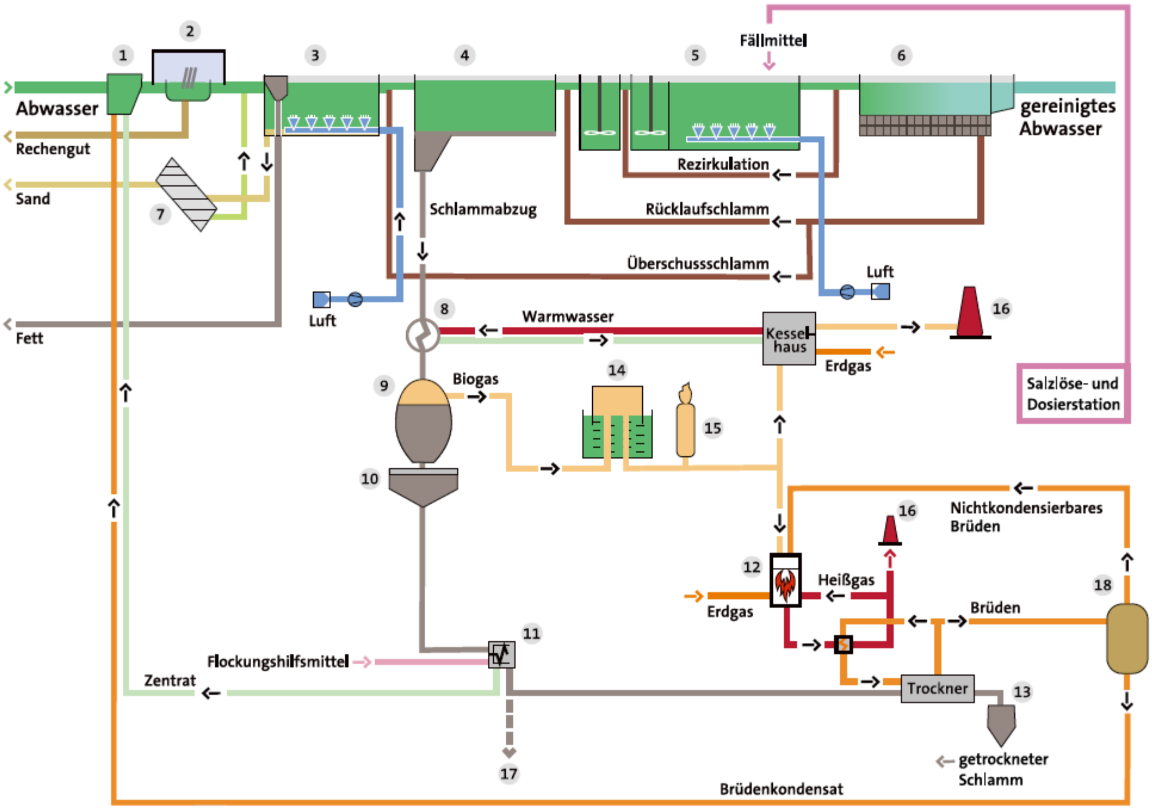


Figure 3: Process scheme of wastewater treatment in Schönerlinde (BWB, 2019)

Mechanical treatment:

Five rake screens remove 1.5 tons of screenings from the wastewater daily. Three aerated double grit chamber classifier approximately two tons of sand per day. Eight rectangular sedimentation tanks are available as Pre-treatment tanks with a total volume of 14,800 cubic meters.

Biological purification:

The aeration tanks consist of eight basins as anaerobic zone, as well as fourteen basins as anoxic and aerobic zone. These have a total volume of 130,500 cubic meters. Aeration systems installed in the activated sludge tank consists of membrane aerators as well as ceramic aerators. As clarification serve twelve rectangular tanks with a total volume of 42,660 cubic meters and two round basins with a total volume of 10,500 cubic meters.

Biogas utilization:

The produced biogas is stored in two gas containers and used for drying the sewage sludge, for heating purposes and for power generation.

3.2. Technology upgrade of the pilot

The integrated approach envisioned in Reef 2W encompasses a wide range of technological steps and processes. Except the enrichment of sludge through bio-waste to enhance biogas yields, many of them are realized at Schönerlinde. The steps will be established to increase the biogas yield through hydrolysis and to convert biogas into bio-methane. Additionally, facilities will be installed to take lower-value electricity from the grid turning in order to turn it into hydrogen, which will be used together with carbon dioxide from biogas upgrading for generating additional bio-methane.

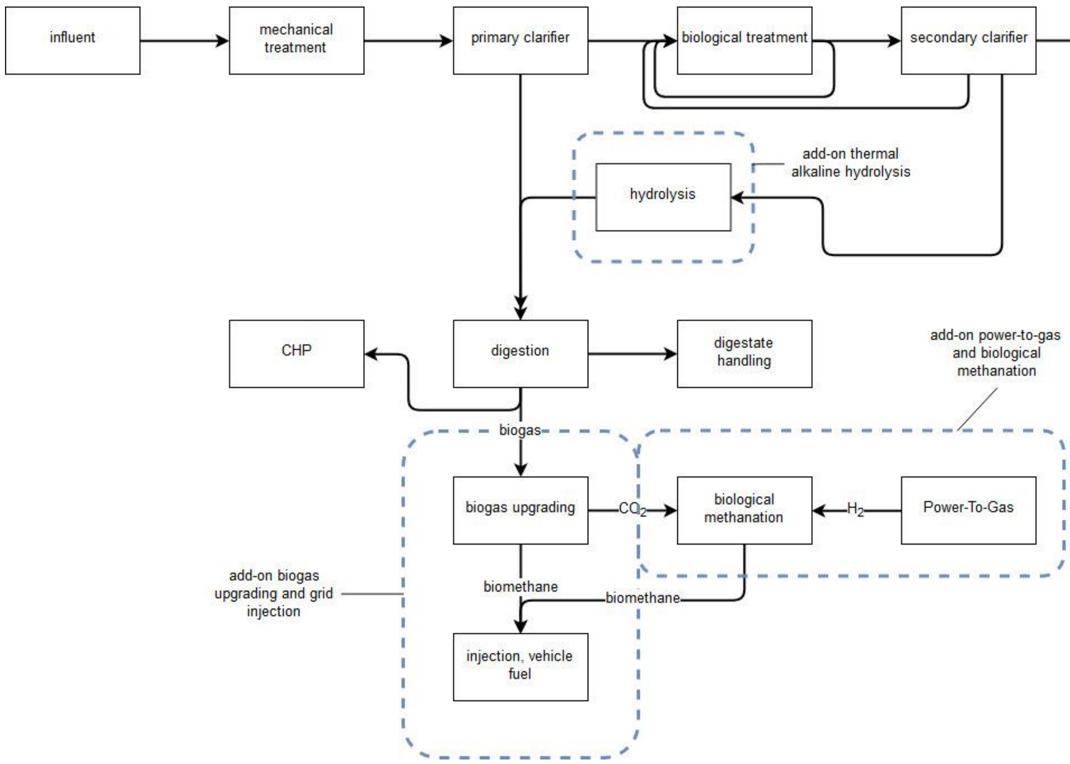


Figure 4: schemata of the new pilot site including the new REEF 2W technologies

Thermal Hydrolysis

The new pilot site will incorporate a thermal hydrolysis stage which will receive a part or the complete flow of the separated sludge from the primary clarifiers to increase the biogas yield during anaerobic digestion and reduce the overall digestate.

Biogas Upgrading

A biogas upgrading unit will receive the biogas produced during anaerobic digestion and upgrade it into bio-methane. 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 of the wastewater or can be used for the prospective ozonisation step as fourth treatment stage.

Grid Injection

Hydrogen produced in the electrolysis stage and the carbon dioxide stream from biogas upgrading will be injected into a biological methanation unit producing high quality bio-methane. The 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.

The hydrolysis stage and biogas upgrading can be independently operated and toggled on or off. The electrolysis/methanation stage needs the running biogas upgrading module as CO2 source and for the grid injection.

3.3. Data availability and quality

For the evaluation of the tool, it is important to use high-quality and real data measured at a 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 a WWTP operator, who in the case of Schönerlinde is BWB. 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 Schönerlinde. 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 Schönerlinde.

Therefore, a more detailed analysis on this data is not possible. Only the energy efficiency of the plant as a whole was evaluated and compared with benchmark values (see next section).

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 Schönerlinde WWTP in 2016. 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 WTTP

4.1. Evaluation of energy efficiency

The evaluation of the energy performance 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 well-managed 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 result of electrical energy efficiency is shown in Table 2.

Table 2: Electric energy efficiency of the selected WWTP

Electric energy consumption		***Standard range***	
WWTP total [kWh/PE120/a]	23,27	***20,00***	***50,00***
1) inflow pumping station and mechanical pre-treatment [kWh/PE120/a]	1,05	***2,50***	***5,50***
2) mechanical-biological treatment [kWh/PE120/a]	17,60	***14,50***	***33,00***
3) sludge treatment [kWh/PE120/a]	3,50	***2,00***	***7,00***
4) infrastructure [kWh/PE120/a]	1,12	***1,00***	***4,50***

As shown in the figure above, all main treatment steps are in the defined performance range in the REEF 2W tool. Therefore, it was expected that the total electrical energy efficiency is also in the standard range of energy efficiency (23.27 kWh/PE120/a), whereby the value is close to the lower interval range.

The result of this analysis was also compared to several benchmarks published by the German water association (DWA) 2015. The next figure (figure 5) compares the energy efficiency of Schönerlinde with the benchmark.

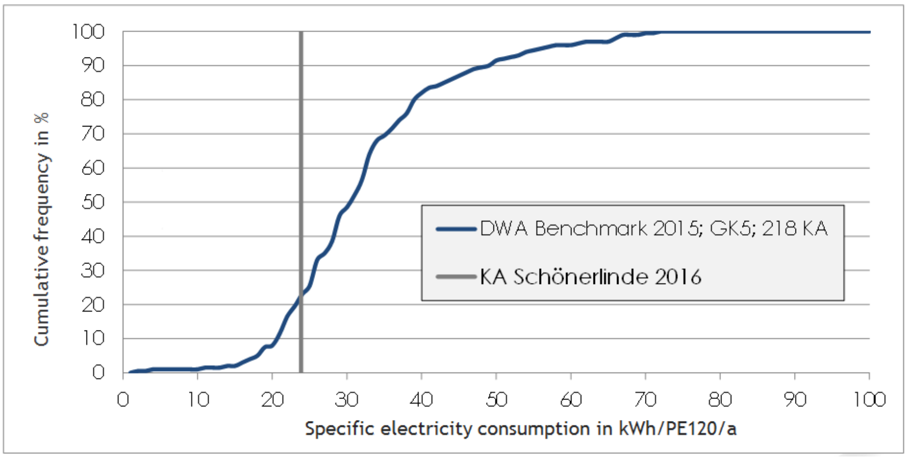


Figure 5: Specific electricity consumption of Schönerlinde compared to DWA benchmark

As shown in the figure above, the specific electricity consumption of Schönerlinde is comparable to the 20% best plants in the DWA benchmark **Es ist eine ungültige Quelle angegeben.**. Only 43 WWTPs are better performed than this plant.

The result of thermal energy efficiency is shown in Table 3.

Table 3: Thermal energy efficiency of the selected WWTP

Thermal energy comsumption		***Standard range***	
WWTP total [kWh/PE120/a]	13,15	***0,00***	***30,00***
sludge heating [kWh/PE120/a]	10,42	***8,00***	***12,00***
transmission loss, digester tower heating [kWh/PE120/a]	0,54	***0,00***	***4,00***
generation, storage and distrivution loss [kWh/PE120/a]	1,10	***0,00***	***2,00***
heat for buildings [kWh/PE120/a]	1,09	***0,00***	***2,00***

With regard to thermal EE, the selected treatment plant is also within the standard range. With a heat consumption of 13.15 kWh/PE120/a, the WWTP is also in the standard range for thermal EE, in the medium interval range. At this WWTP, excess heat is generated, which, however, is released unused to the environment due to lack of external consumers.

Considering the EE results, the Schönerlinde WWTP is energetically a well-performed WWTP. However, the energy costs of this plant can still be reduced by improving the EE of wastewater facilities' equipment and operations and by capturing the energy of the wastewater for electricity and heat generation.

Moreover, the integration of new technology such as a thermal hydrolysis stage, which increases the biogas yield during anaerobic digestion and reduces the overall digestate, could be a proper measure to generate more energy from the wastewater and thus to increase the energy self-efficiency (see section 6).

In the next step of the tool, the annual biogas production was compared to the amount of biogas production calculated in the tool. The comparison of biogas production with real data shows a 5 % deviation, which is acceptable.

5. Analysis of the WWTP spatial context

The spatial context of the WWTP and the presence of existing heat consumers, determine the potentials for an efficient integration of surplus heat into local energy supply concepts.

The urban compatibility assessment (UCA) can show the possibilities whether potential surplus/excess energy generated at the WWTP like excess heat and electricity can be utilized in the surroundings of the WWTP. The following figure (figure 6) demonstrates the location of Schönerlinde WWTP.

Figure 6: Visualization of WWTP Schönerlinde (google maps)

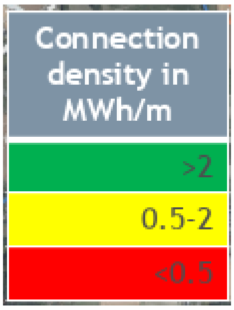
As shown in the figure above, there are not many costumers in the surroundings of this WWTP. After the rough analysis, a small village in the WWTP's surrounding was selected for this evaluation (red square). This village is approximately 2 kilometres away from Schönerlinde WWTP and has an area of approx. 450000 m2, which is equal to 45 hectares.

In order to calculate the urban compatibility in the REEF 2W, the external distance between consumers and WWTP should be assumed and entered into the tool. The closer the heat consumer is located to the WWTP the better. The next figure (figure 7) shows the estimated distance between both areas.

Figure 7: Visualization of distance between WWTP and heat costumer (google maps)

This gap between both areas is estimated at about 1.5 kilometers (external distance). The user can use the default value for internal grid connection in the selected area (network connection in the red square).

The result of this tool is shown in the connection density which is defined in MWh/m. There different cases for connection density can be distinguished:



- The value is higher than 2, which means a heat transport is energetically feasible. (green color)
- The value is between 0.5 and 2, which means a heat transport is still feasible, however; detailed analysis is needed. (orange color)
- The value is lower than 0.5, which means a heat transport is not feasible. (red color)

After inputting of data, the connection density is about 4 MWh/m, which is in green range. Therefore, a district heating network is a viable option connecting the WWTP and the adjacent residential area. In the further course of the analysis, in order to determine a final statement on feasibility, an economic evaluation is important.

6. Application of renewable energies and associated energy output improvements

From the REEF 2W technologies the following are considered:

- 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 criteria for selecting these technologies are their technological feasibility and their ability to increas EE and/or the share of RE. The integration of these technologies enables WWTPs to generate substantial amounts of energy which they can use on site, to the extent that they become self-sufficient and feed surplus energy into the grid. In general, from a technical perspective, it is possible to integrate all considered RE at the Schönerlinde WWTP. However, some of these technologies are not suitable due to following reasons:

- Hydroelectric plant: The installation of a hydroelectric plant is of no energetic interest to the WWTP Schönerlinde, as the topographical gradient of the effluent channel of the plant is too small, resulting in a low energy yield.
- Heat pump and solar thermal plant: As explained in the previous chapter, the WWTP Schönerlinde can already cover its heat demand with a CHP system and also has surplus thermal energy that is emitted into the environment, as there are no further possibilities for use on site and in the immediate vicinity for these surpluses (e.g. district heating). Therefore, a heat pump or a solar thermal plant for the availability of further thermal energy is not an energetically sensible option for the selected WWTP.
- Co-fermentation: The enrichment of sludge with bio-waste has been already tested at the Waßmannsdorf WWTP in Berlin. Due to several problems regarding economic efficiency of this technological solution and foam formation in the digester, BWB decided against the integration of this technology in the 6 WWTPs in Berlin. For this reason, this REEF 2W solution is not considered in the present study.

The remaining REEF 2W technology solutions are biogas upgrading, power-to-gas and thermal hydrolysis, for which the application at the Schönderline WWTP will be evaluated in this section. In the following, the selected technologies are briefly described.

6.1. Selected technologies

6.1.1. Thermal hydrolysis

Anaerobic sludge stabilization at Schönerlinde is performed by means of a digester. A major advantage of anaerobic digestion is that methane results as a byproduct of the process, which can be used as biofuel. In many cases, a WWTP can generate enough biogas to meet a part of the energy needs of a WWTP. Biogas is a renewable resource that can usefully be increased in view of the growing need for renewable energy and sustainability. Thermal hydrolysis is a technology that can increase the digestion performance by disintegration of sludge. The disintegration of sludge acts as a pre-treatment before anaerobic digestion. Objective is to destroy floc structure and with higher energy input to dissolve cell walls. This disintegration achieves the transformation of non-biodegradable organic substances into bioavailable ones resulting in higher degradation rates of the volatile substances. Result is an increased biogas yield.

6.1.2. Biogas upgrading

Using the energy in wastewater by burning biogas from anaerobic digesters in a CHP unit allows wastewater facilities to generate some or all of their own electricity and heat demand. However, there is an excess of heat energy, especially in summer due to a lower heat demand of the WWTP resulting from weather conditions. Heat is usually produced in excess at a WWTP, but most of the time, the excess is lost due to the location of WWTPs which are too far away from potential external consumers. Therefore, a complete upgrading of the digester gas and feeding into natural gas pipelines 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 thus can replace it by providing a carbon-neutral form of energy. It is possible to produce fuel quality biomethane for an existing CNG fleet. Producing the biomethane and biofuel can enhance the image of the operator and may set trends for a main biogas utilization with higher technology standard than simply burn biogas in CHPs.

6.1.3. Power to Gas

With the Urban Development Plan for the Climate (StEP) approved on 31 May 2011, Berlin started to fit the city for the future. The following main goals were defined for Berlin:

- Reduction of carbon dioxide emissions by 85 percent by 2050 (reference year 1990)
- The city of Berlin becomes climate-neutral by 2050 (EWG Bln)

Berlin's climate policy demands for not only electricity generated from RE, but also other climate-neutral energy sources such as biomethane for the mobility, heating and industrial sectors.

Power-to-gas technology is a promising option for Berlin as the city is an urban area that lacks many possibilities for biogas production.

As mentioned above, the WWTP Schönerlinde has already three wind turbines. A power-to-gas module could capture and store electricity from these turbines. The storage of generated hydrogen from the Power-to-Gas unit would take place in the natural gas grid so that generation and consumption of RE can be decoupled. However, the injection of hydrogen into the natrual gas grid is limited up to maximum of 9 % of hydrogen share (DVGW 260). Therefore, a subsequent methanation of the hydrogen would be an appropriate measure. For this, carbon dioxide and the produced hydrogen are converted into CH_4 via biological reaction. The carbon dioxide for this process can be taken from various sources at a WWTP e.g. from biogas upgrading. Furthermore, the very pure oxygen stream, which is generated as a side product during electrolysis, can be used

to save on aeration costs during the aerobic biological treatment stage. Due to the higher oxygen content than ambient air, less electrical energy is required for the blowers to achieve the same oxygen content in the water.

6.1.4. Renewable Energies

Photovoltaic (PV) power plant and hybrid collectors are particularly suitable to install at this WWTP, as both technologies can generate electricity, which could lead to electric energy self-sufficiency. As already mentioned, there are three wind turbines, each with an output of two megawatts at the WWTP plant Schönerlinde. In order to conduct a comparative analysis of renewable energy consumption in the tool, the area needed for one wind turbine (approximately 350 m2) is used in the tool to evaluate the energy performance of other renewable energies (photovoltaic and hybrid collectors) **Es ist eine ungültige Quelle angegeben.**. Using the same area makes it possible to compare these renewable technologies with each other.

6.2. Evaluation of techologies using REEF 2W tool

6.2.1. Photovoltaic power plant vs. hybrid collectors

This section provides a brief analysis on the comparison of renewable energy use in the tool. To compare the results, the area of 350 m2 was used for all two technologies (photovoltaic and hybrid collector). In the first part, two renewable energy technologies are compared with the status quo. The changes in energy generation are shown in the following figures.

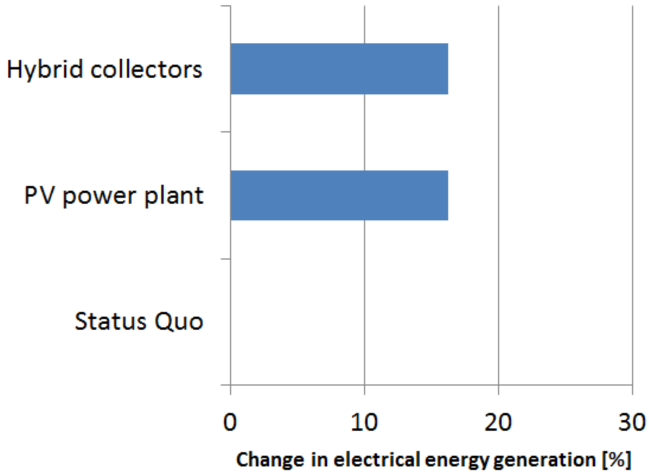


Figure 8: Comparison of electrical energy generation with status quo

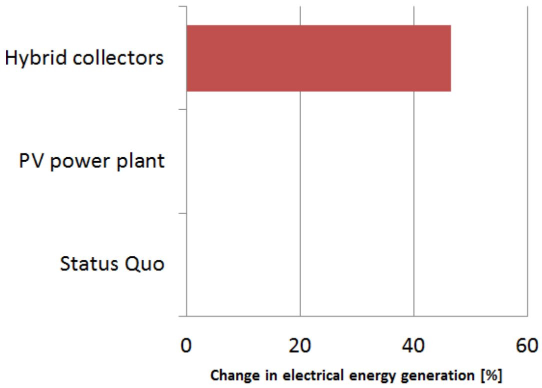


Figure 9: Comparison of thermal energy generation with status quo

As shown in Figure 8, using a photovoltaic power plant or hybrid collectors increases the electricity generation as well as electric self-sufficiency of the WWTP by 16 %. In addition, the hybrid plant increases the thermal energy generation by 45 % (see Figure 9), which, however, cannot be used on site as explained in previous sections. The following Figure 10 shows the decrease in energy demand of the WWTP Schönerlinde using PV plant or hybrid collectors, which is 16 %. Therefore, the integration of a photovoltaic plant could be a good option from an energetic point of view. However, in order to make a final overall stantement on the integration of both technology solutions at the WWTP Schönerlinde, both technological solutions must be further analysed with regard to their economic and ecological advantages and disadvantages.

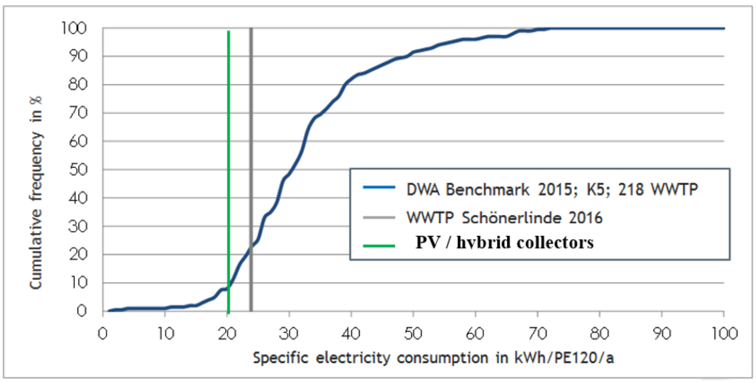


Figure 10: Specific electricity consumption of Schönerlinde WWTP

6.2.2. Thermal Hydrolysis

The hydrolysis step will enhance the biogas yield. The thermal hydrolysis stage is integrated into REEF 2W tool. The user can select between two options: Thermo-chemical (65 °C) and Thermo-pressure (165 °C). The following figure (Figure 13) shows how the gas generation of the WWTP could be changed if this technology is integrated into the selected plant.

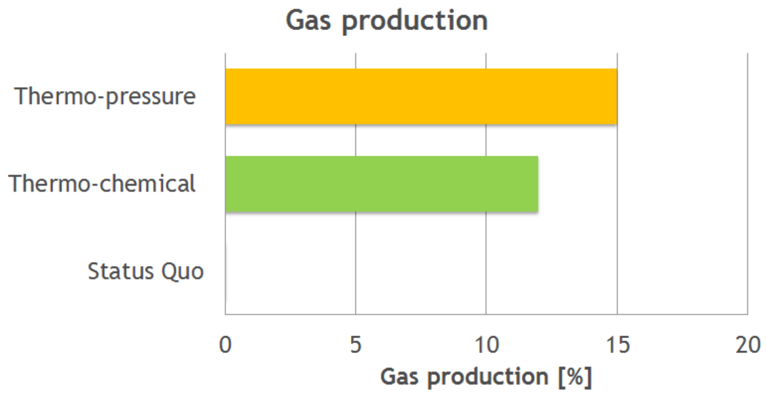


Figure 11: Comparison of biogas production using different thermal hydrolysis technologies

Figure 11 compares the biogas generation using thermal hydrolysis in the selected WWTP. Compared to the status quo, biogas generation in the digester is increased by up to 12 % through the use of thermo-chemical hydrolysis and up to 15 % through the use of thermo-pressure technology. Both technologies can be installed at the WWTP at the Schönerlinde WWTP.

From an energetic point of view, the thermo-pressure technology requires approximately 1.7 times more electrical and thermal energy than the thermo-chemical hydrolysis. However, the thermo-chemical hydrolysis requires on the other hand the addition of chemicals for disintegration of sludge. The next Figure 12 shows the improvement in the energy performance of the WWTP Schönerlinde by integrating a thermo-chemical process.

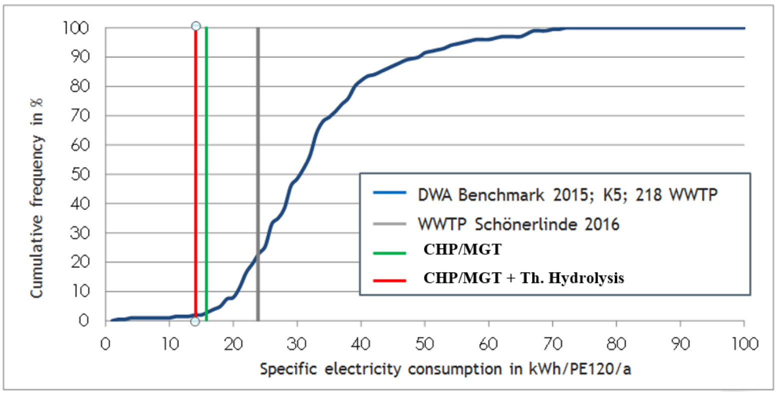


Figure 12: Change in specific electricity consumption (thermal hydrolysis)

The biogas produced in Schönerlinde is already combusted in a CHP unit and MGTs and generated energy is directly used in the WWTP. Thermal hydrolysis can increase the digestion performance by disintegration of sludge. The result is a higher biogas yield from sludge and an increase in energy efficiency and energy generation. Therefore, the generation of electrical energy can be increased up to 6% (see figure 12).

To sum up, the choice of the right hydrolysis options depends on the operator and specific condition of a WWTP.

6.2.3. Biogas Upgrading

As mentioned before, using the energy in wastewater by burning biogas from anaerobic digesters in a CHP unit and micro gas turbines allows wastewater facilities to generate some or all of their own electricity and heat demand. To avoid the energy loss, biogas can be upgraded to biomethane, which enhances its quality through a separation process. Upgrading unit separates the raw biogas into a methane-rich product stream and a CO2-rich offgas. Four main separation technologies are implemented in REEF tool and can be selected: pressure water scrubbing (PWS), pressure swing adsorption (PSA), membrane and cryogenic. The energy consumption of four upgrading technologies is calculated in the tool and the results are shown in figure 13.

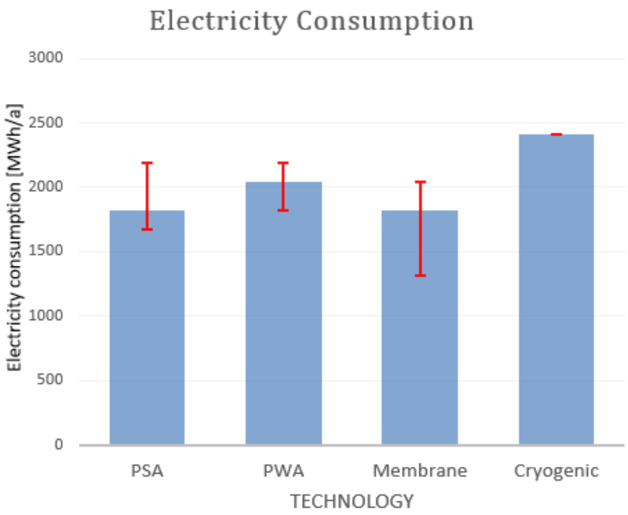


Figure 13: Comparison of electricity consumption of all four technologies

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. The investment costs for this system (capacity: 850 m3 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 less costly option. It is even cheaper than CHPs which need to be overhauled roughly at latest every 10 years.

Biogas upgrading and feeding into the gas grid enable biomethane to be used independently of time and place. Biogas upgrading is an energetically efficient way of using digester gas, as no excess thermal energy is released compared to the current situation at the WWTP Schönerlinde. Moreover, the biogas upgrading technology can compete with the gas engines in a WWTP due to legal changes (Renewable Energy Act, Combined Heat and Power Act). This technology is more economical for new investment projects due to its low investment and operating costs. However, when upgrading the entire biogas stream, the plant operator must cover the total energy demand by external suppliers.

Therefore, a combination of a CHP plant and a biogas upgrading technology is an energetically efficient way to utilise digester gas, to cover part of the electrical energy demand and to reduce the excess heat from CHP unit.

6.2.4. Power-to-Gas

Two megawatt PtG plant was selected in the second scenario. This plant can produce around 3 Mio. cubic meters of hydrogen per year (assumption: electrolyser works under full load and consumes 16 GWh of electricity). 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 cubic meter CO2 (about 20% of total CO2 in biogas) can be captured and converted into biomethane (750,000 m3). 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 (i.e. pumped storage power).

Nevertheless, the economy of power-to-gas also depends on the available electricity as well as the law and regulations. Government incentives such as direct and indirect subsidies could make this technology interesting in the future.

Regarding the environmental assessment, the carbon foot print of this WWTP can be decreased per m3 of biomethane production (assumption: excess electricity is used for PtG), since the generated biomethane replaces the natural gas in the gas network. The CO2 credits generated with 750,000 m3 of biomethane amounts to 1800 tonnes of carbon dioxide equivalents. In addition, 20% of CO2 in biogas is captured in the methanation process.

6.3. Discussion & 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 from the WWTP Schönerlinde were not available for comparison. The evaluation of the energy performance of the case study site as well as the gas production and consumption were simplified. The results of the first part of this Feasibility Study show that the Schönerlinde WWTP is energetically within the defined energy efficiency range. However, the energy costs can still be reduced by improving the EE of wastewater facilities' equipment and operations and by capturing the energy in wastewater to generate electricity and heat. Furthermore, it could be shown, that the calculated amounts of biogas in the tool correspond the real production at the case study site, which proves that the tool works correctly. The the results of the first part are acceptable and sufficient for the first analysis. However, the outcomes are not adequate for precise planning, as all calculations are based on monthly and annual averages. In order to be able to calculate precise energy production of renewable sources, at least the daily weather data are necessary. In addition, the weather-related availability of renewable energies (intermittent availability of sun and wind) is neglected on monthly and annual averages. The second part of the tool compares and evaluates the combination of different renewable energy technologies in the selected WWTP. The result shows that a solar plant could improve electrical energy self-sufficiency. Two other technologies (solar thermal plant and heat pump) increase the thermal energy generation, however; the selected WWTP has already enough heat from the CHP system. These two technologies would be interesting if customer for the heat surpluses exist. The use of renewable energy technologies in the Schönerlinde WWTP can improve the energy self-sufficiency and increase the potential to become energy-neutral. However, the integration of these technologies is highly dependent on various factors such as available space, investment costs, and energy demand. Due to the results, thermal hydrolysis can boost the biogas generation and hence energy generation. Upgrading of biogas to biomethane and its injection into natural gas grid allow the highest efficiency levels to be achieved, both in the generation of electricity and in direct heat utilisation. This practice is mature enough and commercially available. The last technology evaluated in this analysis was power-to-gas. This technology can be used to enhance the biomethane production and to use the excess power from RE technologies.

Comparing the result of both parts of the tool indicates that the integration of RE and REEF 2W solution concepts such as thermal hydrolysis has the potential to lead the case study site to energy neutrality.

7. ISA of pilot in the region of Prague

7.1. Pilot and applied REEF 2W technology specification

The integrated approach envisioned in REEF 2W encompasses a wide range of technological steps and processes. Except the enrichment of sludge through bio-waste to enhance biogas yields, many of them are realized at Schönerlinde. The steps will be established to increase the biogas yield through hydrolysis and to convert biogas into bio-methane. Additionally, facilities will be installed to take lower-value electricity from the grid turning in order to turn it into hydrogen, which will be used together with carbon dioxide from biogas upgrading for generating additional bio-methane. (Figure 14)

Currently, the produced biogas is stored in two gas containers and used for drying the sewage sludge, for heating purposes and for power generation.

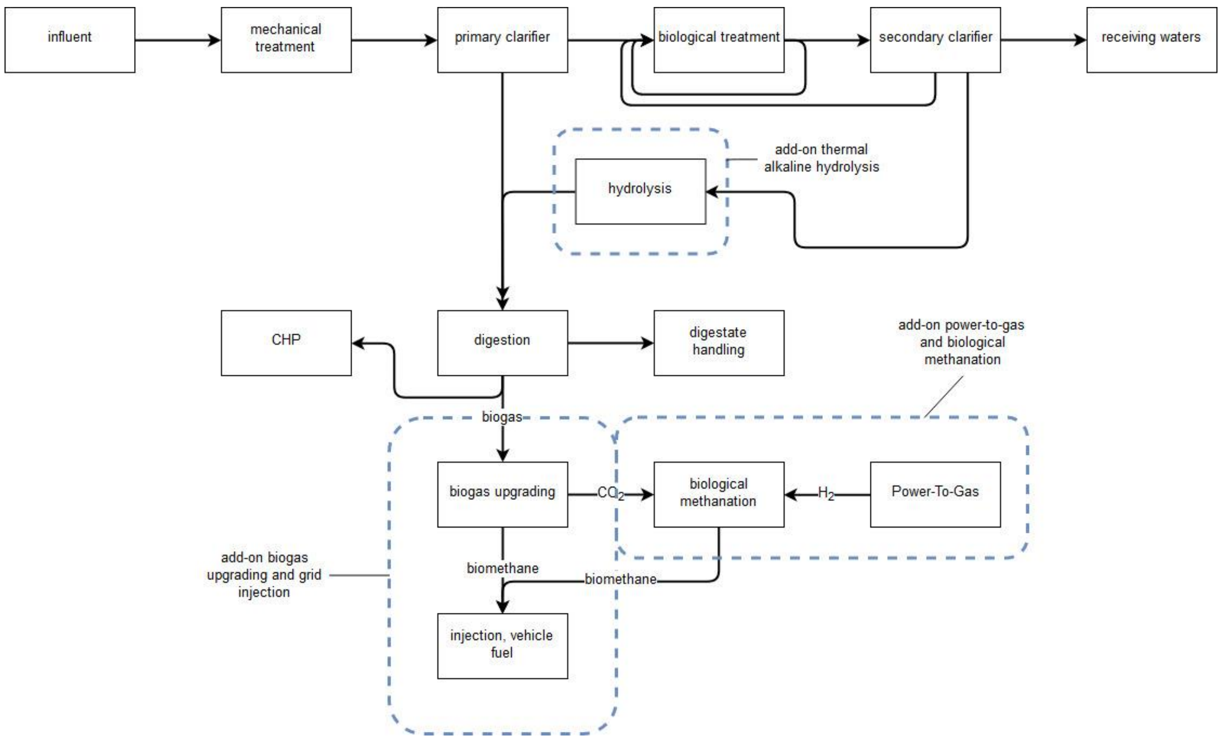


Figure 14: schemata of the new pilot site including the new REEF 2W technologies

<u>Thermal Hydrolysis</u>

The new pilot site will incorporate a thermal hydrolysis stage which will receive a part or the complete flow of the separated sludge from the primary clarifiers to increase the biogas yield during anaerobic digestion and reduce the overall digestate.

<u>Biogas Upgrading</u>

A biogas upgrading unit will receive the biogas produced during anaerobic digestion and upgrade it into bio-methane. 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 of the wastewater or can be used for the prospective ozonisation step as fourth treatment stage.

Grid Injection

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

7.2. General indicator evaluation

In this chapter, the status quo of selected WWTP in Berlin was compared with the implemented REEF 2W technologies. For this pre-assessment, the following cases were selected:

Status quo: the WWTP as described in the previous section

Scenario I: integration of thermal hydrolysis for production more biogas in status quo

Scenario II: integration of biogas upgrading (biomethane injection)

Scenario III: integration of biogas upgrading and PtG technology (biomethane injection)

The pre-assessment was done by software tool N1 and N2 and the result are shown in table 4.

Table 4 : General indicators used for the pre-assessment

Sustainability criteria	General indicator	Measurement	Categories	Graduation	Status Quo	REEF 2W S I	REEF 2W S II	REEF 2W S III
Availability of excess energy (Software tool N.1)	Electric excess energy provision	Difference between electric energy production and consumption in kWh	> 0 ≤ 0	A B	A	B	B	B
	Thermal excess energy provision	Difference between thermal energy production and consumption in kWh	> 0 ≤ 0	A B	A	A	B	B
	Excess digester gas provision	Difference between digester gas production and consumption in m^3	> 0 ≤ 0	A B	B	B	A	A
Availability of energy consumers (Software tool N.2)	Excess electricity demand	Electricity demand in the vicinity of the WWTP and in kWh	> 0 = 0	A B	A	A	A	A
	Excess heat	Heat demand in	> 0	A	B	B	B	B

	demand	the vicinity of the WWTP and in kWh	= 0	B				
	Excess digester gas demand	Digester gas demand in the vicinity of the WWTP and in kWh	> 0 = 0	A B	A	A	A	A

As shown in the table above, there is an excess of heat energy in the status quo, especially in summer due to a lower heat demand of the WWTP and overproduction in CHP system. This heat surplus is emitted in the environment, since there are not potential heat consumers and the relevant heat supply network in the vicinity of the WWTP. In the REEF 2W (SII and SIII) scenarios, there is no excess heat. Besides, the potential surplus biomethane generated at the WWTP can be utilised in the surroundings of the WWTP. However, the external electricity demand is increased in both scenarios.

7.3. Specific indicator evaluation

As explained before, the implementing the REEF 2W technologies (here in Berlin case) changes the energy flows (electric and thermal energy demand and /or production). In the table below (table 5), the status quo of the selected WWTP was compared with REEF2W scenarios. The comparison includes a set of indicators, which are split into four types: environmental, social, economic and technical.

Table 5: The comparison of sustainability criteria

Sustainability criteria	Indicator	Measurement	Categories	Graduation	Status Quo	REEF 2W SI	REEF 2W SII	REEF 2W SIII	Weight
Environmental context	CO_2 emissions reduction for consumed electric energy (internal and external)	%	> 0 = 0	A C	A (79%)	A (95%)	C (0)	C (0)	0.2
	CO_2 emissions reduction for consumed thermal energy (internal and external)	%	> 0 = 0	A C	A (90%)	A (100%)	C (0)	C (0)	0.1
	Share of renewable electricity (internal and external)	%	> 100 100-0 0	A B C	B (82%)	B (90%)	C (0%)	C (0%)	0.2
	Share of renewable thermal energy (internal and external)	%	> 100 100-0 0	A B C	A (162%)	A (162%)	C (0%)	C (0%)	0.1
	Share of	%	> 100	A	External	External	External	External	

Sustainability criteria	Indicator	Measurement	Categories	Graduation	Status Quo	REEF 2W SI	REEF 2W SII	REEF 2W SIII	Weight
	renewable gas (external)		100-0 0	B C	C (0%)	C (0%)	B (100%)	A(105%)	0.3
	Sludge production change	Delta t DM / year	<0 0 >0	A B C	B	A	B	B	0.1
Social context									
	Affordable energy	%	Lower Same (+-10 %) Higher	A B C	B	B	B	B	0
	Number of applied technologies for electric energy provision (*Resilience*)	Quantity	3 1-2 0	A B C	B	B	C	C	0.2
	Number of applied technologies for thermal energy provision (*Resilience*)	Quantity	3 1-2 0	A B C	B	B	C	C	0.2
	Additional employment	Change of employment, job creation or loss	>0 0 <0	A B C	B	B	B	A	0.3
	Local environmental welfare	Indication of local welfare change	Positive Neutral Negative	A B C	B	A	A	A	0.3
Economic context	Return of Investment (ROI)	Years	<3 3-10 >10	A B C	B	B	A	C	0.4
	Additional income	€	>0 0 <0	A B C	B	B	B	B	0.3

Sustainability criteria	Indicator	Measurement	Categories	Graduation	Status Quo	REEF 2W SI	REEF 2W SII	REEF 2W SIII	Weight
	Energy costs saving	€	>0 0 <0	A B C	B	B	B	B	0.3
Technical context (energetic & spatial)	Degree of electric self-sufficiency	Ratio between electric energy production and consumption in %	>75 25-75 <25	A B C	A (84%)	A (95%)	C(0%)	C(0%)	0.2
	Degree of thermal self-sufficiency	Ratio between thermal energy production and consumption in %	>100 20-100 <20	A B C	B(95%)	A(105%)	C(0%)	C(0%)	0.2
	Degree of externally usable excess heat	Ratio between heat production and consumption in %	> 0 0	A C	C	A (40%)	C	C	0.1
	Degree of usable excess gas	Ratio between gas production and consumption in %	> 0 0	A C	C	C	A	A	0.3
	Electric energy consumption at WWTP	kWh/PE$_{120}$.a	< 20 20 - 50 > 50	A B C	B (29)	B (29)	B (29)	B (29)	0.05

Sustainability criteria	Indicator	Measurement	Categories	Graduation	Status Quo	REEF 2W SI	REEF 2W SII	REEF 2W SIII	Weight
	Thermal energy consumption at WWTP	kWh/PE120.a	<30 > 30	A C	A (14)	A (14)	A (14)	A (14)	0.05
	Electric energy generation at WWTP (with anaerobic stabilisation)	kWh/PE120.a	>20 10-20 <10	A B C	A (21)	A (24)	C (0)	C (0)	0.05
	Thermal energy generation at WWTP (with anaerobic stabilisation)	kWh/PE120.a	>40 20-40 <20	A B C	B 25.8	B (29)	C (0)	C (0)	0.05

The change in energy flow plays an important role for multi-criteria decision analysis (see next chapter). The increase / decrease in energy consumption and production affect directly the economic, ecological and technical criteria.

An important part of the above table is the weighting of the selected indicators.

7.4. Multi-criteria decision analysis (MCDA)

To have detailed information about specific parts of ISA (social, environmental, economic and technical) will be calculated separately and decision maker can use it for own analysis and decision (see chapter 8). The following formula was used for the evaluation of each criterion.

$$CI_{s,en,ec,tech} = \sum_{i=1}^{n} w_i \, u_i$$

where CI is the composite index of the ISA for social, environmental, economic and technical segment, w is value of indicator and u is weight of indicator. The result of each ISA criterion is shown in the following table (table 6).

Table 6: the result of multi-criteria decision analysis

Criterion	Composite Index (Status Quo)	Composite Index SI	Composite Index SII	Composite Index SIII
Environmental	2.8	2.8	4.2	3.6
Social	3	2.4	3.2	2.6
Economic	3	3	2.2	3.8

Technical	3.4	2.4	3.5	3.5

Considering the comprehensive technical, social and economic analysis, scenario SI (CHP + thermal hydrolysis) is recommended as the most sustainable and future-proof option for the selected WWTP. As shown in the table above, the scenario SI has the best composite index in these categories, which means, both technologies (CHP and thermal hydrolysis) could bring additional benefits in all views. From an ecological point of view, biogas upgrading will become more interesting in the future to contribute to climate policy. The net GWP is heavily influenced by the electrical consumption from the grid and its substitution depending on the used energy mix. Electrical energy generated by using biogas in the CHP unit (status quo) is more beneficial in GWP than the biomethane credits generated from the same amount of biogas (SII). Similarly, PtG (SIII) is not worthwhile in environmental terms, also because biogas use for electricity production is more beneficial than substituting natural gas in the grid.

It is also observed that a combination of PtG technology (SIII) in the selected WWTP offers the investor no advantage over the scenarios without this technology. This technology severely increases the investment risk. Currently, the lack of support scheme for this technology makes this concept uneconomical.

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