REEF 2W

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

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INDEX - TABLE OF CONTENTS

1

INTRODUCTION

INTRODUCTION

Overpopulation and climate change are two of the most pressing challenges the world faces. Due to population growth and industrialization, the energy demand has permanently increased in the last decades. In addition to the increase of energy demand, this also led to a high consumption of water resources and a major increase in industrial and urban wastewater and waste.

European Commission is aware that climate change and environmental degradation are an existential threat to Europe and the world. To overcome these challenges, Europe needs a new growth strategy that will transform the Union into a modern, resource-efficient and competitive economy, where there are no emissions of greenhouse gases by 2050; economic growth is decoupled from resource use and no person and no place is left behind. European Green Deal set by European Commission is planned to make EU's economy sustainable. This can be done by turning climate and environmental challenges into opportunities, and making the transition just and inclusive for all. European Green Deal provides an action plan for making Europe climate neutral by 2050, boosting the economy through green technology, creating sustainable industry and transport, cutting pollution. It is going to be funded through public and private finance. Nowadays, the economic, ecological, technical and political standpoints have a major impact on the wastewater and waste management in the different countries. Whereas lots of less developed countries still have serious problems with their municipal wastewater and solid wastes, many developed ones, such as the USA, Canada and European countries, have already implemented wastewater and solid waste management based on continuously advancing treatments standards. However, optimising the energy use is an ongoing challenge in this sector. In addition, recent years also show an increased interest in resource and energy recovery from wastewater and waste.

To be more specific on the energy relevant context of wastewater, the recast of Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources shall be briefly addresses and highlighted.

As written in Article 1, *"a common framework for the promotion of energy from renewable sources. It sets a binding Union target for the overall share of energy from renewable sources in the Union's gross final consumption of energy in 2030. It also lays down rules on financial support for electricity from renewable sources, on self-consumption of such electricity, on the use of energy from re-*

newable sources in the heating and cooling sector and in transport sector, or regional cooperation between Member States, and between Member States and third countries, or guarantees of origin, on administrative procedures and on information and training. It also establishes sustainability and greenhouse gas emissions saving criteria for biofuels, bioliquids and biomass fuels."

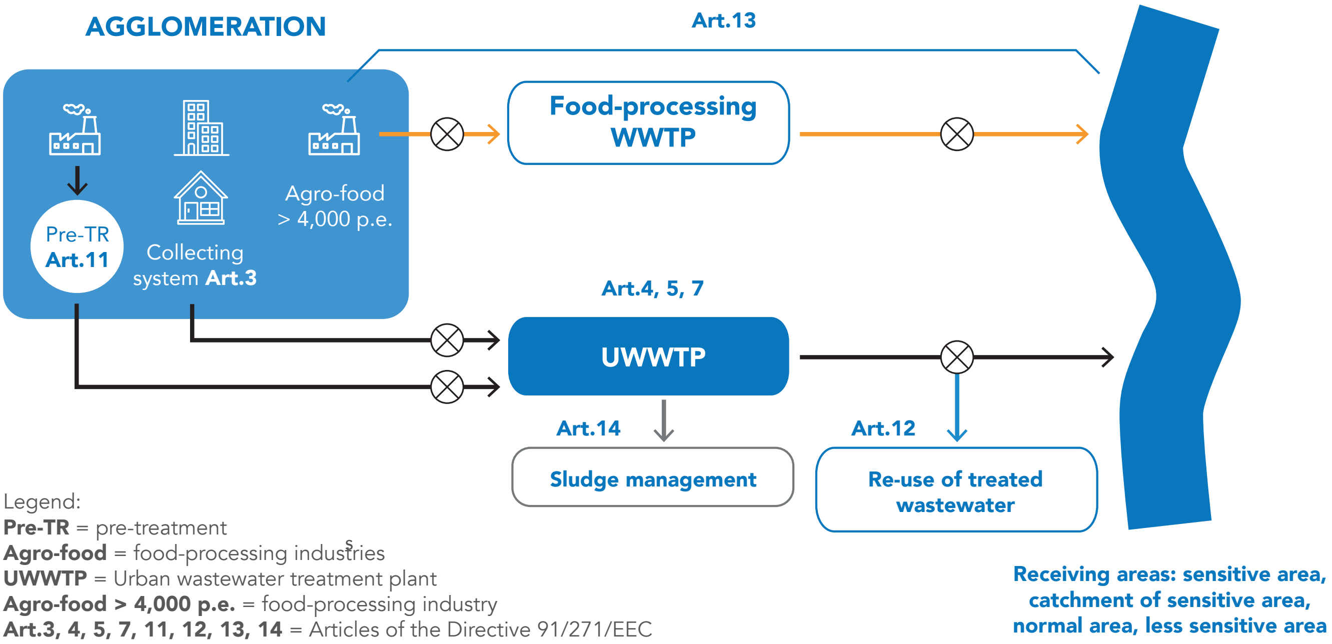
In Article 2 the Directive defines the different types of renewable energies:
Paragraph 1 states, that " *'energy from renewable sources' or 'renewable energy' means energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas;"*
Paragraph 2 concretise, that " *'ambient energy' means naturally occurring thermal energy and energy accumulated in the environment with constrained boundaries, which can be stored in the ambient air, excluding in exhaust air, or in surface or sewage water;"*

This means that both wastewater-based energies, the digester gas (biogas) as well as the recovered heat are (have to be) fully recognised as renewable sources of energy in the entire European Union. The same applies of solar energy generated at the premises of a wastewater treatment plant. Consequently, the recast of the Directive provides an excellent basis for a further promotion of the energetic use of wastewater. To better evaluate the available technologies and their impacts, the concept of Circular Economy has taken place during last decades. This concept can also be applied in both sectors to recover valuable nutrients like phosphate and nitrogen as well as energy.

The priority of a wastewater treatment plant (WWTP) is to treat the wastewater, which contains (apart from nutrients, pathogens, bacteria etc.) organic and inorganic substances, including harmless substances as well as toxic or endocrine disruption. The wastewater treatment steps are different from plant to plant and from country to country, and mostly depend on the level of impurities as well as law requirements (J. A. Nathanson and A. Ambulkar, 2018). At EU level a lot of laws directly or indirectly touch the field of wastewater treatment such as: starting from the Urban Wastewater Treatment Directive published in 1991 to one of the pillars of the water management in Europe, the Water Framework Directive from 2000; followed by other directives as the IPPC Directive, the Bathing Water Bodies Directive and much more. These regulations have been adapted into national legislation of each Member State. In Germany for example, the Federal Water Act is one of the most important laws. The following figure 1.1 shows an example of practical effects of the UWWT Directive in urban agglomerate and in an industrial site.

Figure 1.1

Example of practical effects of the UWWT Directive in urban agglomerate and in an industrial site (European Commission, 2019)



Legend:
Pre-TR = pre-treatment
Agro-food = food-processing industries
UWWTP = Urban wastewater treatment plant
Agro-food > 4,000 p.e. = food-processing industry
Art.3, 4, 5, 7, 11, 12, 13, 14 = Articles of the Directive 91/271/EEC

As mentioned above, the priority goal of a WWTP is to remove undesired wastewater contents (impurities) to reach an acceptable quality level (according to the regulations) before discharging it to a receiving (running) water body. Hereby, the fulfilment of legal requirements has a great impact on the energy demand of a WWTP. Wastewater treatment plants are the largest energy consumers in a municipality and often have key shares in the carbon footprint of municipalities and urban governments.

In Europe, the annual electricity consumption of WWTPs is estimated about 17 TWh (annual electricity generation of two large 1,000 MW power plants), that represent around 0.6 % of the total energy consumed in EU28 in 2016, but with large differences between the different countries. Concurrently, the chemical energy potential of wastewater in Europe is estimated about 87.5 TWh, which is five times higher than that annual annual electric energy consumption of all treatment plants (Cazalet, WP5 - Integration towards full plant concept, assessment and market replication, 2018). Recent research (Tarallo, Utilities of Future Energy Findings, 2014) shows that utilities are not only capable of becoming energy self-sufficient, but also suppliers of energy.

The combination of innovating technologies and improving energy efficiency at WWTPs can not only reduce energy consumption, but also greenhouse gases emissions. In

Germany, for example, the 10,000 WWTPs in operation produce around three million tons of CO2 per year (K. Fricke, 2009; Statistisches Bundesamt, 2015).

Also the waste sector in combination with WWTPs can play an important role in the sectoral coupling to produce renewable energy. Only in Germany 1,150 WWTPs are equipped with anaerobic digesters for sludge treatment and biogas production (B. Haberkern et al., 2006; U. Schließmann et al., 2018). As mentioned above, biogas produced by anaerobic digestion is a renewable energy carrier and can be deployed for the generation of heat and power or can be injected into the gas grid after an upgrading process. This "green" gas, called biomethane, can be used in the industry, transport, and energy sector. Compared to other renewable energy sources, such as wind and sun, biogas is independent from the weather and is available at all times. Therefore, it is of great interest to improve and increase biogas production by innovative processes such as co-digestion of bio-waste in the digester.

The project "Increased renewable energy and energy efficiency by integrating, combining and empowering urban wastewater and organic waste management systems" (REEF 2W) is funded by the INTERREG CENTRAL EUROPE Program and is carried out through 11 research institutes and wastewater utilities from Italy, Czech Republic, Germany, Croatia, and Austria (www.interreg-central.eu/Content.Node/REEF-2W.html). The goal of the project is not only energy efficiency, but also combining renewable energy sources in waste and WWTP to upgrade them in local energy cells. The members aim to develop a decision support tool that helps and informs operators of WWTP as well as decision makers who want to get a fast overview how efficient their treatment plant is and to identify benefits and drawbacks of combining new technologies at their plant from different perspectives, such as economical as well as ecological ones. Existing approaches often address only one criterion/aspect for analysis and assessment. In contrast, the REFF 2W approach is based on a multi-criteria evaluation using an Integrated Sustainability Assessment (ISA) methodology. It consists of two main evaluation areas and three subareas as follows:

- **Main parts:** Energy efficiency and renewable energies
- **Subareas:** Urban compatibility, Economic and environmental assessment

2

REEF 2W APPROACH

In the following chapter the basic concept as well as the different thematic aspects considered in the REEF 2W approach will be described.

BASIC CONCEPT

2.1

The energetic use of wastewater can be a rather complex task. Wastewater treatment plant (WWTP) internal use of digester gas-based electricity and heat can be considered as a rather simple and straight-forward approach. Consequently, it has been common practice at many WWTPs around the world for decades. In contrast, recent considerations concerning energy generation at WWTPs from additional (renewable) sources and the subsequent supply of WWTP external energy demands certainly require more holistic and integrated concepts.

The REEF 2W approach applies this new thinking by combining several perspectives:

- **Energetic context:** A first step addresses the identification of potential optimisation in the efficient use of electric and thermal energy as well as the identification of available (and so fare untapped) renewable energy sources at a WWTP. These evaluations provide an idea on surplus energy potentials production at a WWTP.
- **Spatial context:** A second step considers the energy aspects of the settlement structures in the surroundings of the investigated WWTP. The assessment of the urban compatibility integrates WWTP surplus energy generation and energy demand in the adjacent settlement structures. If both parameters, energy generation and demand, basically match, additional investigations can follow.
- **Environmental context:** A related third step then concerns the environmental (climatic) benefits of the intended WWTP renewable energy-based supply. This investigation addresses CO2 emissions of the investigated scenario.
- **Economic context:** The fourth step considers the economic aspects of the intended WWTP renewable energy-based supply. This investigation addresses the costs (for investment and operation) of the investigated scenario.
- **Integrated sustainability assessment:** The concluding fifth step combines the information collected during the four previous ones in an integrated sustainability assessment. Apart from energetic, spatial, environmental and economic indicators this assessment further includes additional social and technical parameters. The comparison of the different indicators with pre-defined scales allows a final evaluation of the intended WWTP renewable energy-based supply from a holistic and integrated perspective.

In the following chapters the key issues concerning the different steps/aspects will be presented in more detail.

ENERGETIC CONTEXT

2.2

2.2.1 Energetic efficiency at WWTPs

The energy consumption at common WWTPs (activated sludge technology) is manifold. Electric energy consumption primarily concerns the inflow pumping station, mechanical wastewater pre-treatment (e. g. automated screen cleaning), biological wastewater treatment (e. g. aeration), sewage sludge treatment (e. g. mechanical dewatering) and the operational/administrative infrastructure (e. g. offices).

Thermal energy is less diverse and concerns above all the sewage sludge treatment (e. g. sludge pre-heating, heating of the digester) and the heating of the operational/administrative infrastructure (e. g. heating of offices, hot water generation).

The basic principle for evaluating the current energy efficiency of a WWTP is the comparison of its electric and thermal energy consumption with standard ranges from Austrian literature (Lindtner, 2008). Tables 2.1 and 2.2 display the standard ranges for electric and thermal energy consumption of different WWTP processes and structures.

Hereby, standard ranges refer to population equivalents (PE) of 120 g COD per capita (P) and day.

Table 2.1

Standard ranges for electric energy consumption in Austria (Lindtner, 2008, adapted)

WWTP total	$kWh/PE_{120}/year$	Standard range	
		20	50
1. inflow pumping station and mechanical pre-treatment	**$kWh/PE_{120}/year$**	**2.5**	**5.5**
1.1 pumping station	$kWh/PE_{120}/year$	1.5	3.5
1.2 screening	$kWh/PE_{120}/year$	0.5	1
1.3 sand trap and primary clarifier	$kWh/PE_{120}/year$	0.5	1
2. mechanical-biological treatment	**$kWh/PE_{120}/year$**	**14.5**	**33**
2.1 aeration	$kWh/PE_{120}/year$	11.5	22
2.2 stirrers	$kWh/PE_{120}/year$	1.5	4.5
2.3 return sludge pumps	$kWh/PE_{120}/year$	1	4.5
2.4 miscellaneous (sec. clarifier)	$kWh/PE_{120}/year$	0.5	2
3. sludge treatment	**$kWh/PE_{120}/year$**	**2**	**7**
3.1 thickening	$kWh/PE_{120}/year$	0.5	1
3.2 digestion	$kWh/PE_{120}/year$	1	2.5
3.3 dewatering	$kWh/PE_{120}/year$	0.5	3.5
4. infrastructure	**$kWh/PE_{120}/year$**	**1**	**4.5**
4.1 heating	$kWh/PE_{120}/year$	0	2.5
4.2 miscellaneous infrastructure	$kWh/PE_{120}/year$	1	2

Table 2.2

Standard ranges for thermal energy consumption (Lindtner, 2008, adapted)

WWTP total	kWh/PE/year	Standard range	
		0	30
Sludge heating	kWh/PE/year	8	12
Transmission loss, digester tower heating	kWh/PE/year	0	4
Generation, storage and distribution loss	kWh/PE/year	0	2
Heat for buildings	kWh/PE/year	0	2
Heat for supply air unit	kWh/PE/year	0	10

2.2.2 Renewable energy generation at WWTPs

At a WWTP remarkable amounts of electric and thermal energy can be generated due to a large variety and quantity of suitable sources. In the following paragraphs an overview of the opportunities to generate energy at a WWTP is given. In the first part options for the generation of electricity are described, the second part is dedicated to thermal energy generation. Relevant formulas to calculate the potentials are listed in **Appendix 1.**

2.2.3 Electric energy generation

Digester gas combustion

Digester gas (biogas) is produced in digester towers under anaerobic conditions by applying a temperature of around 40 °C to the sewage sludge. In general, it is a mixture of about 62 % methane, 36 % CO2 and a variety of other gases (mainly H2 and H2S). The methane fraction can be used in the same ways as natural gas, bearing in mind that for some purposes the purity requirements are to be met. Digester gas can be used to generate electricity and/or heat inside the WWTP or outside at external combined heat and power (CHP) units. As an alternative, it can be fed into a gas grid when meeting quality thresholds, or it can used for mobility purposes (e. g. natural gas buses). Typically, only larger WWTPs have digester towers, today, due to economic reasons. Co-fermentation by adding mostly fluid organic waste to the sewage sludge can increase the gas output substantially. Today, the application of a CHP unit applied with digester gas used for combined heat and electricity generation is a wide spread state-of-the-art technology. With this energy certain amounts of the energy demand/consumption of WWTPs can be covered. Digester gas is considered as renewable energy.

Hydropower

Often there is a height difference between in the effluent of a WWTP which can be used for running small hydropower plants. However, although applied at certain locations, this approach is not very common yet.

Photovoltaics

Photovoltaics (PV) is a standard solution in the field of renewable energy generation. Although this type of energy generation is not wastewater based, it is an interesting option for WWTPs as there are often large suitable roofs or unused land areas available. Due to typically low feed-in tariffs a large fraction of self-consumption is preferable. Large consumers as aeration and stirrers can be timely adapted to the electric energy production (subject to the variability of solar irradiation during the day) to some extent.

Wind power

This type of energy generation is not wastewater based as well. However, the most suitable areas for large wind energy plants are those fulfilling the distance requirements which depend on the national or regional legislations. As many WWTPs are situated at a certain distance to other buildings (settlements), they can be a possible location for wind energy generation, in a smaller or larger extent.

In contrast, small wind energy plants can be installed on almost any WWTP site. The definition of small wind power plants depends on the peak load and the threshold is dependent on national or regional specifications. This WWTP application is also not very wide spread today.

2.2.4 Thermal energy generation

Digester gas combustion

Heat from digester gas combustion is a high temperature thermal energy source. Therefore, it makes sense to cover processes which require higher temperatures. Low temperature processes like heating of the digester tower (as it is common practice) shall in future rather be covered by low temperature sources as e. g. wastewater heat provided by heat pumps.

Wastewater heat recovery

The thermal energy output from the effluent (treated) wastewater is the largest thermal energy source at a WWTP. Wastewater normally has temperatures between 8 and 20 °C, mainly depending on the outside temperature, the type/mixture of wastewater (residential, industrial, etc.) and the considered location in the wastewater system. This source is mainly suitable for low temperature heat consumption (e. g. floor heating rather than radiators). Heat pumps can transfer the temperature to higher levels (theoretically up to about 100 °C), but ecologically and economically optimal concepts should not exceed 60 °C on average (also depending on the electricity costs and sources).

This thermal energy reservoir can either be used in the sewer system or in the effluent of a WWTP. At WWTPs all wastewater is concentrated on one point which makes large projects easier to realize and also more cost-efficient. Furthermore, the wastewater is treated which makes it easier to handle (e. g. heat exchangers). As a temperature reduction (due to in-sewer heat recovery) can positively affect the treatment performance of a WWTP, using the effluent as a heating source is advantageous. On the other hand, in many cases possible heat consumers are located closer to a sewer than to a WWTP. This makes the in-sewer solution more flexible and - if a certain building has to be supplied - easier to realize in many cases.

Solar thermal energy and hybrid collectors

As photovoltaics, these types of energy generation are also not wastewater based, but provide interesting options for WWTPs. Solar thermal collectors are a standard technology. As stated for PV plants, WWTPs can be a suitable place for implementing solar thermal collectors, e. g. roofs of offices, digestion towers and all other open and unused spaces. Hybrid collectors (PVT) are a combination of PV and solar thermal collectors. At the same collector surface there are PV cells and underneath a water cycle is using the waste heat to produce warm water. This enlarges the electric energy output and makes solar energy generation more space efficient. If a WWTP operator wants to establish the WWTP as energy supplier this aspect is of relevance. Still it must be stated that the heat output from the effluent is a lot higher and hybrid collectors produce low temperature heat (typically cooler than solar thermal plants).

SPATIAL CONTEXT

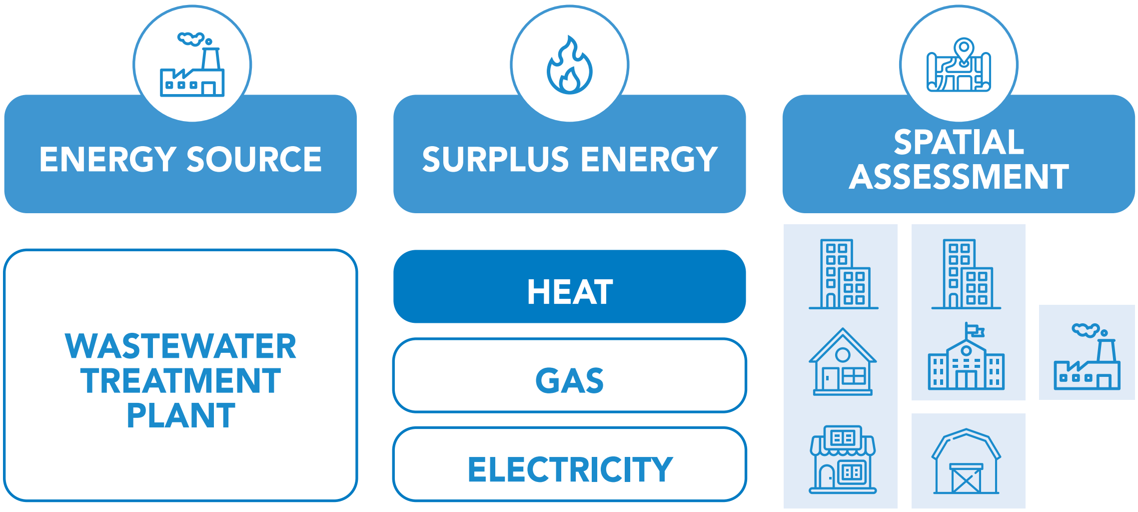
2.3

After assessing the energetic context of the WWTP and its surplus energy potentials, a spatial assessment of energy demand in the vicinity of the treatment plant can be followed. As demonstrated by numerous studies (Neugebauer et al., 2015, Kollmann et al., 2017 or Hao et al., 2019), thermal energy recovery from the effluent of WWTPs is a sustainable renewable energy source (RES) with promising potentials. Likewise, the European Parliament officially defined ambient energy from wastewater as energy from renewable sources (EU 2018). Compared to electricity or upgraded biogas, thermal energy is a RES that cannot be transported over large distances. Hence, suitable energy sinks (e. g. heat consumers in the form of settlements, comprising residential buildings or industrial areas) need to be identified and a district heating network (DHN) needs to be realised (Erker et al. 2019). Figure 2.1 shows the path from the energy source (WWTP), including different types of surplus energy, to potential energy consumers.

In the REEF 2W project, the following evaluations are referred to "spatial assessment", including the evaluation of heat demand and relevant infrastructure in the form of DHNs. In this context, spatially relevant analyses of energy demand and supply as well as corresponding infrastructure are part of the holistic scientific field of Integrated Spatial and Energy Planning (Stoeglehner et al. 2016).

Figure 2.1

Scheme for evaluating the utilisation of surplus energy via spatial assessment (own illustration)



As highlighted in Figure 2.1, the subsequent explanations refer to the utilisation of surplus heat in the adjacent settlements. Following the principal approach of Erker et al. (2019) and Hegger and Dettmar (2014), different types of heat consumers ("hotspots" of thermal energy consumption) have been elaborated in the REEF 2W project and are thus distinguished:

- **Village or town centres:** these hotspots are characterised by a variety of different functions, including residential use or service enterprises, comprising comparably high heat demand per unit area and a high amount of full load hours.
- **Multi-storey buildings:** characterised by a high heat demand compared to other types of residential buildings such as single-family houses or semi-detached houses.
- **Commerce and industry:** depending on the economic sector these areas are characterised with high heating and/or cooling demands.
- **Agriculture and forestry:** since many WWTPs are located next to agricultural or forestry areas, the conditioning of greenhouses or the drying of wood chips represent potential energy sinks (Neugebauer et al. 2015).

Additionally, a closer look is recommended on buildings managed by the municipality itself, since municipal buildings can serve as initial heat consumers and authorities are often interested to supply their "own" buildings with RES. The presented differentiation of thermal energy consumers or "hotspots" is also used in the REEF 2W tool (Lichtenwoehrer et al. 2019). Further results from other tools like the European "Hotmaps" (Müller et al. 2019) or "The Energy Mosaic Austria" (Abart-Heriszt et al. 2019) can support WWTP operators and other decision makers to identify potential heat consumers.

In order to supply settlements with renewable thermal energy from the WWTP, grid-bound supply infrastructure in the form of a DHN is required. Hence, existing road networks can be used as a vector for district heating planning. For more information on thermal energy system planning also see the European Union's Horizon 2020 research project THERMOS (https://www.thermos-project.eu/home/) and the Interreg Central Europe research project ENTRAIN (https://www.interreg-central.eu/Content.Node/ENTRAIN.html).

As implemented in the REEF 2W approach, potential supply areas (settlements representing thermal hotspots in hectares) serve as a basis in the spatial assessment. The representative settlements used in the REEF 2W approach can be found in **Appendix 2**.

A simple multiplication of the supply area with settlement specific heat demands (MWh/ha*year) results in the total annual heat demand (MWh/year). Since it is not common that all buildings within a settlement will connect to the DHN, a certain degree of connected buildings needs to be considered. Finally, the total annual heat demand divided by the estimated lengths of the DHN results in the so-called connection density in MWh/m*year. According to Nussbaumer et al. (2017), a connection density above 0.7 MWh/m*year is considered to be suitable for further considerations.

It can be summarised that the execution of a spatial assessment is essential in order to get an idea about potential heat consumers and corresponding requested infrastructure. The final result of the spatial assessment is an indication of whether thermal energy supply via district heating is feasible. In this way, the long-term orientation of the WWTP as an energy provider can be strategically assessed and planned.

ENVIRONMENTAL CONTEXT

2.4

"An environmental assessment is a procedure that ensures that the environmental implications of decisions are taken into account before the decisions are made."
(European Commission , 03/01/2019).

A suitable method to analyse the potential environmental impacts of products or processes and support those decisions is the approach of Life Cycle Assessment (LCA). Major features of an LCA are the wide perspective of analysis, including both direct impacts of the process, but also upstream and downstream impacts of associated systems (= the entire life cycle), and the quantitative relation to scenarios whose functions are equivalent. The outcome of the LCA can be used to compare potential impacts and highlight how those impacts will affect plants, soil, water and the climate. Therefore, it can help to develop more environmental-friendly products or systems (Yoshida & at el., 2014).

In this sub-chapter, the basics of LCA are briefly explained, and the implementation of LCA as environmental assessment into the REEF2W methodology is described in detail. According to ISO14040, the framework of LCA consists of the following four steps:

Step 1: Goal and scope definition
Step 2: Inventory analysis
Step 3: Impact assessment
Step 4: Interpretation

Step 1: Goal and scope definition

At the beginning of each LCA it is necessary to define the purpose and goal of the analysis; in other terms why the environmental impacts must be analysed. In this phase the intended target group of the planned LCA analysis will be defined (ISO 14040:2006).
An important aspect of this phase is the definition of the system boundary, which must be consistent with the goal of the study. The system boundaries determine which processes must be included in an LCA and which ones will be neglected (Remy, Corominas, & at el., 2017), (ISO 14040:2006). Other definitions relate to the functional unit of the LCA, and the analysed scenarios and underlying data quality.

Step 2: Life Cycle Inventory Analysis (LCI)

According to (ISO 14040:2006), the LCI includes data collection and calculation procedures to quantify relevant inputs and outputs of the system from or into the environment.
Within this phase, the input and output products as well as material needed for the process or product are balanced. This balance includes all emissions to air, soil or water streams occurring during the defined life cycle

stage (Remy, Corominas, & at el., 2017). Background processes such as electricity supply or disposal of waste are accounted for using datasets in LCA databases.

Step 3: Life Cycle Impact Assessment (LCIA)

According to (ISO 14040:2006), LCIA uses the results of the LCI (step 2) to assess the measures of environmental impact. Within this phase, the outcomes of LCI are connected with specific environmental impact categories and category indicators, using scientific models for fate and effect factors. The LCIA consist of three mandatory elements:

- **Selection of impact categories:** LCIA consists of different midpoints impact categories such as global warming potential, human toxicity, ozone depletion or acidification. In LCAs of WWTP systems, global warming potential (GWP), acidification and eutrophication receive most attention according to (Remy, Corominas, & at el., 2017).
- **Classification:** Each impact category is assigned to an adequate reference substance. For example, CO2 is selected as a reference substance in the impact category “global warming potential”, which is expressed in CO2-equivalents [kg CO2-eq].
- **Characterization:** Within a class, the impact of each substance flow is characterized with specific factors towards the reference substance. Adding up all characterized flows in one category gives the total indicator score for that impact category.

Step 4: Interpretation

The results of LCI and the LCIA are finally interpreted. The interpretation phase should reflect the goal and scope of the study.

According to (ISO 14044:2006), this phase of LCA consists of three steps:

- **Identification of the significant parameters** on the basis of the results of the LCI and LCIA
- **Assessment of study** taking into account completeness, sensitivity and consistency checks
- **Conclusions, limitations and recommendations**

The environmental assessment in the REEF 2W approach should enable a simple analysis of selected environmental effects of the REEF 2W schemes and their innovative approaches on the life cycle of a WWTP. This perspective can help to identify benefits and drawbacks of different scenarios in environmental terms. For the REEF 2W approach, the LCA focuses on the impact category of greenhouse gas (GHG) emissions or global warming. Hence, the LCA application assists users in using their own data to transform it into a source of valuable information on GHG emissions.

The LCA focuses on the impact category of anthropogenic climate change, calculating the indicator of global warming potential (GWP). The GWP refers to the equivalent amount of GHG released to the atmosphere from a process, which are expressed in terms of CO2 equivalents. GWP can be calculated over a specific time period of 20, 100, or 500 years, and the time period chosen for the REEF 2W approach is 100 years (GWP for 100 years as defined in IPCC report (IPCC, 2014)).

For each relevant process or energy carrier, specific GWP factors are implemented in the REEF 2W approach to account for the related GHG emissions. Two categories of GHG emissions are considered in the REEF 2W approach: GHG emissions associated with the use of energy carriers (e. g. grid electricity, natural gas, heat, etc.), and GHG emissions of other relevant processes such as disposal of sludge, use of chemicals, or the like. The GWP factors used for the REEF 2W approach originate mostly from the LCA database Ecoinvent v3.4 (Ecoinvent), but also from other LCA studies and models of previous research projects. An overview of these factors and indicators and their source is given in tables 1 and 2 in **Appendix 3.**

ECONOMIC CONTEXT

2.5

The economic assessment is a procedure that calculates potential costs and assigns values to expected benefits due to the implementation of REEF 2W technologies. It helps to understand the economic trade-offs between different alternatives in order to choose the best and most appropriate variations of the offered solutions for the wastewater treatment plant. The economic assessment used within the REEF 2W approach is based on a comparison of the initial (zero) state and future situation after application of innovative REEF 2W technology using cost analysis and possible incomes resulting from the application of REEF 2W technologies. General benefits arising from the implementation of this evaluation are: (i) an overview of potential future operating costs of newly introduced technologies and thus the possibility to plan future expenses and manipulate/optimize future costs; (ii) better awareness of the total investment costs for new technologies and therefore the ability to plan investments for these technologies; (iii) help with the decision to choose a new technology after comparing the results of economic assessment vs. the spatial context of WWTPs and the environmental assessment.

REEF2 W technologies affect the operation of wastewater treatment plants primarily in terms of energy production and energy savings. The economic assessment of these aspects is carried out through the evaluation of energy efficiency and potential renewable energy generation at the WWTP (chapter 2.2). Based on the comparison of these two chapters, the amount of energy that is additionally produced in the form of (a) electrical power, (b) thermal energy, and (c) biogas is quantified. The economic assessment for (a) electric power compares the initial and future situations. In the case of existing utilizable electric energy, it calculates potential income from selling the electricity into the grid. For utilizable (b) thermal energy, the spatial context of WWTPs and energy consumption in adjacent areas is determined (chapter 2.3).

A comparison between the current and the future situation, in this case, results in three possible scenarios; (1) thermal energy demand will be greater than production. It will, therefore, be assumed that all energy will be used and sold in the vicinity of the WWTP; (2) energy demand will be less than production. The part that covers demand for utilizable thermal energy will be assumed to be sold in the close area, and for the rest of the energy it will be up to the operator to use or dissipated it; (3) thermal energy production will be zero or less and thus no evaluation will be done. Biogas (c) is the main source of partial self-sufficiency in a WWTP. By implementing REEF 2W technologies, one can improve gas production, for example, by introducing co-fermentation of new substrates or by converting biogas to biomethane. After upgrading process, biomethane in composition is similar to natural gas; ergo it could also be fed into the grid. From an economic point of view, this will have an impact on the possible revenues/fees associated with receiving new substrates and will provide the operator with a new product for sale in the form of biomethane. The economic analysis will calculate the utilizable energies regarding the scenario which occurs with using prices of energies provided by the operator or predefined averages values to obtain a first insight on potential profits/expenses. For more accurate results, it is recommended to use the actual data available through the operator.

If the energy demand in the vicinity is not satisfied, and the operator decides to expand the WWTP with REEF 2W technologies, the investment and operating costs will be calculated. Investment and operating costs play a crucial role in determining whether to implement new technologies. The estimation of investment cost is not easy due to the wide range of REEF 2W technologies. Main issue is the difference in scale and capacity of projects, where the investment costs for individual technologies vary according to the manufacturer, type and local conditions.

Therefore, prices were processed based on benchmarking data obtained from respective manufacturers. The average prices were then related to specific units affecting the size of the technology. For example, for the investment costs of biogas treatment, the economic analysis is based on average prices for building upgrading units according to the amount of gas treated. Investment costs also consider the costs associated with project planning, where relevant. The REEF 2W solution will give the user a first insight into the possible investment costs related to any of the proposed technologies, which may, however, can also be partially different from the final prices depending on the actual conditions.

A similar procedure has been chosen when determining operating costs, where the benchmarking was more challenging due to variable costs, which can change over time with the number/amount of consumables. To determine operating costs, one has to assess the consumption of energy and reagents in the operation of individual technologies, depending on the size of the technology.

Operating expenses also include maintenance and service costs, where relevant. In some cases, the technology was not offered by industrial manufacturers, and so the investment and operating costs were determined following a survey of data available from the scientific literature. Like in case of investment costs, the operating costs may differ from the information from the manufacturer and experiences of Operator. The economic evaluation of operational costs is focused only on add-on technology implemented by REEF 2W.

After determining investment and operating costs, along with additional incomes/expenses related to the implementation of new technologies, it is possible to use economic indicators such as return on investment (ROI). ROI is one of the basic indicators for measuring rentability and efficiency when evaluating investment plans. The concept of return on investment in the economic evaluation of REEF 2W expresses the time in which the investment in new technology returns to the owner. It considers the offsetting of operating costs and other incomes from the treatment of new substrates or saving money for sludge disposal.

INTEGRATED SUSTAINABILITY ASSESSMENT

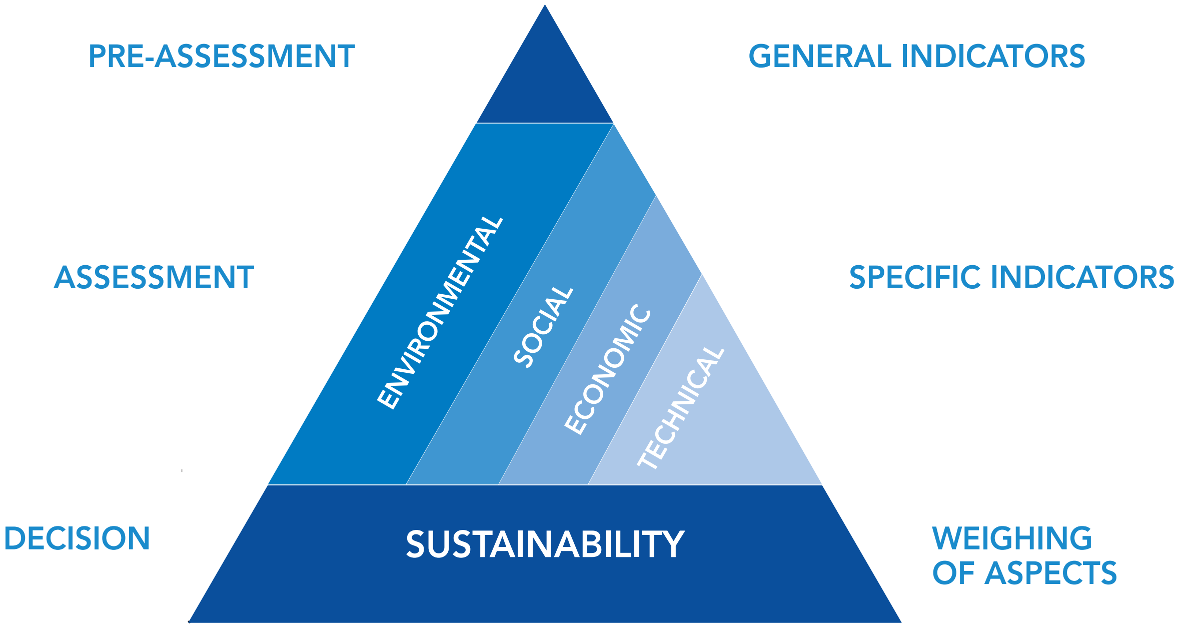
2.6

The previously described perspectives of the REEF 2W approach are now put together, in a specifically developed Integrated Sustainability Assessment (ISA). The main goal of the ISA is to identify sustainable alternatives and to avoid unsustainable solutions. In the context of sustainable development (Hacking and Guthrie, 2008), characterise sustainability assessment as strategic with a broad focus, covering all relevant topics of sustainable development and using a variety of integrated assessment techniques. Further Buytaert et al. (2011), urge to use multicriterial approaches for integrated sustainability assessments. Hence, the developed ISA follows these principles. The final assessment consists of a set of multiple indicators that can be used for multicriterial analysis in order to identify the most sustainable solution and to support decision makers towards sustainable development.

In particular, the starting point of the ISA are four distinguishable perspectives, as outlined in the basic concept of the REEF 2W approach: energetic, spatial, environmental and economic. The energetic context of the WWTP can be further split into energetic efficiency and renewable energy generation. The four perspectives require different assessment methodologies that were described in detail in the previous chapters.

Based on these four perspectives and following scientific approaches of sustainability assessments, a hierarchical procedure was used for the ISA (Stoeglehner and Narodoslawsky 2008). The hierarchical procedure includes two assessment levels. On the top of Figure 2.3 the pre-assessment level, consisting of general indicators, is sketched, followed by the actual assessment using specific indicators. More precisely, the pre-assess-ment level consists of energetic and spatial indicators. This hierarchical approach allows to filter “unsustainable” alternatives on the pre-assessment level. For specific indicators the well-established three-pillar approach, including environmental, social and economic indicators, was taken as a basis and was finally supplemented with technical indicators, as suggested by Wang et al. (2009).

Figure 2.3
Illustration of indicators from a pre-assessment to the final decision (adapted after Stoeglehner and Nardoslawsky 2008)



Hence, general indicators are followed by specific indicators which results in a weighing of aspects and the decision towards sustainability. The final set of indicators is summarised in **Tables 3.1 and 3.2.** In total six general, six environmental, five social, three economic and eight technical indicators were developed.

3

REEF 2W APPLICATION

DATA REQUIREMENTS, EVALUATION PROCEDURE

3.1

The following chapter is split into seven sections. The first section contains relevant indicators for the pre-assessment of sustainable REEF 2W solutions, whereas the second section provides a list of specific indicators that can be used for the Integrated Sustainability Assessment (ISA). With the final list of indicators, an ISA can be carried out in order to determine the most sustainable option. The following five sessions are dedicated to practical examples of the case studies description and evaluation.

3.1.1 General indicators for pre-assessment

In this first section a list of general indicators used for the pre-assessment in the REEF 2W context is presented (see Table 3.1). These indicators are in accordance with the first two evaluation steps of the ISA framework: energetic context and spatial context.

At first the energetic context is examined with respect to the degree of energy (electric and thermal) self-sufficiency. The next step is to evaluate the spatial context by assessing the degree of usable excess energy (electricity, heat and gas). On the pre-assessment level, annual values will be considered for the calculations.

Table 3.1

List of general indicators used for the pre-assessment

Sustainability criteria	General indicator	Measurement	Description	Categories	Graduation	Source
Availability of excess energy (Software tool N.1)	Electric excess energy provision	Difference between electric energy production and consumption in kWh	This indicator describes the amount of electricity provided by the WWTP in relation to consumed electricity	> 0 ≤ 0	positive negative	Own definition
	Thermal excess energy provision	Difference between thermal energy production and consumption in kWh	This indicator describes the amount of thermal energy provided by the WWTP in relation to consumed heat	> 0 ≤ 0	positive negative	Own definition
	Excess digester gas provision	Difference between digester gas production and consumption in m^3	This indicator describes the amount of digester gas provided by the WWTP in relation to the amount internally consumed	> 0 ≤ 0	positive negative	Own definition
Availability of energy consumers (Software tool N.2)	Excess electricity demand	Electricity demand in the vicinity of the WWTP in kWh	This indicator describes the electricity demand in the vicinity of the WWTP	> 0 = 0	positive negative	Own estimation
	Excess heat demand	Heat demand in the vicinity of the WWTP in kWh	This indicator describes the heat demand in the vicinity of the WWTP	> 0 = 0	positive negative	Own estimation
	Excess digester gas demand	Digester gas demand in the vicinity of the WWTP in kWh	This indicator describes the digester gas demand in the vicinity of the WWTP	> 0 = 0	positive negative	Own estimation

3.1.2 Specific sustainability indicators Integrated Sustainability Assessment (ISA)

The following list of indicators is split into four parts, including the three pillars of sustainability (environmental, social and economic) as well as technical indicators. The indicators are in accordance with the REEF 2W goals. Additionally, the calculated/estimated results are used to develop the final set of relevant sustainability indicators.
Social criteria are introduced because they are playing extremely important role at decision making process. The selected social criteria include following factors related to REEF 2W technologies introduction: potential of energy price decrease, increase of resilience and diversity of energy resources, additional employment and, as general umbrella indicator, the improvement of local environmental welfare including many further aspects.

The derived list of indicators defined in Table 3.2 is subsequently used for the execution of the ISA.

Table 3.2

List of indicators applicable for MCDA

Sustainability criteria	General indicator	Measurement	Description	Categories	Graduation	Source
Environmental context	CO_2 emissions reduction for consumed electric energy (internal and external)	kg CO2/kWh	This indicator compares the CO2 emissions of a current REEF 2W electricity supply scenario with a just fossil based supply of the investigated (REEF 2W) area (effect of substituting fossils by REEF 2W energy)	< 0.05 1.1-0.05 > 1.1	A B C	REEF 2W estimation
	CO_2 emissions reduction for consumed gas (internal and external)	kg CO2/kWh	This indicator compares the CO2 emissions of a current REEF 2W gas supply scenario with a just fossil based supply of the investigated (REEF 2W) area (effect of substituting fossils by REEF 2W energy)	< 0.22 > 0.22	A B C	REEF 2W estimation
	CO_2 emissions reduction for consumed thermal energy (internal and external)	kg CO2/kWh	This indicator compares the CO2 emissions of a current REEF 2W heat supply scenario with a just fossil based supply of the investigated (REEF 2W) area (effect of substituting fossils by REEF 2W energy)	< 0.12 0.23 - 0.12 > 0.23	A B C	REEF 2W estimation
	Share of renewable electricity (internal and external)	%	This indicator expresses the ratio between internal and external renewable electricity provision compared to total electricity consumption in the investigated (REEF 2W) area	> 100 100-40 < 40	A B C	REEF 2W estimation
	Share of renewable thermal energy (internal and external)	%	This indicator expresses the ratio between internal and external renewable thermal energy provision compared to total thermal energy consumption in the investigated (REEF 2W) area	> 100 100-40 < 40	A B C	REEF 2W estimation
	Share of renewable gas (internal and external)	%	This indicator expresses the ratio between internal and external biogas provision compared to total gas consumption in the investigated (REEF 2W) area	> 100 100-40 < 40	A B C	REEF 2W estimation
	Sludge production change	Delta t DM / year	This indicator expresses the change of amount of sludge produced in WWTP	< 0 0 > 0	A B C	REEF 2W estimation

Sustainability criteria	General indicator	Measurement	Description	Categories	Graduation	Source
Social context	Affordable energy	%	This indicator compares the current energy price (EU and national specific) with the price of provided energy from the WWTP	Lower Same (± 10 %) Higher	A B C	REEF 2W estimation
	Number of applied technologies for electric energy provision (Resilience)	Quantity	This indicator counts the total number of applied technologies for electricity provision at the REEF 2W WWTP (e.g. CHP, hydropower and PV)	3 1-2 0	A B C	REEF 2W estimation
	Number of applied technologies for thermal energy provision (Resilience)	Quantity	This indicator counts the total number of applied technologies for thermal energy provision at the REEF 2W WWTP (e.g. CHP, heat recovery and solar thermal)	3 1-2 0	A B C	REEF 2W estimation
	Additional employment	Change of employment, job creation or loss	This indicator counts the change of total number of employees related to introduced REEF technology	< 0 0 > 0	A B C	REEF 2W estimation Colijn B. (2014)
	Local environmental welfare	Indication of local welfare change	Examples of local welfare change: reduction of traffic, cheaper or renewable heat delivery, minimizing of odour production etc.	Positive Neutral Negative	A B C	REEF 2W estimation, (Hoi-Seong J., 2013)

Sustainability criteria	General indicator	Measurement	Description
Economic context	Return of Investment (ROI)	Years	This indicator considers the investment and operational costs of different technologies in ratio to financial benefits (additional income and cost savings) from an investment of some resources
	Additional income	€	This indicator considers additional income due to external sell of generated energy (electricity, heat and gas) at the WWTP
	Energy costs saving	€	Financial savings due to WWTP internal energy efficiency measures

Categories	Graduation	Source
< 3 3-10 > 10	A B C	REEF 2W estimation
> 0 0 < 0	A B C	REEF 2W estimation
> 0 0 < 0	A B C	REEF 2W estimation

Sustainability criteria	General indicator	Measurement	Description	Categories	Graduation	Source
Technical context (energetic & spatial)	Degree of electric self-sufficiency	Ratio between electric energy production and consumption in %	This indicator describes the percentage of electricity provided by the WWTP in relation to consumed electricity	> 75 25-75 < 25	A B C	REEF 2W definition
	Degree of thermal self-sufficiency	Ratio between thermal energy production and consumption in %	This indicator describes the percentage of thermal energy provided by the WWTP in relation to consumed heat	> 100 20-1 < 20	A B C	REEF 2W definition
	Degree of usable excess heat	Ratio between heat production and consumption in %	This indicator describes the percentage of available excess heat in relation to the heat demand in the vicinity of the WWTP	> 100 < 100	A C	REEF 2W estimation
	Degree of usable excess gas	Ratio between gas production and consumption in %	This indicator describes the percentage of available excess gas in relation to the gas demand in the vicinity of the WWTP	> 100 < 100	A C	REEF 2W estimation
	Electric energy consumption at WWTP	kWh/PE_{120}*year	This indicator expresses the electric energy consumption of the WWTP in kWh/PE.a compared to a standard range defined in literature	< 20 20 - 50 > 50	A B C	(Lindtner 2008)
	Thermal energy consumption at WWTP	kWh/PE_{120}*year	This indicator expresses the thermal energy consumption of the WWTP in kWh/PE.a compared to a standard range defined in literature	≤ 30 > 30	A C	(Lindtner 2008)
	Electric energy generation at WWTP (with anaerobic stabilisation)	kWh/PE_{120}*year	This indicator expresses the electric energy provision of all applied technologies (CHP, hydropower and PV)	> 20 10-20 < 10	A B C	(Lindtner 2008)
	Electric energy generation at WWTP (with aerobic stabilisation)	kWh/PE_{120}*year	This indicator expresses the electric energy provision of all applied technologies (Hydropower and PV)	> 0 0	A C	REEF 2W definition
	Thermal energy generation at WWTP (with anaerobic stabilisation)	kWh/PE_{120}*year	This indicator expresses the thermal energy provision of all applied technologies (CHP, heat recovery and solar thermal)	> 40 20-40 < 20	A B C	(Lindtner 2008)
	Thermal energy generation at WWTP (with aerobic stabilisation)	kWh/PE_{120}*year	This indicator expresses the thermal energy provision of all applied technologies (Hydropower and PV)	> 0 0	A B	REEF 2W definition

INTERPRETATION OF RESULTS

3.2

The complex ISA evaluation is based on determining sustainability indicators definition and using of these indicators for calculation of final composite index which is integrating all aspects of ISA.

Firstly, all indicators are normalized (dimensionless value score within the range of 1-5) to allow the comparison without scale effects (A=1, B=3, C=5).

Secondly, the indicators are aggregated in accordance with the relative importance of each indicator -see Table 3.3 -and then the composite index is calculated as follows.
To have detailed information about specific parts of ISA (social, environmental, economic and technical), these same will be calculated separately and decision maker will be able to use it for own analysis and decision.

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

where **CI** is the composite index of the ISA for social, environmental, economic and technical segment
w is value of indicator
u is weight of indicator
n is 6 for environmental indicators, 5 for social indicators, 3 for economic indicators and 6 for technical indicators.

Table 3.3
Indicators for MCDA and applied weight factors

Sustainability criteria	Indicator	Weight
Environmental	CO_2 emissions reduction for consumed electric energy (internal and external)	Defined by stakeholder, Range (0-1) so that the sum of the weights of all environmental criteria is equal to 1
	CO_2 emissions reduction for consumed gas (internal and external)	
	CO_2 emissions reduction for consumed thermal energy (internal and external)	
	Share of renewable electricity (internal and external)	
	Share of renewable thermal energy (internal and external)	
	Share of renewable gas (internal and external)	
	Sludge production change	
Social	Affordable energy	Defined by stakeholder, Range (0-1) so that the sum of the weights of all social criteria is equal to 1
	Number of applied technologies for electric energy provision (Resilience)	
	Number of applied technologies for thermal energy provision (Resilience)	
	Additional employment	
	Local environmental welfare	
Economic	Return of Investment (ROI)	Defined by stakeholder, Range (0-1) so that the sum of the weights of all economic criteria is equal to 1
	Additional income	
	Energy costs saving	

Sustainability criteria	Indicator	Weight
Technical/others	Degree of electric self-sufficiency	Defined by stakeholder, Range (0-1) so that the sum of the weights of all technical criteria is equal to 1
	Degree of thermal self-sufficiency	
	Degree of usable excess heat	
	Degree of usable excess gas	
	Electric energy consumption at WWTP	
	Thermal energy consumption at WWTP	
	Electric energy generation at WWTP (with anaerobic stabilisation)	
	Electric energy generation at WWTP (with aerobic stabilisation)	
	Thermal energy generation at WWTP (with anaerobic stabilisation)	
	Thermal energy generation at WWTP (with aerobic stabilisation)	

Two main possibilities exist for the evaluation team, for comparing the merits of the different interventions using scoring:

- multi-criteria analysis by compensation or
- multi-criteria analysis based on outranking.

Outranking does not always produce clear conclusions, whereas analysis based on compensation it is always conclusive. From a technical point of view, the compensation variant is also easier to implement. The most pragmatic way of designing the multi-criteria evaluation matrix is for the evaluation team to design scoring scales to all the evaluation conclusions, whether quantitative or qualitative. The multi-criteria evaluation matrix is then equivalent to the impact scoring matrix. Usually the compensation method is used unless members of the steering identify a problem which might justify the use of the veto system.

Therefore it was decided to use analysis by compensation, however for each case of innovative REEF 2W technology application must be identified if there are specific critetions which disqualify the technology to such extent that veto system needs to be used if they are ranked below certain threshold level.

CASE STUDY ITALY

3.3

3.3.1 Description of Treatment Plant

The Italian feasibility study was realized by the multi-utility Montefeltro Servizi S.p.A. servicing the area of High Valmarecchia (Figure 3.1), located between the regions of Tuscany and Marche, the Republic of San Marino and Emilia-Romagna, to which it belongs. The area has a low population density and includes seven municipalities.

Figure 3.1

The area of High Valmarecchia

Montefeltro Servizi provides environmental services for all the seven municipalities with a total population of about 17,000 inhabitants. At present, the company only manages the waste produced in the area and sorts and delivers it to specialised centres for the final disposal, whereas due to a recent change in the regional reorganisation of waste and wastewater management, the company is no longer involved in wastewater treatment.

The collected waste contains a large proportion of dry organic waste that cannot be used for anaerobic digestion and must be stabilized in the composting process. Composting is a well-known and energy-intensive process that in the specific case of Montefeltro Servizi is conducted in another plant several kilometres away from the collection point.

Table 3.4

Present annual waste collection

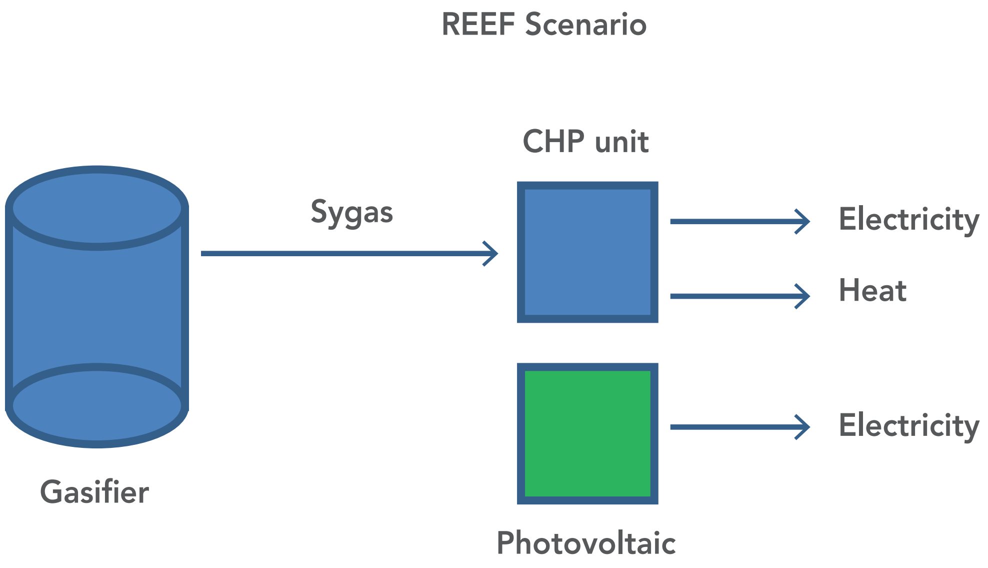
Type of waste	Tons per year
Undifferentiated municipal waste	5,100.00
Differentiated organic fraction	405.98
Prunings	261.51
Exhaust vegetal oil	1.58

3.3.2 Selected scenarios by REEF 2W decision support tool

Presently, there is no energy production at the treatment plants, against a total electricity consumption of about 17,247 kWhel./year and a total thermal energy consumption of about 22,400 kWhth./year, produced by using about 2,100 cubic meters of methane. The feasibility study realized showed that a marked improvement of the situation could be reached through the optimization of the collected biomass and its gasification, coupled with a photovoltaic plant. In fact, the most favourable scenario optimizes the quantity of biomass available for the gasification process integrating all the biomass available: the organic fraction of municipal waste, prunings deriving from the maintenance of public green and from mowing of brushwood along the banks of rivers, exhaust mushroom litter coming from an enterprise of the territory, the excess sludge of three small WWTPs.

Figure 3.2

The technological scheme of the status planned plants



3.3.3 Results and Discussion

Energetic point of view

The expected situation after the pilot implementation is completely different than the status quo: in the REEF 2W scenario, the production of about 1,070 MWhel. will allow Montefeltro Servizi to become from consumer to net producer of energy. In particular, the production of 19.52 MWh of electricity from photovoltaics will cover practically all its electricity needs, allowing to use the additional production of 1,050 MWhel. from biogas for other needs, whereas the production of about 1,200 MWh of thermal energy will cover all the plant needs in the absence of external users.

Economic point of view

From an economic point of view, the possibility to use on site the produced energy and the presence of incentive measures are key factors. In our case, the situation is even more favourable thanks to a specific measure provided by the Italian legislation called "scambio sul posto altrove" (exchange on the site elsewhere). Based on this regulation, public bodies can produce electricity in any place of the Italian territory and use it in any other place where the same public bodies have a utilization point. In our case, the place where the electricity will be produced, that is the Montefeltro Servizi treatment platform, is directly owned by the seven municipalities and the excess of electricity produced can be used by the same municipalities for all their electricity needs (public lighting, provide energy at schools, social centres, etc.). Under this conditions, the pilot plant can generate consistent savings for the cost of electricity for the seven municipalities of about Euro 189,000 per year, allowing an investment return time of 5 years.

Ecological point of view

The environmental assessment of the considered solutions shows a strong advantage in terms of reduction of carbon emissions. In the assessment, only the electric energy produced and eventually introduced in the grid has been considered. The reason for this choice is directly related to the spatial assessment done that reports a strong disadvantage for the use of heat. Consequently, considering only this aspect, more than 19,000 tons of CO2eq. could be removed, if the gasification of the biomasses can be applied.

3.3.4 Conclusion

The feasibility study for the pilot case of Montefeltro Servizi in Emilia-Romagna region showed that the implementation of a gasification plant, allowing the production of both electricity and heat using all available biomass, coupled with photovoltaic panels, could be highly beneficial even in case of very small multi-utilities serving dispersed communities. Table 3.5 shows how the REEF 2W implementation can improve the present situation (status quo) not only for a best composite index, but also under all the single aspects: environmental, social, economic, technical.

Table 3.5

The result of multi-criteria decision analysis

Criterion	Composite Index (Status quo)	Composite Index REEF 2W technology
Environmental	21	29
Social	9	21
Economic	5	9
Technical	15	29

CASE STUDY GERMANY

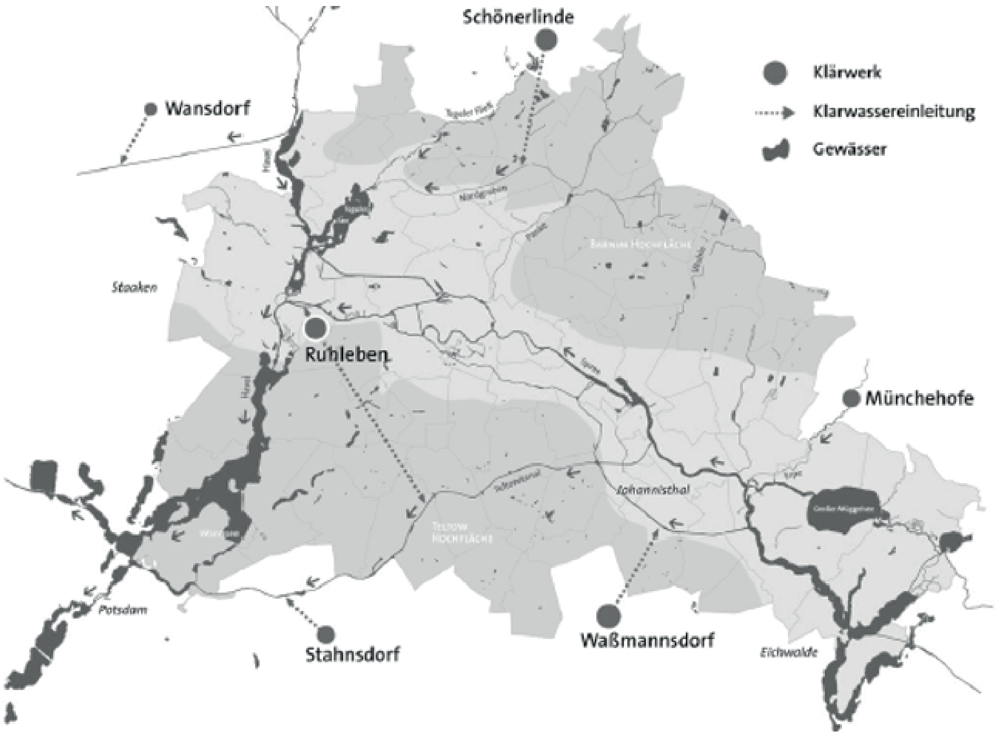
3.4

3.4.1 Description of Wastewater Treatment Plant

The selected WWTP is one of the six treatment plants in Berlin operated by the Berlin Water Works (Berliner Wasserbetriebe - BWB). The selected plant treats wastewater of approx. 230,000 m3/d (dry weather capacity) correlating to approx. 1.6 Mio. population equivalents as COD load (BWB, 2018).

Figure 3.3

Location of Berlin's WWTPs and effluent discharge points (BWB, 2019)



The plant uses a conventional approach with mechanical and biological treatment, nitrification and denitrification, biological phosphorus elimination, mesophilic digestion and utilization of biogas in CHPs for heat and electrical power generation.

3.4.2 Selected scenarios by REEF 2W decision support tool

For a first evaluation the REEF 2W decision support tool was used as described in **Appendix 5**. Based on the outcomes of this evaluation, three different scenarios (see Table 3.6) were selected for a more detailed analysis in the Berlin case study.

Table 3.6
Selected scenarios for detailed analysis after screening with REEF 2W decision support tool

Scenario	CHP	Biogas upgrading system	Electrolyser for PtG
Status quo (I)	6 MW	0 m^3/h biogas	0 MW
Scenario II	0 MW	1,800 m^3/h biogas	0 MW
Scenario III	0 MW	1,800 m^3/h biogas	7.8 MW

3.4.3 Results and Discussion

Energetic point of view

The detailed energy analysis was carried out with a dynamic model, developed by Kompetenzzentrum Wasser Berlin. The model was developed in Microsoft Excel due to its ubiquity, usability and portability of the created files.

Figure 3.4
Screenshots of user interface as well as results gained by the dynamic model

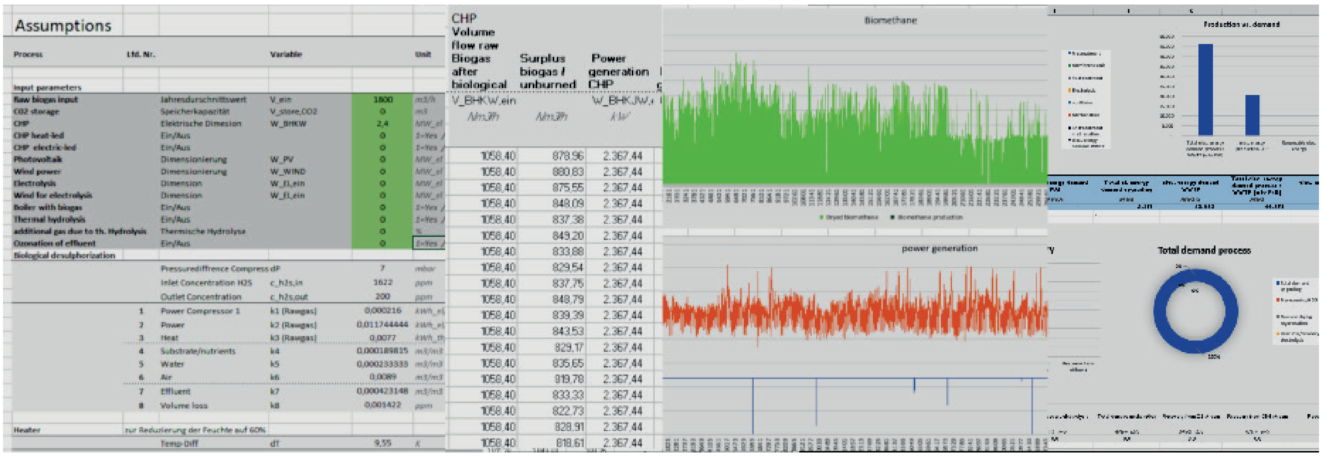
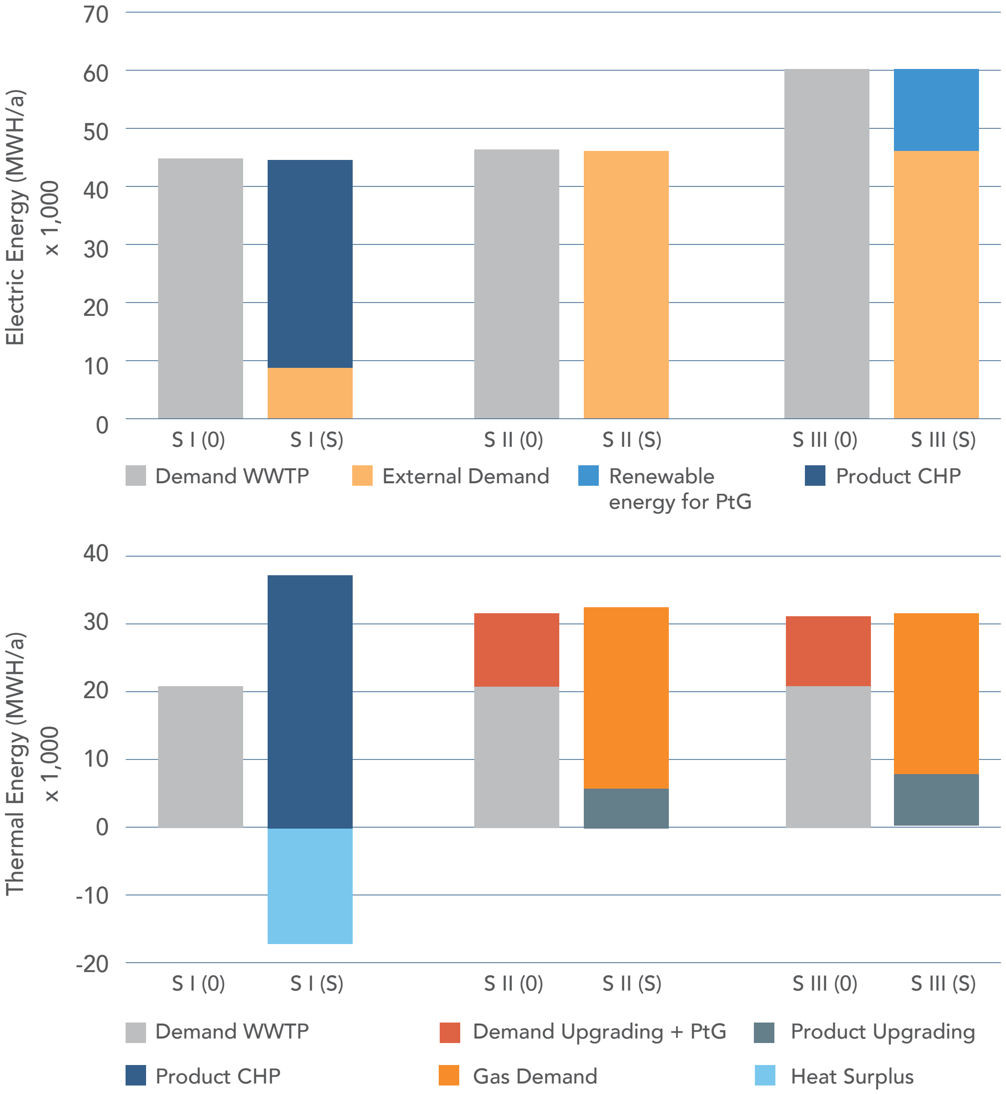


Figure 3.5 presents results regarding the electrical and thermal energy assessment by both demand and supply (internal or external). The comparison between demand and production of the three scenarios shows that the selected WWTP (SI) has 80% electrical self-efficiency, whereas for SII and SIII 100% of electricity has to be purchased externally from the grid to cover the total consumption.

Figure 3.5

Comparison of energy consumption (D), production and the external supply (S) of each scenario



Results given by the dynamic model regarding the thermal energy assessment are also presented in Figure 3.5. In scenario I, the WWTP produces excess heat of ≈ 15 GWh per year as waste heat due to a lack in external customers. Retrofitting the WWTP with technologies such as biogas upgrading or PtG in the future results in no excess heat. To close the overall heat balance between production and consumption at the WWTP, natural gas has to be purchased in amounts of ≈ 20 GWh per year for both those scenarios.

Ecological point of view

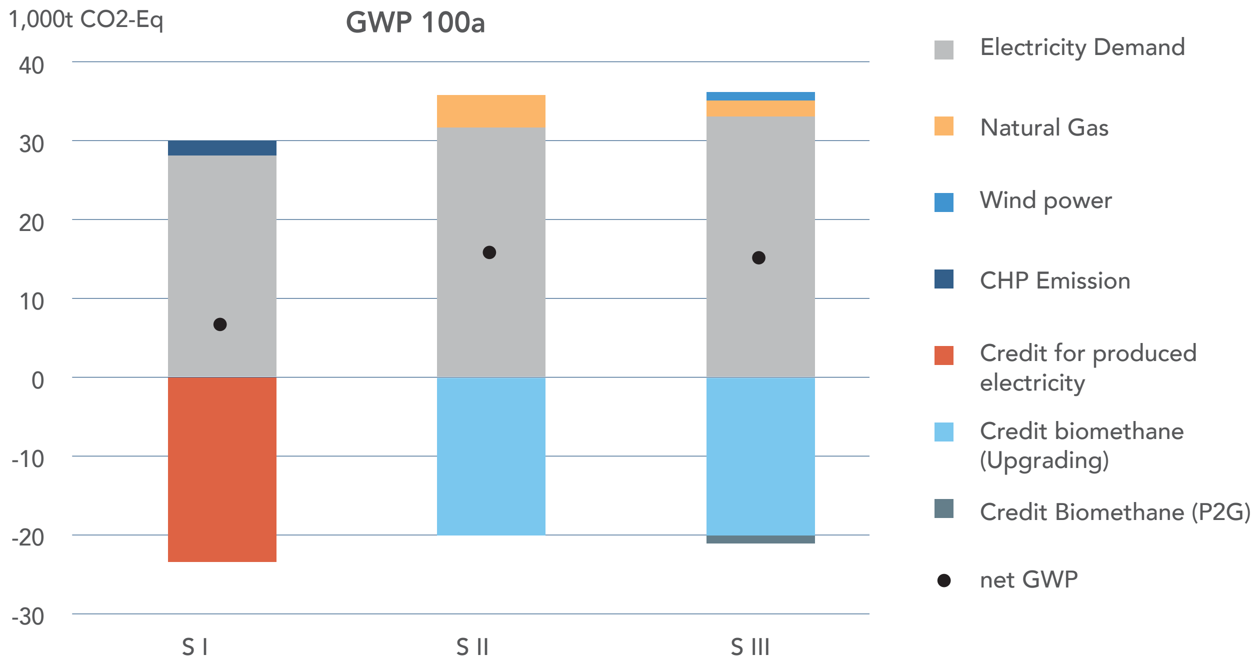
The environmental assessment analysis finally compares the global warming potential for a time horizon of 100 years (GWP100) of the three selected scenarios by using both the actual and also a future grid electricity mix. The function of the system is to utilize the biogas to generate secondary product like heat and electricity.

The functional unit is therefore the biogas amount produced in the year 2017 by the WWTP (16,079,808 m3). The model for the scenarios is created in the LCA software UMBERTO®.

Figure 3.6 shows that the net GWP100 is heavily influenced by the electrical consumption from the grid and its substitution depending on the used energy mix. Electricity generated by using biogas in the CHP unit is more beneficial in GWP than the biomethane credits generated from the same amount of biogas. Similarly, PtG is not worthwhile in environmental terms, also because biogas use for electricity production is more beneficial than substituting natural gas in the grid. The additional amount of produced biomethane on top of the upgraded biogas is quite small in the PtG scenario, indicating that the PtG unit is operating only 20 to 30% of the time and thus with low efficiency.

Figure 3.6

Comparison of global warming potential of each scenario



Economic point of view

For the economic assessment, data for CAPEX and OPEX calculations are based on cost data provided by suppliers. For cost of consumables (e.g.: electricity, natural gas, etc.), levies and subsidies, interests and inflation rates (empirical values) recommendations from operators as well as assumptions have been used (Stadtwerke Berlin, 2018).

Table 3.7 shows a summary of the key values for economic assessment.

Table 3.7

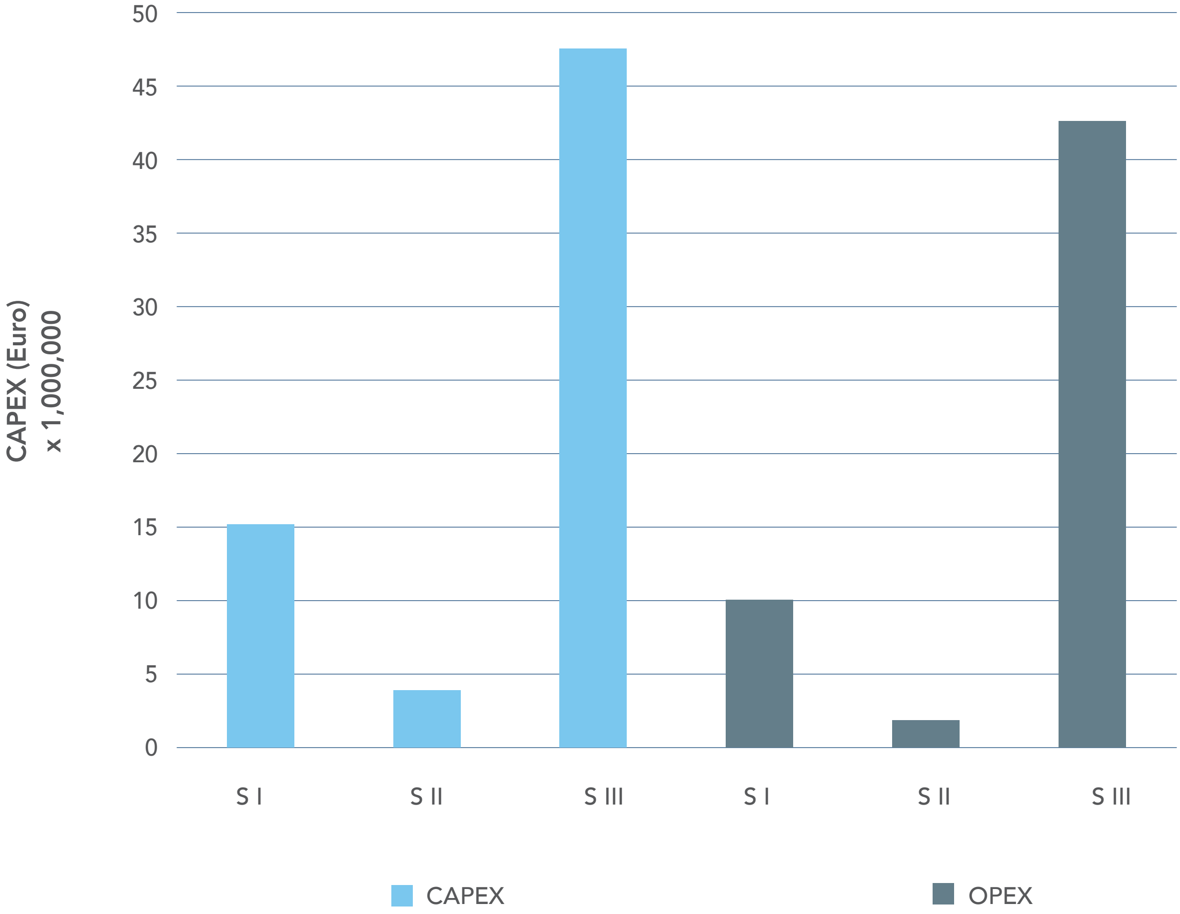
Summary of the key values for economic assessment of the different scenarios

Variables / Parameters	Value	Unit	Reference
Electricity price	199	€/MWh	(Stadtwerke Berlin, 2018)
Electricity for PtG	40	€/MWh	(Stadtwerke Berlin, 2018)
Natural gas	30	€/MWh	(Stadtwerke Berlin, 2018)
Biomethane (sell price) + avoided grid charge	55+7	€/MWh	(Stadtwerke Berlin, 2018)
Biomethane price increase	0.50	%/year	(Stadtwerke Berlin, 2018)
Water	1.80	€/m^3	(BWB, 2017)
Oxygen	0.12	€/m^3	Estimated

Figure 3.7 shows the results for CAPEX and OPEX of the different scenarios. Regarding the CAPEX it is apparent that a biogas upgrading plant (SII) is the least expensive option. It is even cheaper than investing in a CHP unit (SI). SIII has the highest investment cost, resulting from the very high cost for the methanation plant and especially the corresponding electrolyser, tripling the CAPEX compared to SI. The operational costs behave similarly to CAPEX in all the scenarios. As shown in the Figure 3.7, biogas upgrading (SII) is the cheapest option, followed by CHP unit (SI). The PtG process (SIII) has the highest operating costs.

Figure 3.7

Comparison of CAPEX and OPEX of different technologies



3.4.4 Conclusion

Recommendations from this study depend on where the focus is laid and which parameters are chosen. Considering the comprehensive energetic and economic analysis, scenario SII (upgrading of biogas and grid injection) is recommended as the most sustainable and future-proof option. From an ecological point of view, biogas upgrading will become more interesting in the future to contribute to climate policy. It remains to assess to which extent the biomethane production at the WWTP can contribute to the climate related goals and reduction of GHG emissions. If the focus is laid only on the GHG emissions, since explicit political commitments have been made in this field, the benefits of biogas upgrading will be realized only after a greener grid electricity mix is present.

It is observed that under current conditions, a combination of PtG technology with biogas upgrading in a WWTP offers no advantage over the scenarios without this technology. Currently, the lack of support scheme for PtG makes this concept uneconomical. For the moment, such a technology is reported to be not mature and too costly to be economically feasible. But its future role for the energy system is emphasized since other benchmark technologies to store energy have limited expansion capacity (i.e. pumped storage power). These statements coincide with results of this study and the created plant design.

In conclusion, it was shown that a biogas upgrading to produce biomethane using the presented technologies is a feasible option for the surveyed WWTP, especially in the near future under the assumed circumstances and parameters.

CASE STUDY CZECH REPUBLIC

3.5

3.5.1 Description of Wastewater Treatment Plant

Central Prague WWTP is a large site with a capacity of 1,641,000 PE (population equivalent), WWTP is the mechanical-biological system with the thermophilic anaerobic digestion of sludge. WWTP is situated in the northern part of Prague at river island, very close to residential areas as you can see in Figure 3.8. In 2019 new biological treatment line was put into operation. Sludge produced at both treatment lines of Prague WWTP is processed by thermophilic anaerobic digestion (AD).

Veolia operates Prague central WWTP including sludge line with AD thermophilic process. The biogas is now burned at CHP plant 5 MW of electric power (gas piston engines) with limited heat utilizing, which affected overall energy efficiency. The results of AD and energetic data are shown in Table 3.8

Figure 3.8
Aerial view of the Prague WWTP

Table 3.8

Average results of AD

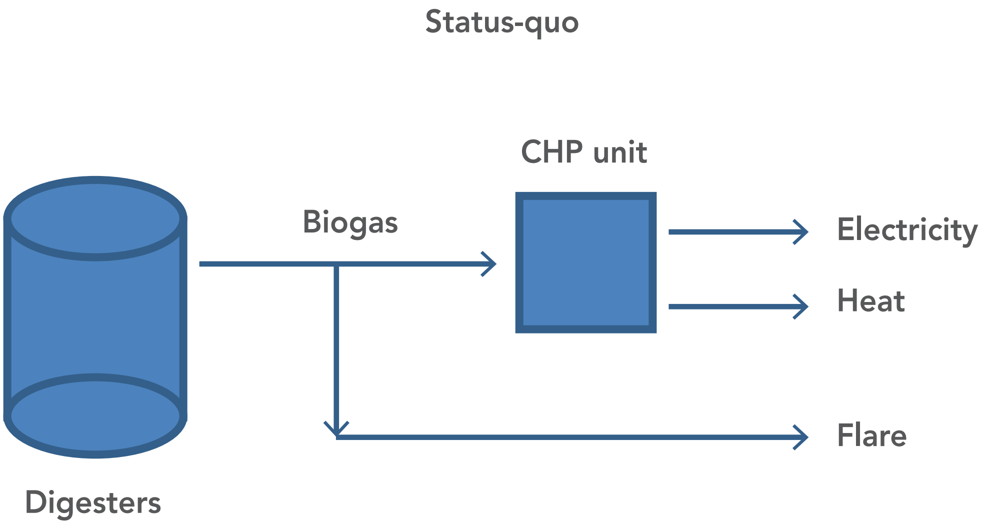
Biogas production (Nm^3/year)	18,066,974
Electricity production (kWh/year)	32,029,000
Plant self sufficiency	75 %
Biogas for other purposes (Nm^3/year) (now burned on flares without purpose)	1,150,000
Methane content of raw biogas	61 %

3.5.2 Selected scenarios by REEF 2W decision support tool

For Prague WWTP there is designed membrane biogas upgrading unit for biomethane production and vehicle refueling station. This measure changes the status quo when part of the biogas is burnt in the flare as shown in Figure 3.9. The biomethane plant can positively affect the energy efficiency of WWTP and reduce the air pollution generated by transport.

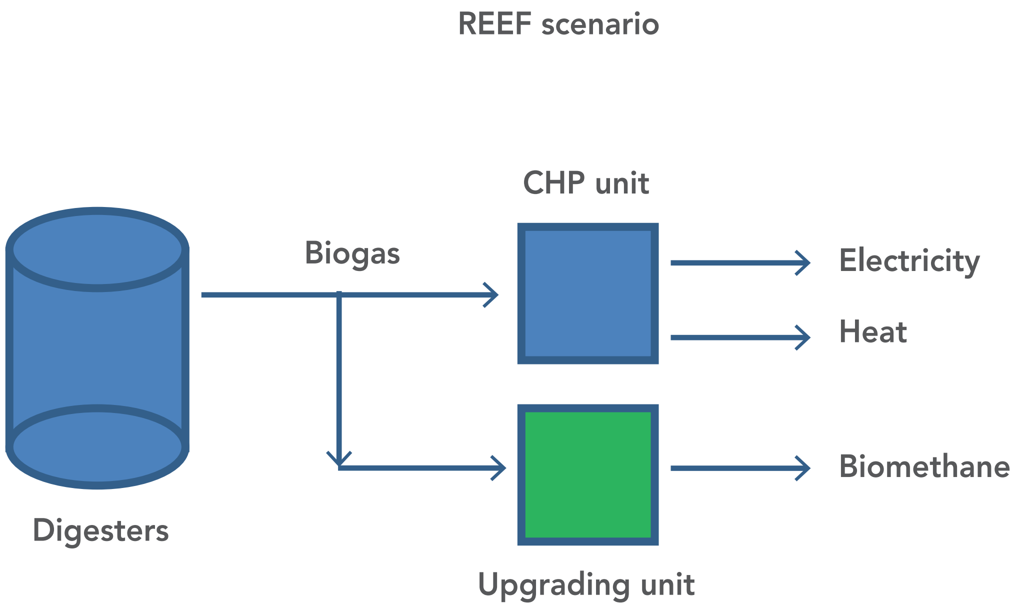
Figure 3.9

The technological scheme of the current state



The installation of biogas upgrading unit causes only minor changes to WWTP site as shown in Figure 3.10. Installed technology is small and compact because the unit is situated in standard containers. Only small part of produced biogas (now not used) will be upgraded.

Figure 3.10
The technological scheme of the future situation



Biogas upgrading unit will operate with 250 Nm^3/hour of raw biogas. Biomethane production will be 160 Nm^3/hour. It means that 2,500 kg of CNG per day will be produced. By energy point of view it means 1,370 kWh of green energy will be produced from - now unused - biogas.

3.5.3 Results and Discussion

Energetic point of view

From an energetic point of view, the difference between "Status quo" and "REEF scenario" is negligible. Electricity and heat production from biogas stays unchanged. Biogas currently burned in flare is used for biomethane production, the introduction of membrane biogas upgrading unit increases energy consumption; however this increase is about below 1 kWh/PE$_{120}$*year while the total energy consumption of WWTP is 23.6 kWh/PE$_{120}$*year.

Economic point of view

From an economic point of view, it is important to evaluate what will be the costs and benefits of investing in the membrane biogas upgrading unit. The benefits are in the current conditions of the Czech Republic and Central Europe also highly dependent on subsidies related to biomethane production. Under current circumstances, the benefits from sales of biomethane allow estimating the return of investment as about 6 years, which is acceptable.

Ecological point of view

From an ecological point of view, the crucial benefit is the replacement of fossil fuel (natural gas) by fuel from renewable sources (biomethane). The production of biomethane offers improved use of biogas energy because the heat produced in the current CHP technology is hardly usable in the summer month. Production of the fuel instead of heat is much more environmentally friendly.

3.5.4 Conclusion

Considering the comprehensive environmental, social, economic and technical analysis, the REEF 2W technology -introduction of biomethane production -is beneficial for the selected WWTP. As shown in the Table 3.9. REEF 2W scenario has the better composite index in three categories and it is equal in one of them, which means that implementation of proposed REEF 2W solution could bring additional benefits in these fields.

Table 3.9

The result of multi-criteria decision analysis

Criterion	Composite Index (Status quo)	Composite Index REEF 2W technology
Environmental	3.2	2.4
Social	3.2	2.0
Economic	4.0	2.4
Technical	2.2	2.2

CASE STUDY AUSTRIA

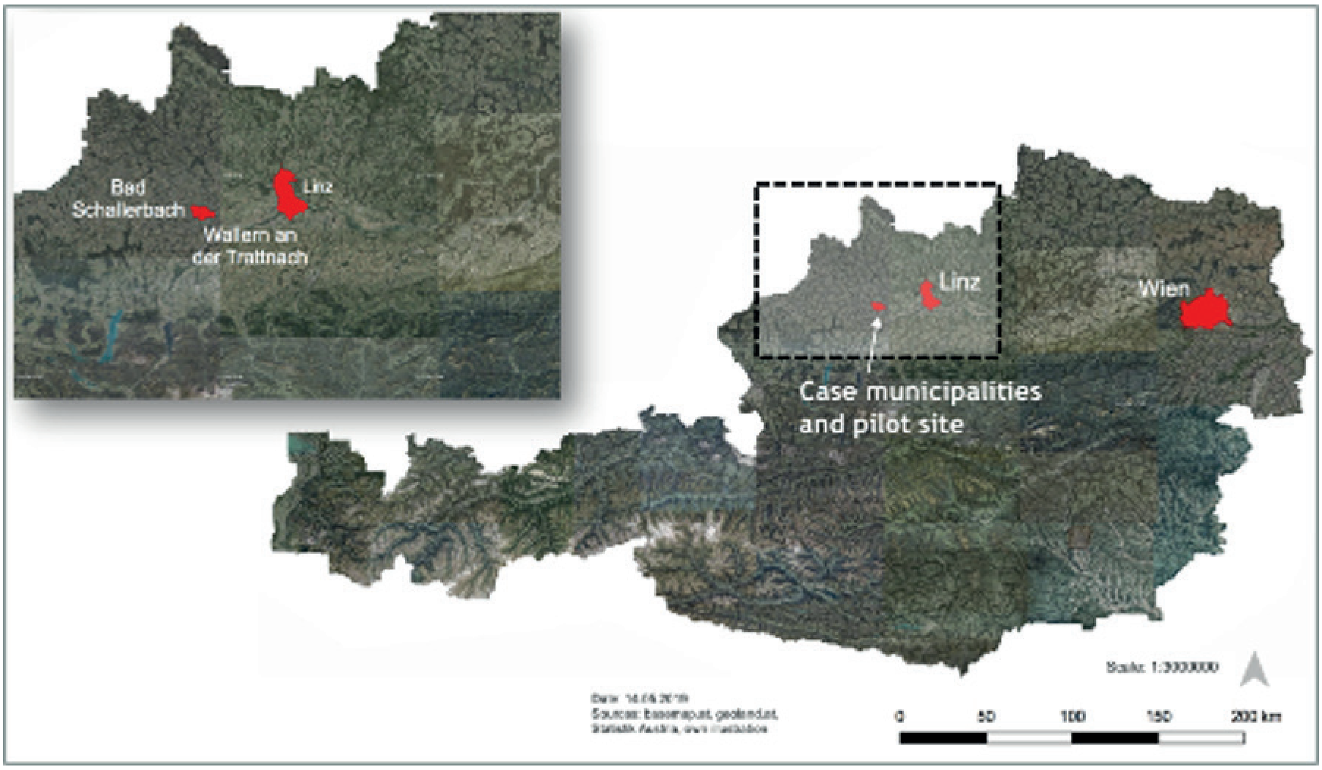
3.6

3.6.1 Description of Wastewater Treatment Plant

The Austrian pilot WWTP is the plant of RHV Trattnachtal, located 15 km north of Wels in Upper Austria (Figure 3.11), with a capacity of 74.000 population equivalent (PE) and an annual wastewater flow volume of around 6 million m³. Since 2008 a waste co-fermentation on the site of the WWTP has been implemented. The investigated strategies within this study are:

1. Reducing the energy demand of the WWTP
2. Increasing the energy output by using the resources available on-site
3. Developing strategies to use the surplus (heat) energy at surrounding consumers' sites

Figure 3.11
Location of the pilot WWTP in Upper Austria (Lichtenwoehrer et al., submitted)



Current energy consumption and production

The annual electricity consumption is 2,041 MWh (2016) which corresponds to 27.6 kWh per PE_{max} (74,000 PE) or 40.8 kWh per $PE_{average}$ (50.000 PE) or 0.34 kWh per m³ of wastewater (6,024,000 m³) and is split up into aeration (25%), return sludge cycle (17%), digesters incl. sludge line (11%), screening and sand trap (9%) and diverse consumers (38%). RHV has set up technologies using own electricity, e. g. for decanter press and for membrane filtration.

The surplus electricity (in 2016 1,755 MWh), which was nearly half of the produced electricity of 3,744 MWh, is sold to the grid for market price of only 3-6 Cent/kWh, therefore a subsidized tariff would be beneficial. The costs for natural gas were below 5,000 € (mainly measuring and net costs). Only 51 MWh were bought from the grid.

The heat consumption in 2016 amounted to 2,309,000 kWh, which is 31.2 kWh per PE_{max} or 46.2 kWh per $PE_{average}$ or 0.38 kWh per m³ of wastewater. 2,020,000 kWh were needed for digester heating (sludge treatment). The plant produces around 100 m3 preliminary sludge daily with a dry matter content of 3-6% and 20 m^3 excess sludge with 2-3% dry matter. On the other hand, 2,848,000 kWh of heat were produced.

Compared to the Austrian benchmarking values (Lindtner, 2008), the total electric energy consumption (40.8 kWh/PEaverage) lies within the standard range of 20 to 50 kWh/PE, screening and sand trap (4 kWh/PE) lies above the standard range of 1-2 kWh/PE, aeration (10 kWh/PE) is below (11.5 to 22 kWh/PE) and the digesters incl. sludge line (4 kWh/PE) lie within the standard range of 2 to 7 kWh/PE. The heat consumption of 48 kWh/PE lies above the standard range of 0 to 30 kWh/PE, mainly due to a high consumption of digester towers (around 80 % of the total amount).

3.6.2 Technology upgrade of the pilot

Due to co-fermentation the WWTP has already over 100 % self-supply in electricity and heat. In order to use this heat via heat grid in an optimal way (as intended by above mentioned strategy 3), it is desirable to increase this surplus (as intended by strategies 1 and 2). Currently there is no need for this as the surplus energy cannot be used.

Reducing the energy demand

Insulation of the digester towers

Currently the digester towers are insulated with 9 cm of glass wool which corresponds to about 0.45 W/m²K. The heat consumption indicates that this value is higher. Therefore, it should be checked that the glass wool is dry. In any case, extending the thickness of the insulation from 9 to 12 cm and using PIR -Polyisocyanurate would result in better insulation values of about 0.18 W/m²K. Biological insulation materials would be another option. Around 300,000 kWh savings could be achieved.

Optimize temperature in the digester tower

The temperature should be as high as needed to produce biogas (production will slow down if digesters are kept too cold and the volume of the towers is limited), but as low as possible to minimize heat consumption. Up to 5 °C and 250,000 kWh/year are realistic values.

Reducing water amount in the sludge

The higher the dry matter content in the sludge the less water needs to be heated. Therefore, a preliminary dewatering of sludge before anaerobic digestion could be an option. The potential savings are in the same range as for the two previous measures.

Optimizing the energy output

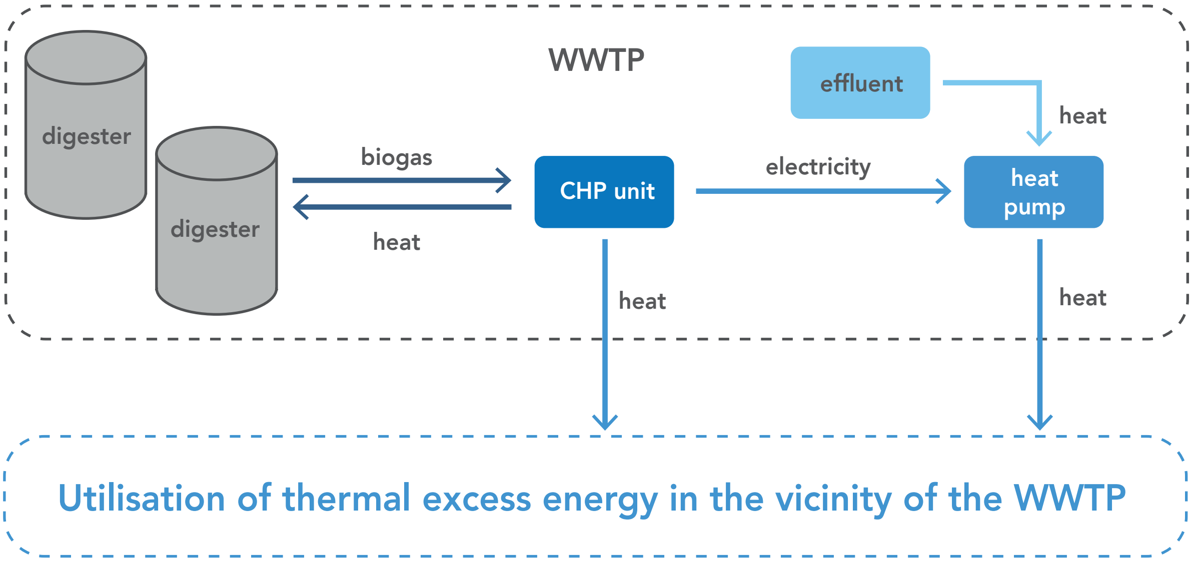
Main energy sources on a WWTP are the thermal energy of the wastewater (for heat up to 65 °C) and the energy from digester gas (for electricity and heat). Wind energy, solar energy and hydropower (applied for the effluent of the WWTP) are not considered as agreed with the WWTP operator.

Thermal energy content of wastewater-Heat recovery from wastewater

The mean wastewater flow at the WWTP is around 6,000,000 m^3 per year or 191 l/s (average of 2016 and 2017), the minimum is 120 l/s. With a delta T of 2K a power of 120 l/s*4,18 kJ/kgK*2K = 1 MW can be extracted, resulting in an electricity consumption for heat pumps (COP = 4, which results from a mean source temperature of 14 °C, a mean supply temperature of 50 °C and a Carnot factor of 0.45) of 333 kW. In annual average the wastewater treatment plant has an electric surplus energy of 200 kW (January and February with lowest surplus), which means that heat pumps can be supplied by surplus electricity of the WWTP. The following illustration (Figure 3.12) shows the general approach of heat recovery from wastewater using surplus electricity for the heat pump operation.

Figure 3.12

Scheme of providing surplus heat from the wastewater treatment plant



As electric energy demand and consumption will be optimized, an even higher amount for the heat pumps is realistic. The wastewater temperature varies between 9.5 °C in January and 19.5 °C in August. Table 3.10 gives an overview on the wastewater heat recovery potential.

Table 3.10
Wastewater heat recovery potential

Mean used wastewater flow in l/s	Delta T in K	Heat extracted from wastewater in MWh/year	Needed electricity in MWh/ year	Total heat potential in MWh/ year	Mean thermal power in kW
120	2	8,788	2,929	11,717	1,338
120	4	17,576	5,859	23,435	2,675
191	2	13,988	4,663	18,650	2,129
191	4	27,975	9,325	37,300	4,258

A higher delta T or dimensioning the plant to use the complete wastewater flow increases the energy potential. The table 3.10 shows 4 scenarios and the resulting thermal energy potential. It has to be taken into account, that storage and grid losses will reduce the usable amount of heat.

Grid losses can typically be estimated to 15 % (Statistik Austria, 2020) with optimization potential for new grids with lower temperatures as planned in this case (and for higher densities), whereas storage losses highly depend on the system details. Lower demand in summer, repairs, shutdowns, etc. will further reduce the potential.

Digester gas utilization

The digester gas plays a completely different role compared to wastewater energy:

- It can be used for heat supply without using electric energy (e. g. for heat pumps),
- for heat supply at a high temperature level,
- and can additionally be used for electricity production.

Therefore, these two types of resources serve for different heat demands (e. g. low temperature domestic heat, high temperature domestic heat, domestic warm water, digester heat, etc.). An optimized storage strategy helps to cover all different heat energy needs.

3.6.3 Spatial assessment and potentials to utilise surplus energy from the WWTP

At the Austrian pilot site, a comprehensive spatial assessment was carried out. The goal was to evaluate the thermal energy demand in the vicinity of the treatment plant and to conceptualise a district heating network (DHN) in order to enable heat distribution. Further, the evaluated heat demand allows a comparison with the amount of recovered heat from wastewater.

The pilot plant is located approximately 1.8 km from the village centre of "Wallern an der Trattnach", which is the nearest case municipality. Further west "Bad Schallerbach" is located, which serves as the second case municipality. Within these two municipalities essential heat consumers, so called "thermal energy hotspots", were identified and assessed. Applying a spatial assessment, a total of 20 GWh/year of thermal energy demand was calculated. The conceptualised district heating network (DHN) has an overall length of 17,000 metres, connecting approximately 370 individual buildings. Considering the thermal energy demand and the lengths of the DHN, the connection density was calculated to be 1.2 MWh/m*year According to Nussbaumer et al. (2017), a connection density above 0.7 MWh/m*year is considered feasible.

3.6.4 Discussion

Energetic point of view

The REEF 2W solution of recovering thermal energy from wastewater will increase the overall energetic surplus of the WWTP. As indicated by the spatial assessment, there is sufficient heat demand in the vicinity of the WWTP to make use of this surplus. By changing the delta T and the maximum usable wastewater flow, the amount of heat recovery can be adapted to the demand. Finally, from an energetic point of view, the evaluated energy efficiency measures and the renewable energy provision will further contribute to a more sustainable energetic future, both within and outside the treatment plant.

Economic point of view

From an economic point of view the REEF 2W solution competes with various heating systems as gas heating, oil heating and wood heating systems. The dimensioning and the question who will take energy from the grid will influence tremendously the economic feasibility, as it influences the grid design and the relation to the sold amount of heat. Furthermore, the dimensioning of heat pumps and storages will play an important role as well as the price for electricity, the inserted interest rate and the expected lifetime of the system and its components. At this stage of research, a detailed economic analysis is not possible. However, parameters as high achievable heat density and usable own-produced electricity suggest good overall economic framework conditions.

Ecological point of view

From an ecological point of view the substitution of fossil energy with renewable energy sources can be considered as an essential goal. This substitution can be followed within the WWTP and beyond the WWTP. Besides internal energetic optimisations, the case study in Austria focused on providing surplus energy to the vicinity of the treatment plant. In this context, the current use of fossil energy in both case study municipalities is estimated at approximately 75% of the total energy consumption (Abart-Heriszt et al. 2019). Hence, heat recovery from wastewater as a renewable energy source able to replace fossil heating systems, of for example households or industries, is valued as an essential contribution to the ecological situation of the energy system.

3.6.5 Conclusion

In order to achieve the energy turn, holistic and integrated approaches are necessary. As part of the REEF 2W project, the presented feasibility study at the pilot site in Austria can be taken as a best-practice example on how to optimise the energetic situation at a WWTP, on how to generate surplus energy and finally on how to use the surplus energy in the vicinity of the treatment plant. Since heat accounts for a large share of the overall energy consumption, the substitution of fossil energy with renewable energy can be seen as a major contribution to the energy turn.

CASE STUDY CROATIA - ZAGREB AGGLOMERATION

3.7

3.7.1 Description of Wastewater Treatment Plant

Zagreb Urban Agglomeration (ZUA) has been found in 2016 and includes the City of Zagreb (790,017 inhabitants) as the seat of the Agglomeration, and parts of the Zagreb county (256,689 inh.) and Krapina-Zagorje county (39,822 inh.). More specifically, the ZUA encompasses a total of 30 local government units, 11 cities and 19 municipalities. n the northern part of ZUA is the location of the WWTP Zabok, which will be built by the end 2020. This plant is owned by the public company Zagorski vodovod Ltd. The company has been found by 26 local self-government units, is engaged in public water supply and public drainage, operates in the urban agglomeration of Zagreb and supplies water to 90,000 residents in more than 31,000 terminals. In the year 2006 Zagorski vodovod Ltd has registered the activity of public sewage and wastewater treatment and started preparations for taking over existing sewage systems in the area of Krapina-Zagorje County.

Zagorski vodovod Ltd. Is planning to build WWTP Zabok with the capacity of 36,940 PE, and will be consisted of these stages: Prior purification -separation of particles, Second stage - consisting of temporarily holding the sewage in a quiescent basin where heavy solids can settle to the bottom while oil, grease and lighter solids float to the surface, and Third stage -which removes dissolved and suspended biological matter, as well as includes the dehydration of the sludge. The main data for WWTP Zabok is presented in the Table 3.11.

Table 3.11

The main data for WWTP Zabok

ZUA	Location	Population	WWTP size (PE)	Sludge amount (m^3/y)	Dry matter	Total amount (t/y)
WWTP Zabok	City of Zabok	9,000	36,940	1,490	75%	1,117.5

3.7.2 Selected scenarios by REEF 2W decision support tool

The main intention for the pilot site in ZUA is to establish a pilot case and test the possibility to utilize the separately collected biowaste, as well as the sustainable usage of produced sludge. This will be the main challenge for the WTTP Zabok operator in the future period. The WTTP in its full capacity will be producing 1,117.5 tonnes of dehydrated sludge. The main aspects of the proposed solution are: i) Possibility to use biowaste fraction of municipal waste, ii) Anaerobic treatment - co-digestion of sludge and biowaste, iii) Utilization of biogas -CHP and biomethane, and iv) Application of digestate as a soil improver.

Besides the treatment of wastewater, one of the most important issues of the Zabok WTTP is the sustainable waste management in the ZUA. The combined treatment of waste and wastewater is one of the main benefits of the proposed REEF 2W solutions. The main idea behind this proposal is to successfully utilize separately collected biowaste with current wastewater treatment. This extension will also result in a production of renewable energy.

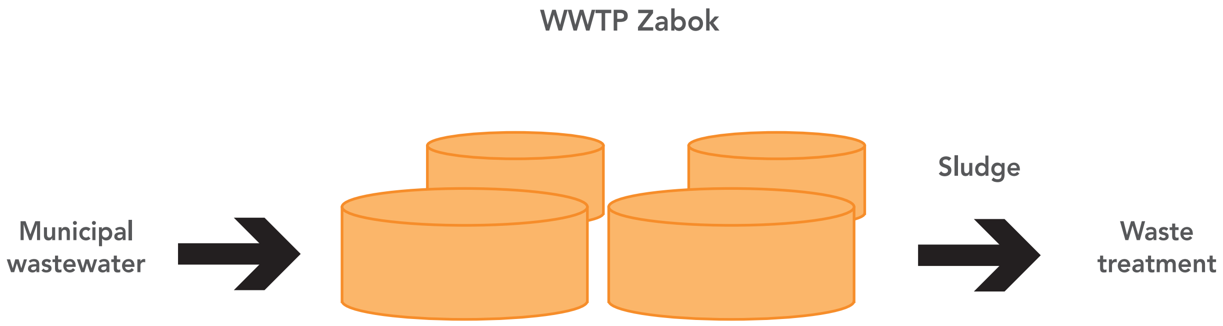
The overview of all solutions is presented in the following scenarios:

Scenario 1: Local sludge utilization

In this scenario business as usual is foreseen, where the plant is processing wastewater and produce 1,117.5 tonnes of sludge each year. In this scenario no energy utilization will be provided. The produced sludge will be treated as a waste and will be facilitated its utilisation as a soil improver at the available local land.

Figure 3.13

Scheme of local sludge utilization

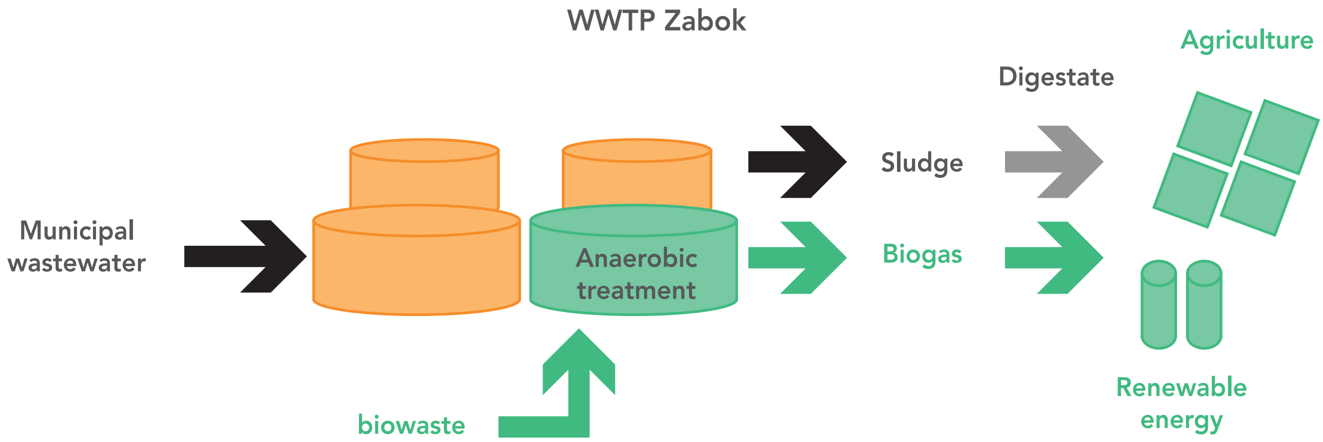


Scenario 2: Anaerobic digestion on site

This scenario is proposing the upgrade of the current facility in Zabok. The upgrade is consisted of the onsite anaerobic treatment of the sludge at the WWTP Zabok as well as the installation of gas engine for the utilization of produced biogas. The WWTP Zabok will produce energy via cogeneration and utilise it. Also, produced sludge will be used locally.

Figure 3.14

Scheme of anaerobic digestion on-site

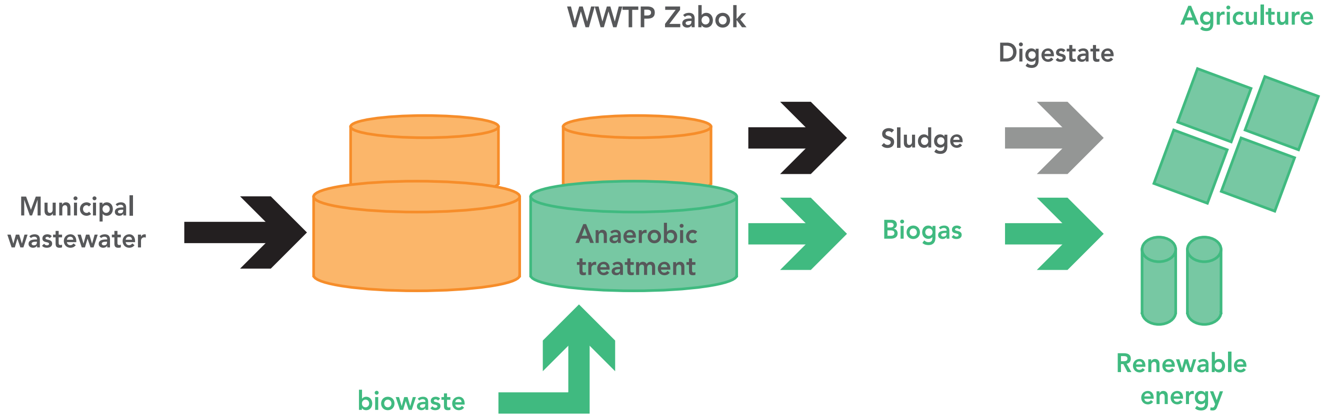


Scenario 3: Utilization of biowaste and sludge at remote biogas plant

In this scenario it is foreseen that the WWTP Zabok will be operating as in scenario 1, but the produced sludge will not be used locally for agriculture, but rather transferred to the remote biogas plant where it will be used for renewable energy production. Also, separately collected biowaste from all three counties that are part of the Zagreb agglomeration will be transferred to the biogas plant in order to be utilised for renewable energy production (cogeneration or biofuel production). The main reason for this approach is the need to define complete energy potential of the biowaste fraction in the ZUA. This is one of the main goals of the REEF 2W project.

Figure 3.15

Scheme of utilization of biowaste and sludge at remote biogas plant



3.7.3 Results and Discussion

Energetic point of view

Table 3.12

The overview of evaluated scenarios

Scenario	Total amount (t/y)	Origin	AD	Energy utilization		Sludge management	
			Biogas potential (m3/y)	CHP (kW)	Biomethane production (t/y)	Produced sludge (t/y)	Required land (ha)
1 - Local utilization of sludge	1,117.5	Sludge	0	0	0	1,117.5	673.2
2 - Onsite anaerobic digestion	3,443.5	Biowaste/ Sludge	299,650	78.7	107.9	2,280.5	1,373.8
3 - Utilization of biowaste and sludge at remote biogas plant	36,442.5	Biowaste/ Sludge	3,599,550	944.9	1,295.8	18,780	11,313.3

Economic point of view

Table 3.13

Overview of overall revenue/expenditure cash flow

Scenario	REVENUE (€/y)				EXPENDITURE (€/y)	
	Energy utilization				Biowaste gate fee	Waste treatment
	Electricity	Heat	Total CHP	Biofuel		
1 - Local utilization of sludge	0	0	0	0	0	70,402.5
2 - Onsite anaerobic digestion	44,048.6	20,136.5	64,185	129,448.8	88,388	114,596.5
3 - Utilization of biowaste and sludge at remote biogas plant	529,133.9	241,889.8	771,023.6	1,555,005.6	1,342,350	1,183,140

Table 3.14

Overview of the WWTP Zabok cash flow

Scenario	REVENUE (€/y)				EXPENDITURE (€/y)	
	Energy utilization				Biowaste gate fee	Waste treatment
	Electricity	Heat	Total CHP	Biofuel		
1 - Local utilization of sludge	0.0	0.0	0.0	0.0	0.0	7,402.5
2 - Onsite anaerobic digestion	44,048.6	20,136.5	64,185.0	129,448.8	88,388.0	114,596.5
3 - Utilization of biowaste and sludge at remote biogas plant	0.0	0.0	0.0	0.0	0.0	70,402.5

Ecological point of view

The overview of the biowaste amounts for the treatment in ZUA is presented in the Table 3.15.

Table 3.15

Overview of the biowaste

ZUA	Total amount of produced mixed municipal waste (t)	Total potential of biowaste (t)	Expected amount of collected biowaste (t)
City of Zagreb	217,380	65,214	26,085
Zagreb County	57,621	17,286	6,914
Krapina-Zagorje County	19,388	5,816	2,326
Total	294,389	88,316	35,325

3.7.4 Conclusion

The analysis performed for the Zagreb Aglometation case study indicates that wastewater treatment is sustainable and can be combined with the utilization of separately collected biowaste. This approach could have not only positive environmental, but also financial impact on the investigated location. The application of sludge in agriculture is already part of practice in many EU regions, and its implementation could be a solution for wastewater treatment plants. New regulations of the sludge application and its monitoring with specific reference to the environmental condition are assuring its safe application in agricultural production.
According to the data, the WWTP Zabok will produce 1,117.5 t/y of sludge possible to use on 673.2 ha of agricultural land. Since the investigate area has sufficient land availability, it can be assumed that possibility of local sludge application is realistic.

The REEF 2W solution also gives a possibility to use sludge for renewable energy production, and in that sense proposed different scenarios. Besides the first proposed scenario, others are giving the overview of the plant upgrade when the separately biowaste fraction is involved in the process. This will for sure improve cash flow of the plant (scenario 2), but certain investment are expected which cannot be foreseen in detail in this stage of plant construction.

Finally, it can be concluded that the use of sludge on agricultural soils is nowadays an efficient way to sustainably treat wastes generated in wastewater treatment plants. Also plant operators will have to take into consideration the fact that sludge has energy potential which can be sustainably combined with the biowaste produced at local or broader area.

4

REEF 2W STRATEGY

ENERGY FROM WASTEWATER IN CEU

4.1

4.1.1 Inventory of wastewater treatment plants

A prerequisite to estimate available wastewater-based energy potentials is an inventory of the existing wastewater treatment plants (WWTPs). The CEU program area hereby includes the following countries:

- Austria (AT)
- Czech Republic (CZ)
- the eastern and southern parts of Germany (DE)
- Croatia (HR)
- Hungary (HU)
- The northern part of Italy (IT)
- Poland (PL)
- Slovenia (SI)
- Slovakia (SK)

The basis of the inventory is provided by the "Waterbase" of the European Environmental Agency (EEA s.a.), which summarizes the reported data of all EU member states concerning the Urban Wastewater Treatment Directive. This database provides, among others, an overview on the existing wastewater treatment plants including information on their location, capacities and current loads.

Table 4.1 summarizes the related figures for the respective countries and the entire CEU area.

Table 4.1

Wastewater treatment plants (WWTPs) in CEU (Kretschmer and Zlonoga, 2020)

Country	Amount of WWTPs	Treatment capacity (PE)	Entering load (PE)	Data Availability
AT	640	21,582,000	14,526,000	100%
CZ	671	15,459,000	9,622,000	91%
DE	2,059	69,614,000	52,166,000	99%
HR	281	4,019,000	3,423,000	34%
HU	635	14,855,000	10,666,000	100%
IT	2,554	48,107,000	33,568,000	58 - 92%
PL	1,692	52,609,000	47,382,000	100%
SI	113	2,321,000	1,872,000	90%
SK	336	6,297,000	3,808,000	82%
Total CEU	8,981	234,863,000	177,033,000	94%

Table 4.1 shows, that almost 9,000 wastewater treatment plants with a treatment capacity of nearly 235 million and a current entering load of around 177 million population equivalents (PE) are installed. This gives a very good first impression on the current situation in CEU. However, there are two restrictions related to this data to be considered:

First, data availability varies from country to country: In AT, DE and HU, for instance, information on treatment capacity and entering load are available for (almost) all wastewater treatment plants. In IT, on the other hand, less information on the treatment capacity (58%) is available than on the entering load (92%). Finally, in HR data availability still appears rather low (34%). This might be explained by the fact, that the "Waterbase" also includes plants under construction/planning. It is obvious, that for those no operational data is available yet.

Second, reported data includes also small wastewater treatment plants. Out of the 8,981 plants included in the "Waterbase" 2,150 (24%) have a treatment capacity below 2,000 PE. For IT this concerns almost half of the reported sites. Due to their size these plants are only of very limited interest for wastewater-based energy generation. However, the aim of this investigation is to show the theoretical potential for energy generation from wastewater. Consequently, all reported wastewater treatment plants are considered here. For subsequent and more detailed studies the consideration of the size distribution is recommended.

For the estimation of the wastewater-based energy potential two parameters are important: (1) the total wastewater flow, to estimate the wastewater heat recovery potential and (2) the availability of anaerobic digestion (AD), to estimate the digester gas (biogas) based electricity and heat generation (from combined heat and power units). Table 4.2 provides an overview on the related data.

Table 4.2

Wastewater amounts and availability of anaerobic digestion (AD) (Kretschmer and Zlonoga, 2020)

Country	Total wastewater flow (m^3/h)	Amount of WWTPs with AD	Share of AD
AT	90,800	155	24%
CZ	60,100	92	14%
DE	326,00	379	18%
HR	21,400	3	1%
HU	66,700	15	2%
IT	209,800	98	4%
PL	296,100	93	5%
SI	11,700	11	10%
SK	23,800	52	15%
Total CEU	1,106,400	898	10%

Table 4.2 shows a total wastewater flow of about 1.1 million m^3/h in the CEU area. Almost 900 wastewater treatment plants with anaerobic sludge management can be found, whereby the share (percentage) on the total amount still varies significantly between the different countries.

The total wastewater flow is derived from the total current load of the wastewater treatment plants multiplied with an assumed wastewater production of 150 l/PE*d. The assignment of anaerobic digestion to the related wastewater treatment plant in the partner countries (AT, CZ, DE, HR, IT) was done by the project partners of the various countries. Concerning those countries not represented in the consortium a plant specific assignment could only be done for SI, for the remaining three countries (HU, PL, SK) total figures (amount of plant with AD, related digester gas production) from literature (Kovac, 2015, Ligetvári et al., 2015, Igliński et al., 2015, Bodík et al., 2011, Hutnan et al., 2015) were used.

4.1.2 Estimated energetic potential at wastewater treatment plants

Based on the presented inventory the potential for (i) digester gas (biogas) production as well as the related generation of (ii) electric and (iii) thermal energy, the potential for (iv) wastewater heat recovery in the effluent as well as the potential for (v) electricity from photovoltaics at the premises of the existing wastewater treatment plant could be estimated.

Table 4.3 gives an overview on the related results for the different countries as well as the entire CEU program area.

Table 4.3

Estimated energetic potential at wastewater treatment plants in CEU program area (Kretschmer and Zlonoga, 2020)

Country	Digester gas (m^3/d)	Digester gas electricity (MWh/y)	Digester gas thermal (MWh/y)	Heat recovery potential (kW)	Heat pump (MWh/y)	PV (solar) electricity (MWh/y)
AT	223,800	167,900	335,800	526,600	3,159,300	41,900
CZ	137,00	102,800	205,600	348,800	2,092,700	32,500
DE	717,200	537,900	1,075,700	1,891,000	11,346,100	83,700
HR	21,500	16,100	32,300	124,100	744,500	12,000
HU	100,000	67,900	127,000	386,600	2,319,900	32,000
IT	354,300	259,000	518,000	1,216,900	7,301,100	48,800
PL	55,000	37,300	69,900	1,717,600	10,305,600	99,500
SI	15,200	11,400	22,800	67,900	407,200	5,600
SK	55,000	37,300	69,900	138,100	828,300	11,400
Total CEU	1,670,000	1,237,600	2,457,000	6,417,600	38,504,700	367,200

Table 4.3 shows that in the CEU program area the amount of digester gas (biogas) produced is estimated to around 1.7 million m³/d. By means of combined heat and power generation about 1.2 million MWh of electricity and about 2.4 million MWh of (high temperature) heat can be provided per year. The heat recovery potential in the wastewater is around 6.5 million kW, by applying a heat pump the significant amount of about 38.5 million MWh of (low temperature) heat could be made accessible. Electricity generation from photovoltaics is estimated to be around 0.4 million MWh per year.

Hereby, the estimation of digester gas (biogas) production is based on the current load of the wastewater treatment plant multiplied by an average gas production of 20 l/PE*d. The estimation of the digester gas-based electricity assumes a generation of 15 kWh/PE*year, for thermal energy 30 kWh/PE*year. These figures are taken from Austrian benchmarking experiences (Lindtner, 2008). The estimation of the wastewater heat recovery potential is based on the hourly wastewater flow, an assumed cooling of the effluent by 5 K considering a (waste)water heat capacity of 1.16 kWh/m³*K. Subsequent heat generation by means of a heat pump assume a coefficient of performance (COP) of 4 and 4,500 operating hours per year (settlement structures of mixed functions).

The estimation of the PV potential is based on available data from existing wastewater treatment plants from five countries with installed photovoltaic units. Correlation was made between them and rest of the plants in a country including other parameters such as geographical position to obtain a rough annual average rate of electricity generation at a wastewater treatment plant.

4.1.3 Spatial Context of wastewater treatment plants

Throughout the course of the REEF 2W project it became apparent that it is not only possible to increase the energy efficiency of wastewater treatment plants (WWTPs), but also to make use of potential excess energy from the treatment plants. Hence, in order to do so, it is important to analyze the spatial context of both energy sources (in this case the WWTPs) and energy sinks (settlements, including residential areas, commercial and industrial areas etc.). The spatial analyses of energy sources and sinks is also the main concept behind Integrated Spatial and Energy Planning (ISEP), as described by Stoeglehner et al. (2016). Only by incorporating spatial analyses an efficient energy system can be planned. The examination of the location of energy sources and energy sinks becomes even more important when dealing with thermal energy (heating or cooling). Since the transportation of thermal energy is associated with heat loss it is necessary that potential energy consumers are located close to the treatment plant.

However, WWTPs in the CEU area are located in different proximities to energy consumers. Some treatment plants are located far from the next settlement, whereas others are located even within settlements, making it easier to utilise thermal energy. Therefore, the main goal of the spatial analysis is to detect those treatment plants that could potentially be used as renewable heat sources and those that are less suitable.

By using the methodology developed by Neugebauer et al. (2015), every single WWTP in the CEU area was classified into one of the following three categories:

- (A) WWTPs located within the settlement,
- (B) WWTPs located near to the settlement and
- (C) WWTPs located far from the settlement.

Relevant WWTPs, derived from the European Environment Agency (EEA s.a.) as described in chapter 3.1., were taken as a basis. Using GIS software (QGIS.org 2020), a total of 6,944 WWTPs with a treatment capacity > 2,000 population equivalent (PE) could be located within the Central Europe program area (© EuroGeographics for the administrative boundaries derived from Eurostat s.a.).

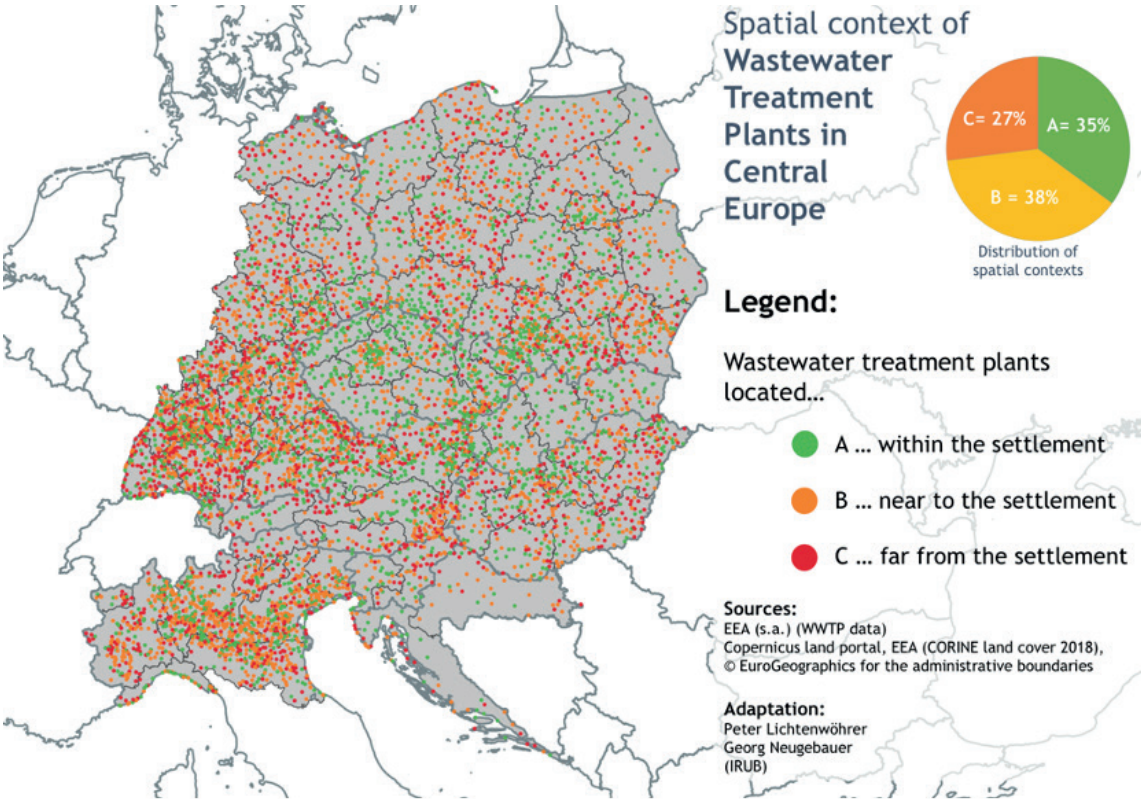
After locating every WWTP it was necessary to evaluate the spatial context whether or not the plant was within, near or far from a settlement. Therefore, the vicinity of the WWTPs was analyzed in circular areas with 150 m and 1,000 m radii in which CORINE land cover categories (CORINE 2018) were used to determine the existence of potential heat consumers. Hence, for the spatial examination the following three classes of artificial surfaces were used:

- 111 – Continuous urban fabric
- 112 – Discontinuous urban fabric
- 121 – Industrial or commercial units.

As a result, Figure 4.1 shows an overview of the spatial contexts of the WWTPs in the CEU area.

Figure 4.1

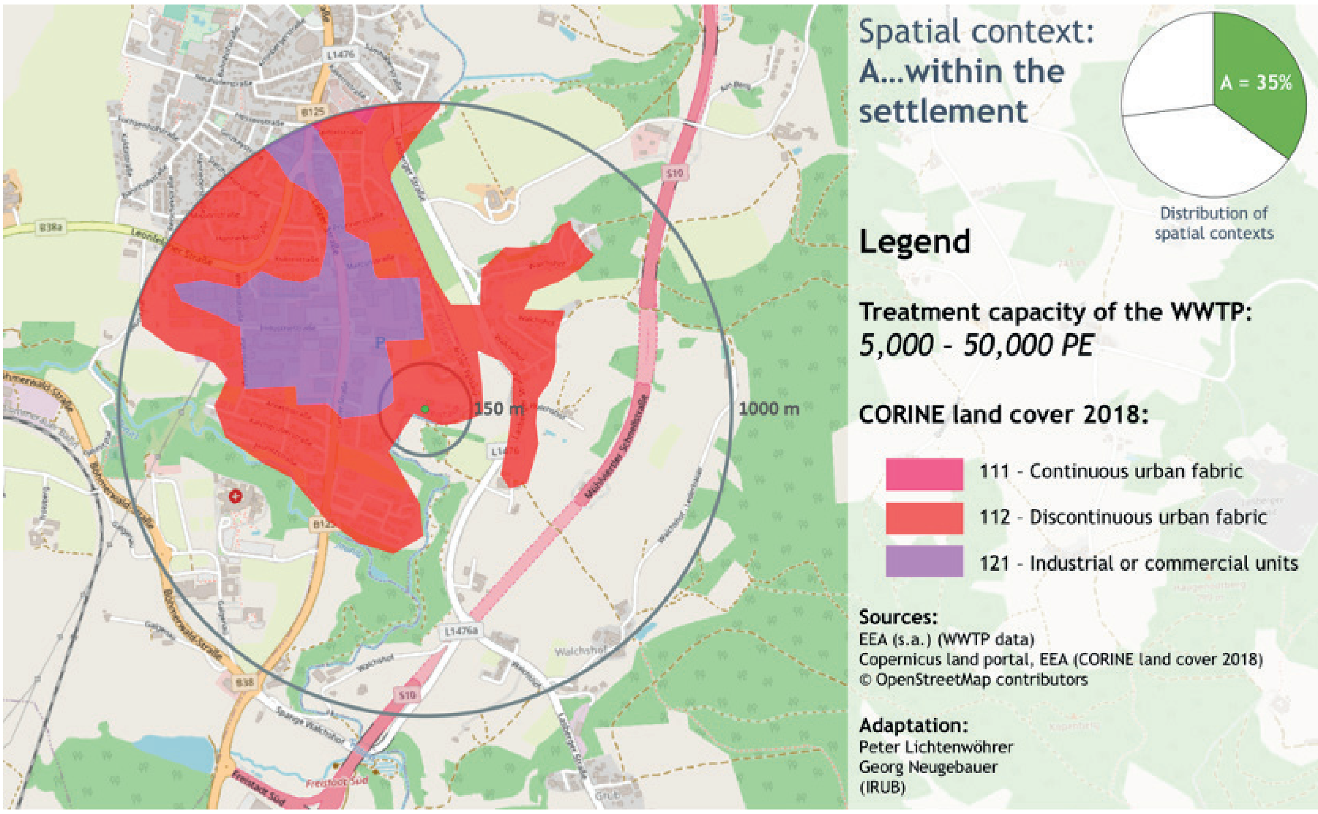
Overview of wastewater treatment plants in Central Europe (Kretschmer et al., submitted)



A total of 35% of the evaluated WWTPs were categorised as "within the settlement". Figure 4.2 shows an example of a treatment plant associated with this category. It can be seen, that the considered land cover classes are located in a distance up to 150 m and cover an essential share of the circular area with a 1,000 m radius.

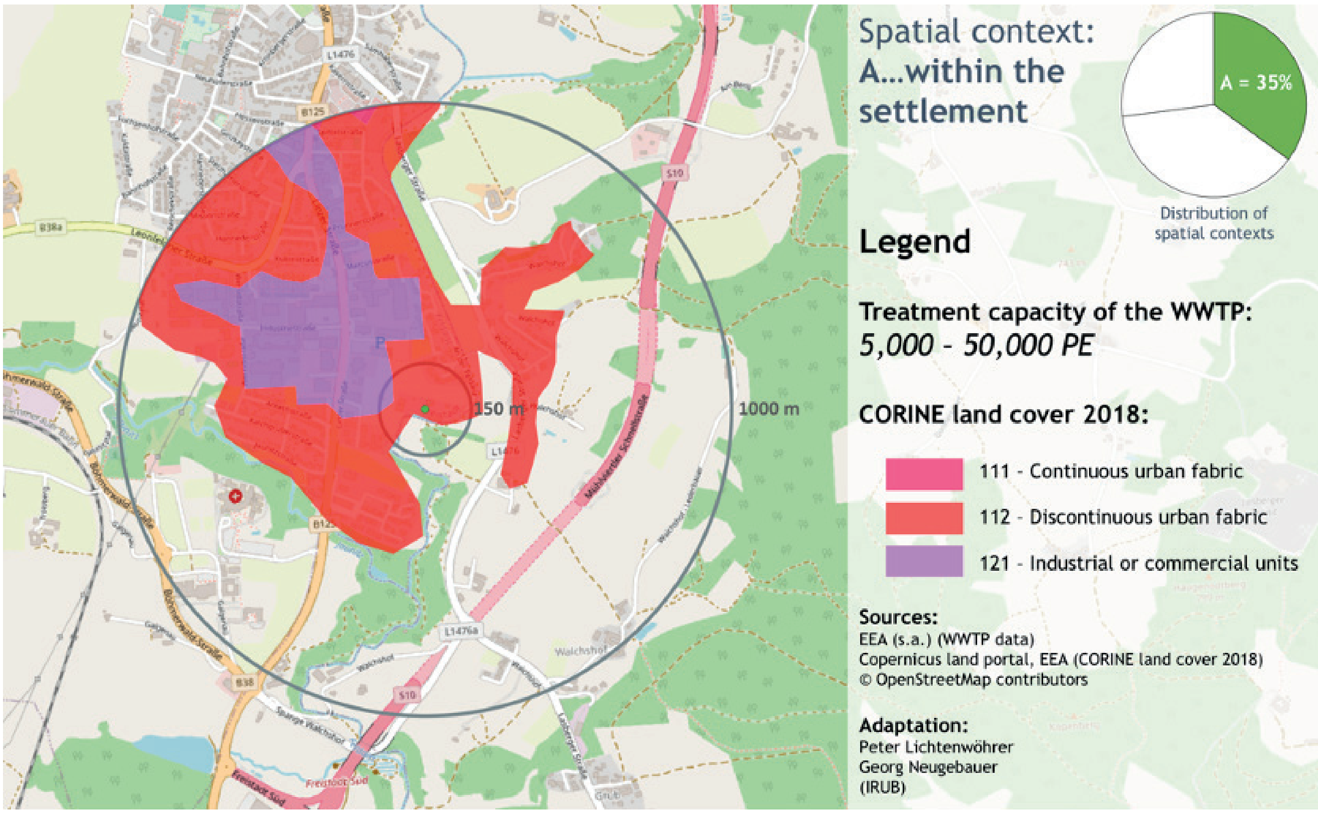
Figure 4.2

Visualisation of a WWTP located within the settlement (own illustration, based on Neugebauer et al., 2015)



Slightly more WWTPs (38%) were detected near to settlements, as illustrated in Figure 4.3. In this category, settlement areas are located within the radius of 1,000 m, which still points to potential energy consumers in the vicinity of the treatment plant.

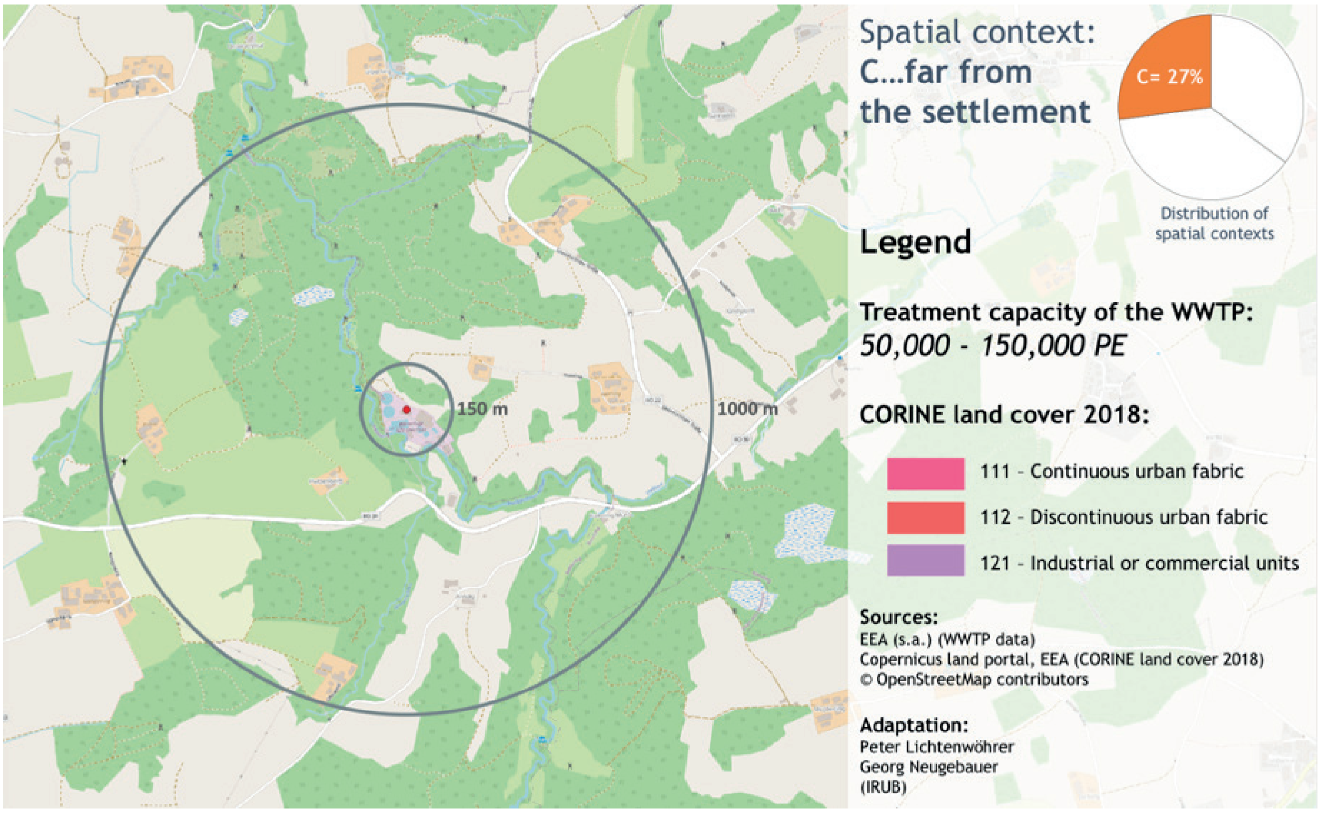
Figure 4.3
Visualisation of a WWTP located near to a settlement (own illustration, based on Neugebauer et al., 2015)



Finally, less than a third (27%) of all evaluated WWTPs in the CEU area were categorised as "far from the settlement", because no significant shares of areas in the considered land cover categories were identified indicating hardly any energy consumers within a radius of 1,000 m (see Figure 4.4 as an example).

Figure 4.4

Visualisation of a WWTP located far from a settlement (own illustration, based on NEUGEBAUER et al., 2015)



CEU PROGRAM AREA STRATEGY

4.2

4.2.1 Basis and Structure

The supposed CEU Program Area Strategy is based on the five regional strategies from Germany, Austria, Czech Republic, Italy and Croatia as well as on the position paper on legislation barriers, all elaborated in the REEF 2W project. It is considered a further developed strategy paper that highlights opportunities and impacts of REEF 2W at CEU level.

Hereby, the strategy consists of four parts/ thematic fields: a (1) legislative, an (2) operational, a (3) financial and a (4) connection part. Each part comprises its specific actions. The overall vision of the CEU Area Strategy is to form a set of actions to foster the use of energy from wastewater and the application of the REEF 2W approach in a broader context. The following contents are based on Kretschmer and Zlonoga, 2020.

4.2.2 Legislative Part

The first part of the strategy is about legislation. In order to foster the use of renewable energy from wastewater, legal and policy frameworks have to be adjusted in order to link energy, wastewater and solid waste sectors with the intention to maximise synergies and remove barriers for implementing joint renewable energy sources solutions.
The required actions are as follows:

Action 1.1. Regulatory pressure
Policy makers, higher officials and other appropriate stakeholders on EU and national level should introduce a certain regulatory pressure in regard to apply renewable energy solutions also considering energy from wastewater and its use and adjacent areas (beyond the premises of a wastewater treatment plant). Regulatory pressure is expected to speed up all processes.

Action 1.2. Adaption of legal frameworks and boundary conditions
Wastewater as renewable source of energy must be integrated in (national, regional, municipal) legal frameworks as well as in energy and climate planning and spatial planning frameworks. For wastewater based renewable energy sources implementation (including sludge treatment) all legal and policy boundary conditions must be set. Overall aim of this actions is to remove all barriers that are preventing renewable energy implementation in the wastewater sector and beyond.

4.2.3 Operational Part

The second part of the strategy is about operation. It concerns the adjustment of operational models of utilities running wastewater treatment plants in order to improve their business cases. Implementation of these actions allows wastewater treatment plants to also perform as a sort of energy provider. The required actions are as follows:

Action 2.1. Integration into existing supply systems

The purpose of this action is to adjust existing but possibly inhibitory regulations on national levels so that utilities running wastewater treatment plants can better invest in energy from wastewater solutions. In order to fully activate available renewable energy potentials, wastewater treatment plants must be recognised as energy producers and providers for their municipalities and communities. Operational preconditions for enabling the integration of electricity, gas and heat to local energy supply systems is imperative.

Action 2.2. Practical application of energy from wastewater

The practical implementation of energy generation from wastewater can be fostered by applying REEF 2W concepts and methodologies. A clear presentation of the benefits (e. g. support for domestic economy, decrease of dependency on energy imports and increase of innovation and research) related to the site-specific context as well as its technical and energetic characteristics will be supportive.

Action 2.3. Including biowaste in sewage sludge digestion

If available, municipal liquid and solid waste can be added to the anaerobic digestion of sewage sludge in a wastewater treatment plant to improve its energetic, economic and possibly also ecological performance.

Action 2.4. Sludge disposal scenarios

There is also a need to offer a holistic approach for sludge disposal. The different disposal scenarios (soil improver, incineration etc.) should be integrated into energy from wastewater considerations to allow comprehensive solutions.

4.2.4 Financial Part

The third part of the strategy is about finance. The application of energetic use of wastewater and the REEF 2W approach requires sufficient, predictable and long-term financial models also tailored to best use synergies between the energy, wastewater and waste sectors. The required action is as follows:

Action 3.1. Establishing financial models

To increase investments in wastewater based renewable energy sources a coordination of EU and national/regional governmental levels must be ensured for establishing clear subsidies, co-financing and other suitable financial models. Established models should include public-private investment models such as PPP (public-private partnership), EPC (energy performing contract) and various community energy investment models.

4.2.5 Connection Part

The fourth part of the strategy is about connection. This concerns the connection of stakeholders from the energy, the wastewater and the waste sector through national platforms, increase information, communication, education and capacity building measures. The required actions are as follows:

Action 4.1. National/transnational platform

A national platform should be established to inform and coordinate all relevant and interested stakeholders of the different institutions (public and private) and sectors (energy, wastewater and waste). Furthermore, the mission of the national platform shall encourage, promote and proactively support the broader implementation of the energetic use of wastewater and the REEF 2W approach. Although the presented strategy is elaborated in the scope of the CEU area it can be expanded towards additional transnational cooperation, to share knowledge and experience in only one transnational platform (representing all national ones). For all stated actions there is need for a combined approach, i.e. synchronized across sectoral legislations and policies at different political-administrative levels (national, regional, municipal). Hereby, a key aspect is to identify all relevant stakeholders on the different levels.

Action 4.2. Raising awareness by education and communication

For establishing energy from wastewater and the REEF 2W approach on as broader scale targeted communication, promotion and education is crucial. Related activities could be coordinated and organised by the before mentioned national platform.

Action 4.3. "Buddy system"

Experience from REEF 2W project shows that there are substantial differences in knowledge and experience concerning the energetic use of wastewater at wastewater treatment plants and the adjacent settlement structures among the different countries and regions involved in the project. To close related gaps the strategy proposes establishing a "buddy system" by matching unexperienced utilities/stakeholders with experienced ones. In this way transfer of good practice and direct education with an even bigger impact is expected.

Action 4.4. Renewable energy community model

Aligned with the Directive (EU) 2018/2001 and the European Green Deal wastewater treatment plants can be introduced into renewable energy community models where citizens, who are aware of energy sustainability, can participate. Because of their spatial location and specific function WWTPs are often perceived as isolated assets and not included in the community's (supply) infrastructure, that perception should be changed in the future.

CHALLENGES AND CONCLUSION

4.3

4.3.1 Challenges

The main challenges public and private operators of wastewater treatment plants are likely to face when implementing (some of the) suggested strategic actions can be summarised as follows:

- Adequate support from municipal/regional/national level of the government;
- Sufficient support from local community;
- Adequate legislative, policy and operational framework;
- System of incentives and finance models in general.

The suggested CEU program area strategy is structured and written in a way to deal with and to overcome those challenges.

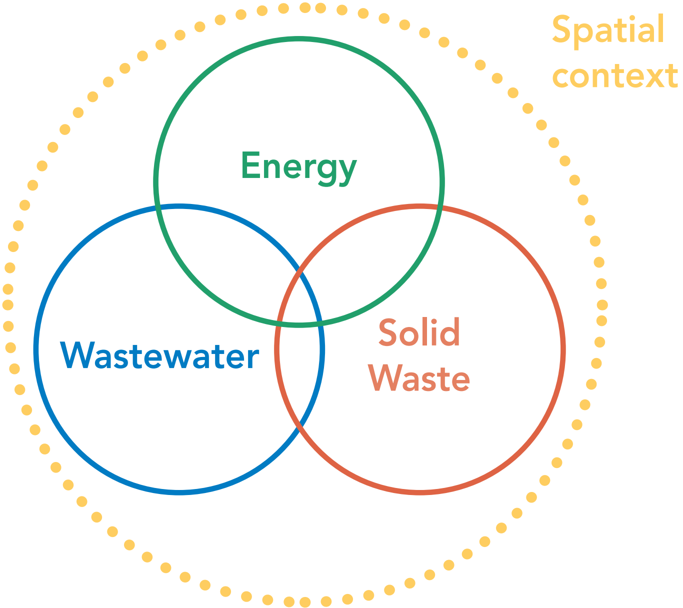
4.3.2 Conclusion

The estimations on the available energy potential (presented in chapter 3) clearly show that there is a large amount of energy available at CEU's wastewater treatment plants. Activating this today still widely unexploited potential can support the energy transition towards more climate-friendly systems and thus support the aims and goals of the European Green Deal.

Additional proactive efforts and actions are needed from all involved institutions, sectors and stakeholders to better harness this great potential of renewable energy sources found in wastewater. In this context it is crucial to link energy, wastewater and (solid) waste sectors in their specific spatial context (compare figure 4.5) also to maximise synergies from the implementation of joint renewable energy solutions to obtain a cleaner, healthier and more sustainable environment and society.

Figure 4.5

Energy, wastewater and (solid) waste sectors in a subordinate spatial context (Kretschmer and Zlonoga, 2020)



5

CONCLUSION

CONCLUSION

Wastewater as a source of renewable energy provides several options to support the ongoing energy transition towards more climate friendly energy systems. The chemical and thermal energy content of wastewater can be used to generate both, electricity and heat. Furthermore, the premises of wastewater infrastructures provide large open space which could be used for solar energy generation. Otherwise, gas from anaerobic digestion treatment (biogas) might also be upgraded to substitute natural gas, and the use of (liquid and solid) municipal waste as co-digestate can even help to increase gas generation outputs at WWTPs.

While the electric self-sufficiency of a WWTP in general only can be achieved by the use of co-digestate, the available thermal energy potential exceeds WWTP internal demand by far. Consequently, to make best use of the thermal potential the availability of external settlement structures in the vicinity of a WWTP can be a promising option as well.

To best support the integration of WWTPs into local energy supply concepts REEF 2W provides an integrated approach (integrated sustainability assessment) addressing a multitude of different aspects (energetic, spatial, environmental, economic and social contexts). It provides decision makers with a “big picture” of possibilities which wastewater as a renewable source of energy could play in their local-specific situations, allowing them to elaborate subsequently a strategic and targeted approach to best activate their still untapped energetic potentials. Practical applications are presented on the examples of five different case studies.

Beyond the local context, REEF 2W also presents different measures to promote wastewater as a source of renewable energy in a (trans-)national context on European level. Hereby, the suggestions address legislative, operational, financial as well as (stakeholder-) connection issues. These points can provide guidance to develop an (organisational) framework for establishing wastewater as one component of a future climate friendly and diversified energy mix in a broad context.

APPENDIX 1

Appendix 1 - Energetic assessment

1.1 Electric and thermal energy from digester gas

Input data required:

- SG_{total} = monthly amount of digester gas in m³/mo (default values also applicable)
- c_{CH4} = methane content in % (default values also applicable)
- e_{cont} = energy content of methane in kWh/m3 (default values also applicable)
- SG_{grid} = monthly part of digester gas fed into the grid in m³/mo (default value 0)
- eff_{el} = electric efficiency of the CHP unit in % (default values also applicable)
- eff_{th} = thermal efficiency of the CHP unit in % (default values also applicable)

Applied formulas:

- $E_{el} = (SG_{total} - SG_{grid}) * c_{CH4} * e_{cont} * eff_{el}$
- $E_{th} = (SG_{total} - SG_{grid}) * c_{CH4} * e_{cont} * eff_{th}$

Calculated outputs:

- E_{el}: monthly generated electric energy from digester gas available at the WWTP in kWh/month
- E_{th}: monthly generated thermal energy from digester gas available at the WWTP in kWh/month

1.2 Thermal energy potential from wastewater heat recovery

Input data required:

- Q_{WW}: monthly average of wastewater flow at the WWTP in m³/mo
- f_{TW}: monthly part of dry weather wastewater flow in % (default values also applicable)
- T_{WW}: monthly average of wastewater temperature at the WWTP in °C
- T_{min}: technical minimum temperature of wastewater after heat recovery in °C (default value 5)
- T_{heat}: temperature needed for the supply (to be reached in the heat pump circuit) in °C (default values also applicable)
- CF: Carnot grade: factor between real COP and maximum possible COP at given temperatures (Carnot cycle) (default value 0,45)

Applied formulas:

- monthly available thermal potential from wastewater heat recovery: $P_{th} = 1,16 * Q_{WW} * f_{TW} * (T_{WW} - T_{min})$
- coefficient of performance per month of the heat pump: $COP = CF * (273 + T_{heat}) / (T_{heat} - T_{WW})$ (default values also applicable)
- monthly needed electric potential: $P_{el} = P_{th} / (COP - 1)$

- monthly available total thermal potential from the heat pump system: $P_{total} = P_{th} + P_{el}$

Calculated outputs:

- P_{th}: monthly thermal potential recovered from wastewater available at the WWTP in kW
- P_{el}: monthly electric energy needed for heat pump(s) in kW
- P_{total}: monthly available thermal energy supply available at the WWTP in kW (sum of thermal energy from wastewater and electric energy for the (compressor) heat pump)

1.3 Additional sources

1.3.1 Solar energy

Input data required (all types)

- W_{sol}: solar irradiance per month in kWh/m²*month (default values also applicable)

1.3.2 Photovoltaics

Additional needed inputs:

- A_{PV}: PV collector surface in m²
- $eff_{el,PV}$: electric efficiency of the PV plant in %

Applied formulas:

- $E_{el,PV} = W_{sol} * A_{PV} * eff_{el,PV}$

Calculated output:

- monthly electric energy generated by the PV plant at the WWTP in kWh/month

1.3.3 Solar thermal

Additional needed inputs

- $A_{sol.th}$: solar thermal collector surface in m^2
- $eff_{th,sol.th}$: thermal efficiency of the solar thermal plant in % (default values also applicable)

Applied formulas:

- $E_{th,sol.th.} = W_{sol} * A_{sol.th.} * eff_{th,sol.th}$

Calculated output:

- monthly thermal energy generated by the solar thermal plant at the WWTP in kWh/month

1.3.4 Hybrid

Additional needed inputs:

- A_{hyb}: applicable PV surface in m²
- $eff_{el,hyb}$ electric efficiency of the solar hybrid power plant in %
- $eff_{th,hyb}$ thermal efficiency of the solar hybrid power plant in %

Applied formulas:

- $E_{el,hyb} = W_{sol} * A_{hyb} * eff_{el,hyb}$
- $E_{th,hyb} = W_{sol} * A_{hyb} * eff_{th,hyb}$

Calculated output:

- monthly electric energy generated by the solar hybrid power plant at the WWTP in kWh/month
- monthly thermal energy generated by the solar hybrid power plant at the WWTP in kWh/month

1.3.5 Solar total

Applied formulas:

- $E_{el} = E_{el,PV} + E_{el,hyb}$
- $E_{th} = E_{th,sol.th} + E_{th,hyb}$

Calculated output:

- monthly electric energy generated by

the solar power plants (of all 3 types together) at the WWTP in kWh/month
- monthly thermal energy generated by solar power plants (of all 3 types together) at the WWTP in kWh/month

1.3.6 Hydropower

Input data required:

- Q_{WW}: monthly average of wastewater flow at the WWTP in m³/month
- h: drop height at the effluent of the WWTP in m
- eff_{hpp}: efficiency of turbine and generator in % (default values also applicable)

Applied formulas:

- $E_{el} = Q_{WW} * h * eff_{hpp} * 9{,}81/3600$

Calculated output:

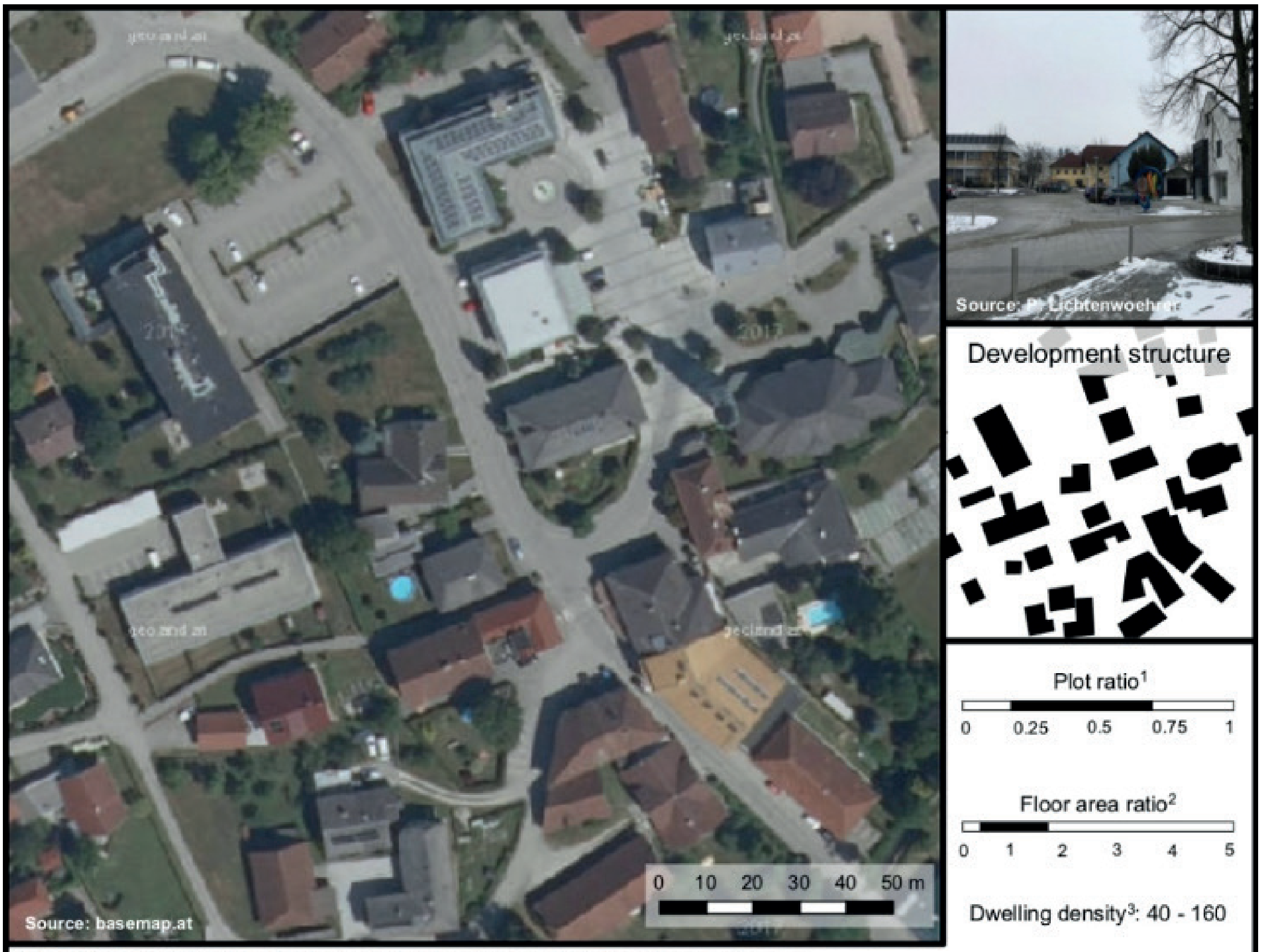
- E_{el}: monthly generated electric energy from hydropower available at the WWTP in kWh/month

APPENDIX 2

Appendix 2 - Spatial assessment

List of settlement structures:

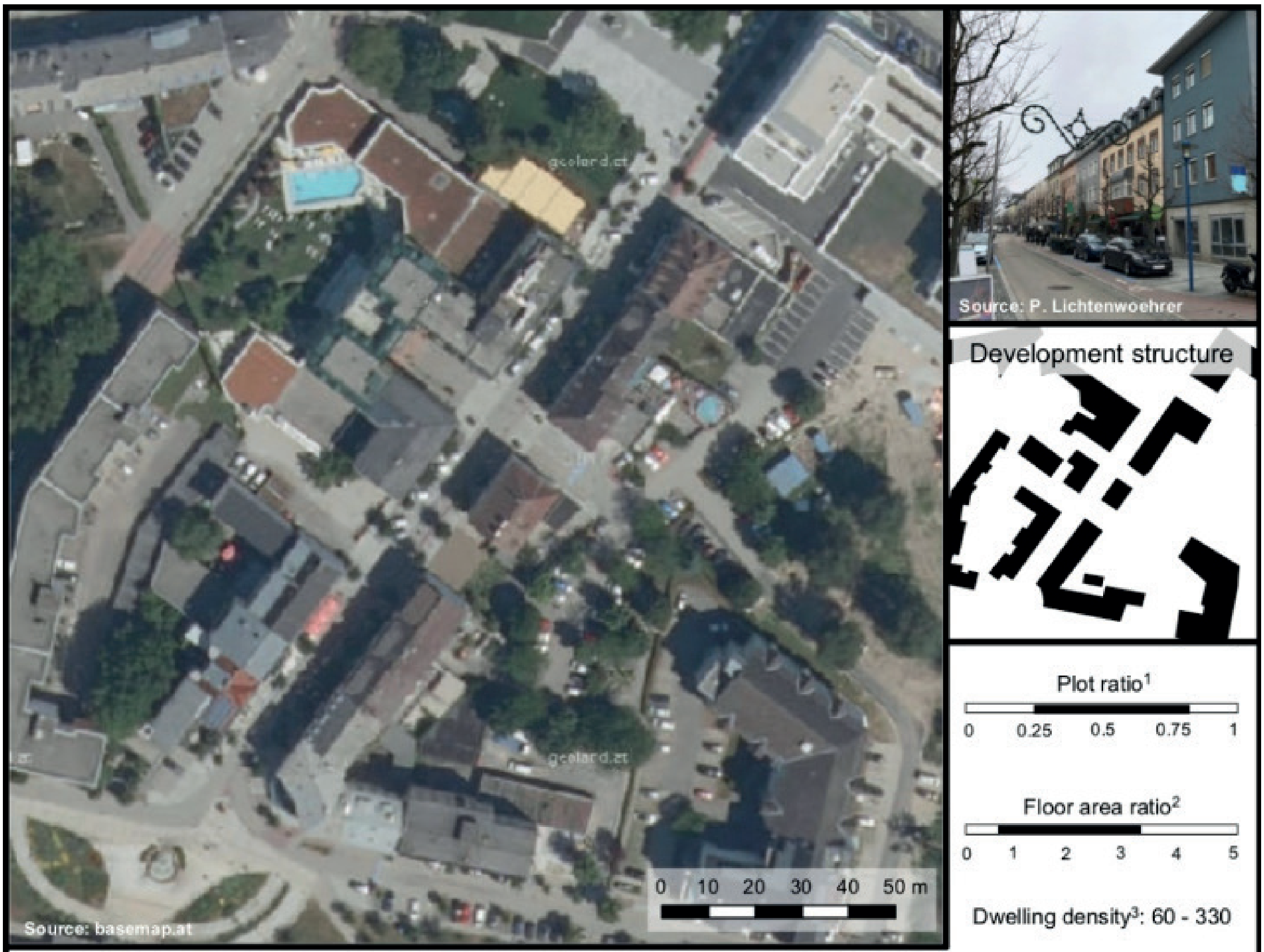
Figure A2.1: Village Centre



[1] The plot ratio describes the building footprint of the buildings in relation to the total area of the plots.
[2] The floor area ratio describes the relation between the usable gross floor area of the buildings in relation to the total area of the plots.
[3] The dwelling density refers to the number of dwelling units per hectare.

(Values derived from Hegger & Dettmar 2014)

Figure A2.2: Small town (centre - low density)



[1] The plot ratio describes the building footprint of the buildings in relation to the total area of the plots.
[2] The floor area ratio describes the relation between the usable gross floor area of the buildings in relation to the total area of the plots.
[3] The dwelling density refers to the number of dwelling units per hectare.

(Values derived from Hegger & Dettmar 2014)

Figure A2.3: Small town (centre - high density)

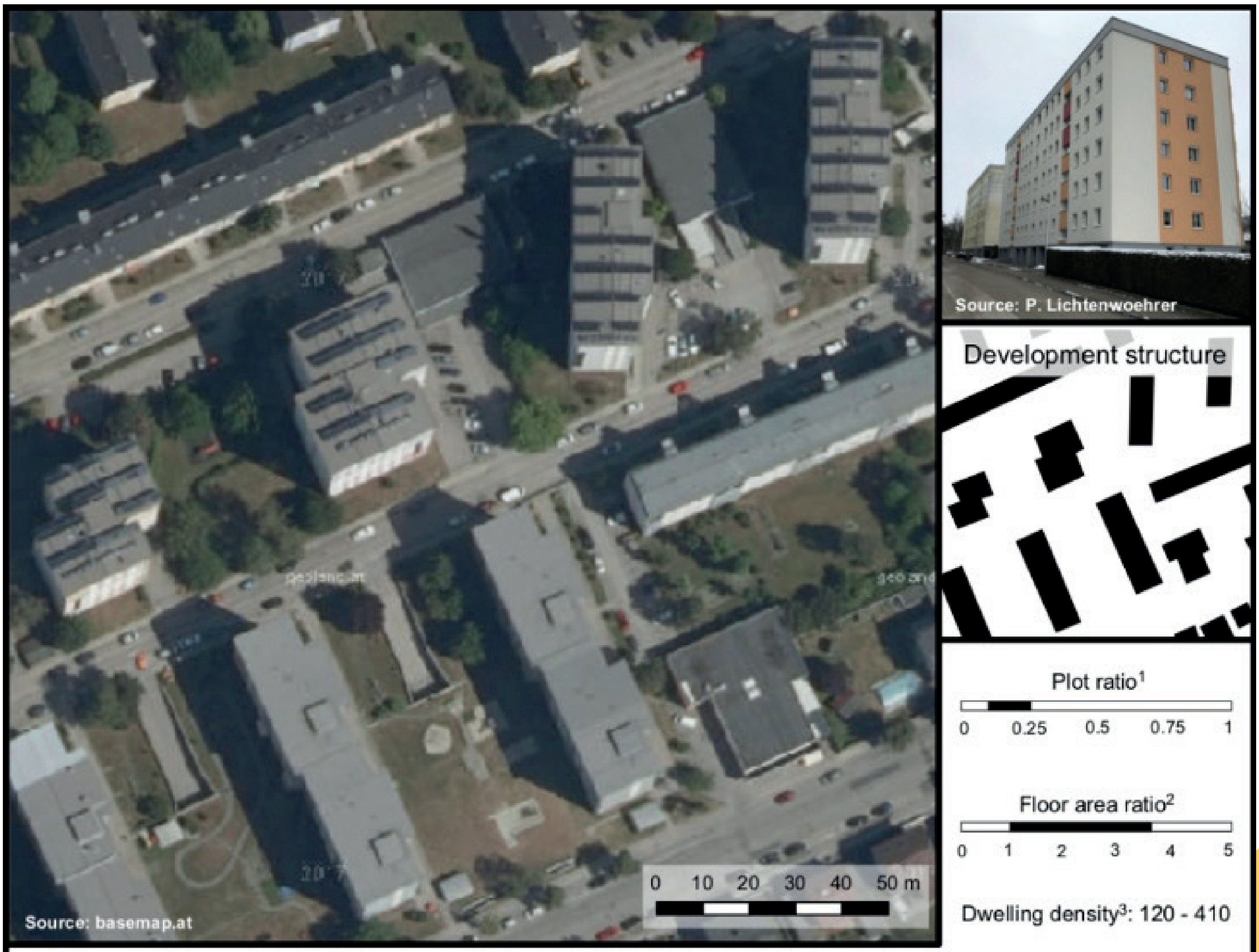
[1] The plot ratio describes the building footprint of the buildings in relation to the total area of the plots.

[2] The floor area ratio describes the relation between the usable gross floor area of the buildings in relation to the total area of the plots.

[3] The dwelling density refers to the number of dwelling units per hectare.

(Values derived from Hegger & Dettmar 2014)

Figure A2.4: Multi-storey buildings (high density)



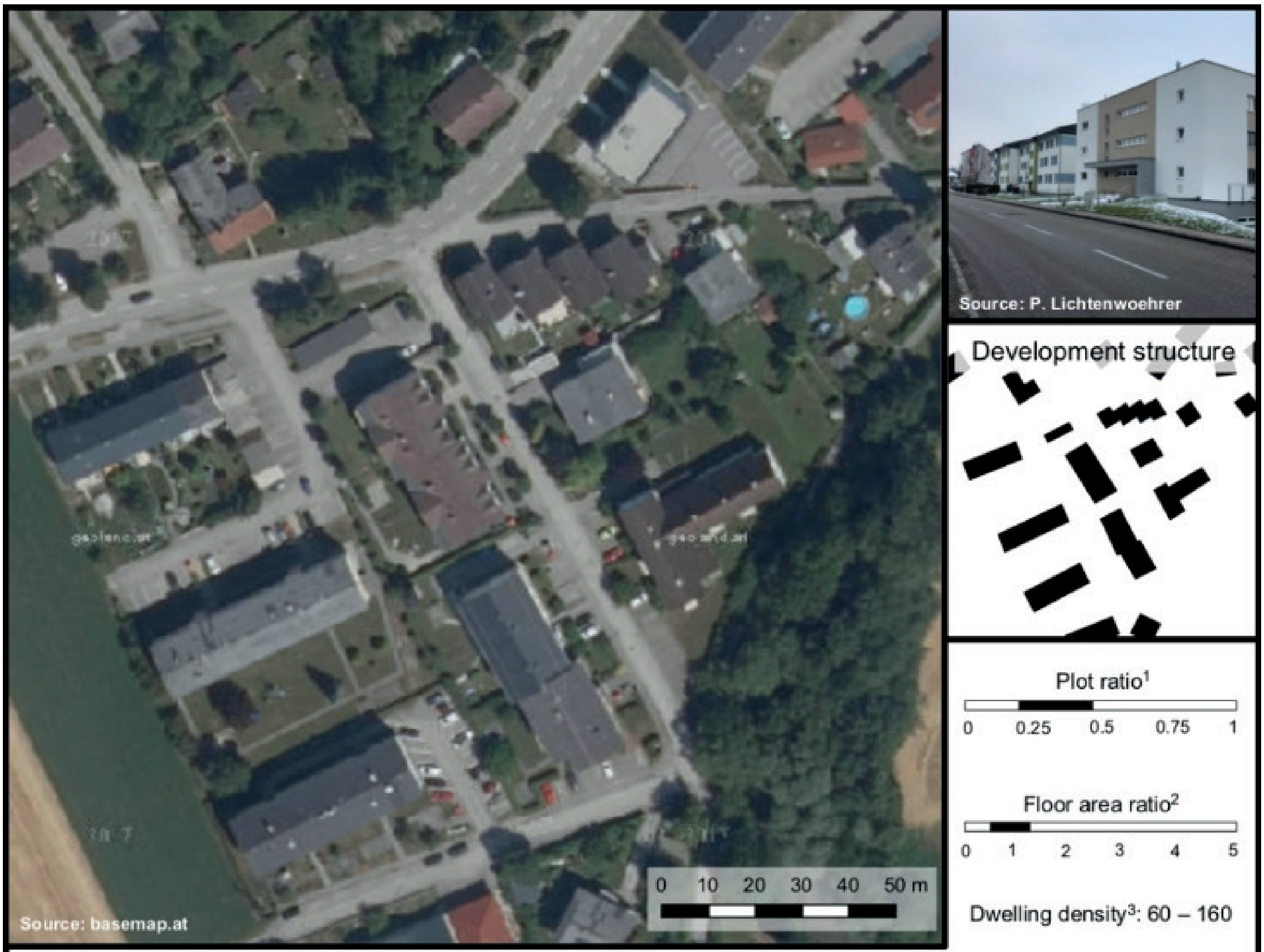
[1] The plot ratio describes the building footprint of the buildings in relation to the total area of the plots.

[2] The floor area ratio describes the relation between the usable gross floor area of the buildings in relation to the total area of the plots.

[3] The dwelling density refers to the number of dwelling units per hectare.

(Values derived from Hegger & Dettmar 2014)

Figure A2.5: Multi-storey buildings (low density)



Source: basemap.at

Source: P. Lichtenwoehrer

[1] The plot ratio describes the building footprint of the buildings in relation to the total area of the plots.

[2] The floor area ratio describes the relation between the usable gross floor area of the buildings in relation to the total area of the plots.

[3] The dwelling density refers to the number of dwelling units per hectare.

(Values derived from Hegger & Dettmar 2014)

Figure A2.6: Commerce and industry

Source: basemap.at

Source: P. Lichtenwoehrer

Figure A2.7: Agriculture and forestry

Source:
Jana Messinger, Ökologisch-Botanischer Garten (ÖBG), Universität Bayreuth

APPENDIX 3

Appendix 3 - Environmental assessment

Table A3.1: GWP factors based on LCA database Ecoinvent

Material / Process	GWP (IPCC 2013 for 100 years)	Unit	Ecoinvent v3.4 dataset
Electricity mix EU	0.39	kg CO_2-eq/kWh	market group for electricity, medium voltage [RER]
Electricity mix DE	0.627	kg CO_2-eq/kWh	market for electricity, medium voltage [DE]
Electricity mix AT	0.295	kg CO_2-eq/kWh	market for electricity, medium voltage [AT]
Electricity mix IT	0.381	kg CO_2-eq/kWh	market for electricity, medium voltage [IT]
Electricity mix HR	0.286	kg CO_2-eq/kWh	market for electricity, medium voltage [HR]
Electricity mix CZ	0.69	kg CO_2-eq/kWh	market for electricity, medium voltage [CZ]
Gas	0.23	kg CO_2-eq/kWh	natural gas, burned in gas motor, for storage [RoW]
Heat	0.202	kg CO_2-eq/kWh	market for heat, district or industrial, natural gas [Europe without Switzerland]
FeCl3	0.949	kg CO_2-eq/kg FeCl3 (100%)	market for iron (III) chloride, without water, in 40% solution state [GLO]
Polyaluminum chloride	1.389	kg CO_2-eq/kg PACl (100%)	market for polyaluminium chloride [GLO]
Polymer	2.087	kg CO_2-eq/kg polymer	market for acrylonitrile [GLO]
Acetate	1.584	kg CO_2-eq/kg acetate	market for acetic acid, without water, in 98% solution state [GLO]
Methanol	0.659	kg CO_2-eq/kg methanol	market for methanol [GLO]

Table A3.2: GWP factors based on LCA database Ecoinvent

Material / Process	GWP (IPCC 2013 for 100 years)	Unit	Ecoinvent v3.4 dataset
N_2O from biological treatment	2.5	kg CO_2-eq/kg N in influent	Wicht 1996
CH_4 in sludge treatment	0.017	kg CO_2-eq/kg TS in digestate	Estimate for CH4 emissions at centrifuge
CHP	0.00347	kg CO_2-eq/MJ CH4 in biogas	Ronchetti et al. 2002
Flare	0.00347	kg CO_2-eq/MJ CH4 in biogas	Ronchetti et al. 2002
Carbon source acetate	1.47	kg CO_2-eq/kg acetate	Based on chemical formula
Carbon source methanol	1.375	kg CO_2-eq/kg methanol	Based on chemical formula
Mono-incineration	325,000	kg CO_2-eq/kg TS in digestate	Remy and Jossa 2015
Co-incineration	-500,000	kg CO_2-eq/kg TS in digestate	Remy and Jossa 2015
HTC	110,000	kg CO_2-eq/kg TS in digestate	Remy et al 2014
Composting	100,000	kg CO_2-eq/kg TS in sludge	Kraus et al 2016
Agricultural use	-10	kg CO_2-eq/kg N in digestate	Dataset of ecoivent v3.3/3.4: market for nitrogen fertiliser, as N [GLO]
	-2.37	kg CO_2-eq/kg P in digestate	market for phosphate fertiliser, as P2O5 [GLO]
Landfilling	1,500,000	kg CO_2-eq/kg TS in sludge	Assumption according to Fehrenbach 2002

APPENDIX 4

Appendix 4 - Integrated Sustainability Assessment (ISA)

Table A4.1: List of indicators

	General indicator	Measurement	Categories	Graduation
Availability of excess energy	Electric excess energy provision	Difference between electric energy production and consumption in kWh	> 0 ≤ 0	A B
	Thermal excess energy provision	Difference between thermal energy production and consumption in kWh	> 0 ≤ 0	A B
	Excess digester gas provision	Difference between digester gas production and consumption in m^3	> 0 ≤ 0	A B
Availability of energy consumers	Excess electricity demand	Electricity demand in the vicinity of the WWTP and in kWh	> 0 = 0	A B
	Excess heat demand	Heat demand in the vicinity of the WWTP and in kWh	> 0 = 0	A B
	Excess digester gas demand	Digester gas demand in the vicinity of the WWTP and in kWh	> 0 = 0	A B

Table A4.2: List of specific indicators

	Indicator	Measurement	Categories	Graduation
Environmental context	CO_2 emissions reduction for consumed electric energy (internal and external)	in %	> 0 = 0	A B
	CO_2 emissions reduction for consumed thermal energy (internal and external)	in %	> 0 = 0	A B
	Share of renewable electricity (internal and external)	in %	> 100 100-0 0	A B C
	Share of renewable thermal energy (internal and external)	in %	> 100 100-0 0	A B C
	Share of renewable gas (external)	in %	> 100 100-0 0	A B C
	Sludge production change	Delta t DM / year	<0 0 >0	A B C
Social context	Affordable energy	in %	Lower Same (+-10 %) Higher	A B C
	Number of applied technologies for electric energy provision (Resilience)	Quantity	3 1-2 0	A B C
	Number of applied technologies for thermal energy provision (Resilience)	Quantity	3 1-2 0	A B C
	Additional employment	Change of employment, job creation or loss	>0 0 <0	A B C
	Local environmental welfare	Indication of local welfare change	Positive Neutral Negative	A B C

	Indicator	Measurement	Categories	Graduation
Economic context	Return of Investment (ROI)	Years	<3 3-10 >10	A B C
	Additional income	in €	>0 0 <0	A B C
	Energy costs saving	in €	>0 0 <0	A B C
Technical context (energetic & spatial)	Degree of electric self-sufficiency	Ratio between electric energy production and consumption in %	>75 25-75 <25	A B C
	Degree of thermal self-sufficiency	Ratio between thermal energy production and consumption in %	>100 20-100 <20	A B C
	Degree of externally usable excess heat	Ratio between heat production and consumption in %	> 0 0	A B
	Degree of usable excess gas	Ratio between gas production and consumption in %	> 0 0	A B
	Electric energy consumption at WWTP	kWh/PE$_{120}$*year	< 20 20 - 50 > 50	A B C
	Thermal energy consumption at WWTP	kWh/PE$_{120}$*year	<30 > 30	A B
	Electric energy generation at WWTP (with anaerobic stabilisation)	kWh/PE$_{120}$*year	>20 10-20 <10	A B C
	Thermal energy generation at WWTP (with anaerobic stabilisation)	kWh/PE$_{120}$*year	>40 20-40 <20	A B C

APPENDIX 5

Appendix 5 - Support tool description

The tool implemented in the framework of the European Project Interreg Central Europe REEF 2W is a decision support model, able to support operators involved in organic waste and wastewater treatment sector in order to identify any energy-less efficient treatment stages, and build future scenarios to implement processes able to recover energy from the available streams or through the implementation of auxiliary technologies.

The tool is born from the need to manage, in a single large container, the municipal wastewater treatment plants energy performance, together with waste management and technologies to produce renewable energy.
Its main objective is the evaluation of the electrical and thermal energy efficiency of the treatment plants according to benchmarks identified by the literature analysis and the previous experience of the partners.
It includes the possibility to investigate the best technology to produce energy from renewable sources, depending on available biomass and existing and future technologies.

It is also composed of a spatial, environmental and economic assessment observing the integration of plants with the municipality, calculating the positive or negative contribution in terms of carbon dioxide emissions into the environment and estimating the investment, operation and maintenance cost.
The possible temporal evaluations within the tool are two: one evaluation, photograph of the state of affairs, in terms of technologies already implemented at the moment when you use the software, and an estimate of the benefit that could be obtained by using other applications in the future.

The tool is developed in VBA - Visual Basic For applications: programming language included in Excel suite in Microsoft Office. This is because it must be accessible to all sector operators, technicians and politicians, without having to install additional applications on their computer. The VBA is a programming language that allows you to integrate dialog boxes, defined Userform, a graphical interface, created “ad hoc”, that allows you to enter and see data, and spreadsheets. In the event that the user is unable to provide all the detailed parameters, the tool can still make an estimate based on the available data in the internal database.

From the implementation of each technology within spreadsheets to integration with dialog boxes
Although in the background there are several linked spreadsheets, to the user initially, after a brief general description, it is asked

whether it wishes to carry out a wastewater treatment plant or a plant for the treatment of the organic fraction of municipal solid waste analysis. The internal database in terms of substrates that can be analysed contains both urban and industrial waste, both liquid and semi-solid.

In case the analysis of a wastewater treatment plant is faced out the first assessment is related to the energy efficiency degree of the existing wastewater treatment. The evaluation is carried out by analysing the treatment process in terms of electrical and thermal energy consumption. Based on these consumptions, benchmarking indices are calculated, in a systematic and continuous process of comparing the performance of an organization with excellence known values, not only in order to match similar levels of performance, but to overcome them. This analysis gives a first indication as to whether it is worth going directly with the implementation of new technologies for the energy production or simply to analyse the critical points highlighted by the energy efficiency study and solve them, bringing the plant within the benchmark values before facing the possibility of producing new energy.

The waste choice, in terms of the used substrates, forms the basis of the analysis for the evaluation and calculation of energy and mass balance contributions for the specific technologies implemented. The analysable technologies list includes anaerobic digestion, biogas upgrading with biomethane production and the possibility of producing methane through power to gas, heat pump and incineration with thermal and electrical energy production. In addition to the technologies more closely related to the wastewater treatment sector, the user is given the opportunity to analyse other clean technologies: photovoltaic, solar thermal, hybrid collector and hydroelectric power plants.

In order to obtain an overall evaluation of plants and municipalities, a spatial assessment was developed in which the integration of the plant, wastewater purification and/or energy production, and surrounding town is verified. This tool provides an assessment of the connection degree between the two, which makes it possible to see how much the connection efficient is.

In view of the 2020 climate & energy package and reduction of the carbon dioxide emission in the atmosphere, the carbon footprint assessment has been included in the tool: for each analysed and selected technology the carbon footprint is assessed, in terms of carbon dioxide issued or on credit.

Finally, the user can conduct an economic assessment for each investigated technology, in terms of investment, operating and maintenance costs incurred.

The database included in the tool, which is not directly visible, helps the user by providing default values if the requested data is not known.

Following the first analysis carried out within the tool, which provides a global indication of the state-of-the-art of the analysed technologies, the user can construct future scenarios by implementing and identifying new processes that meet energy spatial, environmental and economic needs.

The tool advantages

The articulated structure and the smart being make this tool unique. Having been implemented based on the needs that the partners have identified through their experience in order to be useful to a wider audience of users, this tool has many strengths.

Among these, there is the possibility of being able to store all the necessary data giving the user the opportunity to fill in the different fields in successive steps, this in case he was not immediately equipped with all the required data. In addition, it was thought to provide at the opening of the Tool a PDF file that summarizes all the steps and all the software requests. In this way the user can prepare himself before starting the tool by searching for all the data necessary for the correct compilation.

Another strong point of the Tool is the usability and ease of understanding the results. The idea behind the report is precisely to provide the user not only easily decipherable numbers, but above all to make it compact and concrete at the same time. It is presented with a set of basic information representing the starting data and, where possible, with the expression of the result in the form of a graph or numerical percentage. Thanks to the benchmarking analysis, the result is often combined with a reference range in order to be able to evaluate the energy efficiency of the plant compared to similar applications.

Another peculiarity of the tool is the possibility to reset all the data and all the choices at the opening, in case it was compiled in a step: this on the one hand allows to leave track of the previous analyses, without having to reinsert all the data, allowing on the other hand to speed up the cleaning of all data entered.

Future implementation

The tool has been first implemented using the English language in order to make it available to all project partners. It has also been designed to be translated into a number of other languages (i.e. German, Italian) continuously expandable.

The internal structure of the tool allows its adaptability over time to future implementations that concern the possibility to expand its internal database, inserting new technologies and new information. For such a reason, it can be easily connected to an external database, including new spreadsheets and new tools implemented in VBA.

An actionable choice is the possibility to connect the tool to other ones already usable within online platforms: only unknown is the usability of an Internet connection.

REFERENCES

Chapter 1: Introduction

1. BWB, Interviewee, personal communication and exchange with operating personnel(Kennzahlen und Betriebsbilanz). [Interview]. 2018.
2. BWB, „Unsere Tarife für Trinkwasser und Abwasser," Berliner Wasserbetriebe, 10 November 2017. [Online]. Available: http://www.bwb.de/content/language1/html/204.php. [Zugriff am 10 08 2018].
3. BWB, „Vom Schmutzwasser zum Spreewasser," 2019. [Online]. Available: http://www.bwb.de/de/981.php. [Zugriff am 2019].
4. D. Cazalet, C. Loderer und M. Biegel, „WP5 - Integration towards full plant concept, assessment and market replication," 5.6 Market validation for new concepts, 06 2018. [Online]. Available: http://powerstep.eu/system/files/generated/files/resource/d-5-6-market-validation-for-new-concepts.pdf.
5. Ecoinvent, „Ecoinvent data v3.4, ecoinvent reports No. 1-26," Swiss Center for Life Cycle Inventories, www.ecoinvent.org.
6. European Commission, "Environmental Assessment," 03/01/2019. [Online]. Available: http://ec.europa.eu/environment/eia/index_en.htm.
7. European Commission, "Urban Wastewater Directive Overview," 12 2 2019. [Online]. Available: http://ec.europa.eu/environment/water/water-urbanwaste/index_en.html. [Accessed 2 6 2019].
8. K. Fricke, „ENERGIEEFFIZIENZ K," Umweltbundesamt, Oktober 2009. [Online]. Available: https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/3855.pdf. [Zugriff am 10 8 2018].
9. B. Haberkern und at el., „Steigerung der Energieeffizienz auf kommunalen, Dessau" 2006. [Online]. Available: https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/3347.pdf. [Zugriff am 03 07 2018].
10. IPCC, „Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change" IPCC, Geneva, Switzerland, 2014.
11. ISO 14040:2006, Environmental management - Life cycle assessment - Principles and framework, Berlin: Beuth Verlag GmbH.
12. ISO 14044:2006, Umweltmanagement — Ökobilanz — Anforderungen und Anleitungen, Brussels: CEN-CENELEC Management Centre.

13. J. A. Nathanson und A. Ambulkar, „Wastewater treatment," 11 May 2018. [Online]. Available: https://www.britannica.com/technology/wastewater-treatment. [Zugriff am 10 06 2018].

14. C. Remy, L. Corominas und at el., Innovative Wastewater Treatment & Resource Recovery Technologies, 1 Hrsg., London: IWA Publishing, 2017.

15. U. Schließmann und at el., „Energieeffiziente Kläranlagen - Hochlastfaulung für Klärschlamm," Fraunhofer IGB, n.D. [Online]. Available: https://www.igb.fraunhofer.de/content/dam/igb/de/documents/Broschüren/Energieeffiziente_Klaeranlagen__Hochlastfaulung_fuer_Klaerschlamm.pdf. [Zugriff am 1 09 2018].

16. Stadtwerke Berlin, Interviewee, Biomethan- , Strom- , Erdgaspreis. [Interview]. 30 07 2018.

17. Statistisches Bundesamt, „2013: Öffentliche Kläranlagen behandelten," Pressemitteilung - 386/15 Statistisches Bundesamt, 16 Oktober 2015. [Online]. Available: https://www.destatis.de/DE/PresseService/Presse/Pressemitteilungen/2015/10/PD15_386_322pdf.pdf?__blob=publicationFile. [Zugriff am 01 09 2018].

18. Steve Tarallo (2014) Utilities of the Future Energy Findings IWA Publishing https://doi.org/10.2166/9781780406800

19. H. Yoshida und at el., Life cycle assessment of sewage sludge treatment and its use on land, Denmark: Technical unicersity of denmark, 2014.

Chapter 2: REEF 2W approach

20. Abart-Heriszt L, Erker S, Stoeglehner G (2019) The Energy Mosaic Austria - A Nationwide Energy and Greenhouse Gas Inventory on Municipal Level as Action Field of Integrated Spatial and Energy Planning. Energies 12:3065. https://doi.org/10.3390/en12163065.

21. Buytaert V, Muys B, Devriendt N, et al (2011) Towards integrated sustainability assessment for energetic use of biomass: A state of the art evaluation of assessment tools. Renewable and Sustainable Energy Reviews 15:3918-3933. doi: 10.1016/j.rser.2011.07.036.

22. Ecoinvent. (s.a. Datum). Ecoinvent data v3.4, Ecoinvent reports No. 1-26. www.ecoinvent.org: Swiss Center for Life Cycle Inventories.

23. Erker S, Lichtenwoehrer P, Zach F, Stoeglehner G (2019) Interdisciplinary decision support model for grid-bound heat supply systems in urban areas. Energ Sustain Soc 9:11. https://doi.org/10.1186/s13705-019-0193-4.

24. EU (2018) Directive 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. European Parliament and the Council, Brussels.

25. European Commission (03/01/2019). Environmental Assessment. Von Environmental: http://ec.europa.eu/environment/eia/index_en.htm abgerufen

26. Hacking T, Guthrie P (2008) A framework for clarifying the meaning of Triple Bottom-Line, Integrated, and Sustainability Assessment. Environmental Impact Assessment Review 28:73-89. doi: 10.1016/j.eiar.2007.03.002.

27. Hao X, Li J, van Loosdrecht MCM, et al (2019) Energy recovery from wastewater: Heat over organics. Water Research 161:74-77. https://doi.org/10.1016/j.watres.2019.05.106.

28. Hegger M, Dettmar J (eds) (2014) Energetische Stadtraumtypen: strukturelle und energetische Kennwerte von Stadträumen. Fraunhofer IRB Verlag, Stuttgart.

29. ISO 14040:2006. (s.a. Datum). Environmental management - Life cycle assessment - Principles and framework. Berlin: Beuth Verlag GmbH.

30. ISO 14044:2006. (s.a. Datum). Umweltmanagement - Ökobilanz - Anforderungen und Anleitungen. Brussels : CEN-CENELEC Management Centre.

31. IPCC. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC.

32. Kollmann R, Neugebauer G, Kretschmer F, et al (2017) Renewable energy from wastewater - Practical aspects of integrating a wastewater treatment plant into local energy supply concepts. Journal of Cleaner Production 155:119-129. https://doi.org/10.1016/j.jclepro.2016.08.168.

33. Lichtenwoehrer P, Neugebauer G, Zach F, Kretschmer F (2019) Demonstration des REEF 2W-Tools. Wiener Mitteilungen. In: Abwasserwirtschaft im ländlichen Raum 2019. RSA, Wien, pp J1-J13.

34. Lindtner, S. (2008): Leitfaden fuer die Erstellung eines Energiekonzeptes kommunaler Klaeranlagen (Guideline for the development of an energy concept for municipal wastewater treatment plants). Austrian Federal Ministry of Agriculture and Forestry, Environment and Water Management (BMLFUW), Vienna.

35. Müller A, Hummel M, Kranzl L, et al (2019) Open Source Data for Gross Floor Area and Heat Demand Density on the Hectare Level for EU 28. Energies 12:4789. https://doi.org/10.3390/en12244789.

36. Neugebauer G, Kretschmer F, Kollmann R, et al (2015) Mapping Thermal Energy Resource Potentials from Wastewater Treatment Plants. Sustainability 7:12988-13010. https://doi.org/10.3390/su71012988.

37. Nussbaumer T, Thalmann S, Jenni A, Ködel J (2017) Planungshandbuch Fernwärme. Bundesamt für Energie, Ittigen.

38. Stoeglehner G, Narodoslawsky M (2008) Implementing ecological footprinting in decision-making processes. Land Use Policy 25:421-431.

39. Remy, C., Corominas, L., & at el. (2017). Innovative Wastewater Treatment & Resource Recovery Technologies (1 Ausg.). London: IWA Publishing.

40. Stoeglehner G, Narodoslawsky M (2008) Implementing ecological footprinting in decision-making processes. Land Use Policy 25:421-431. doi: 10.1016/j.landusepol.2007.10.002.

41. Stoeglehner G, Neugebauer G, Erker S, Narodoslawsky M (2016) Integrated Spatial and Energy Planning - Supporting Climate Protection and the Energy Turn with Means of Spatial Planning. Springer International Publishing, Cham.

42. Wang J-J, Jing Y-Y, Zhang C-F, Zhao J-H (2009) Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renewable and Sustainable Energy Reviews 13:2263-2278. doi: 10.1016/j.rser.2009.06.021.

43. Yoshida, H., & at el. (2014). Life cycle assessment of sewage sludge treatment and its use on land. Denmark: Technical University of Denmark.

44. Zach F, Lichtenwoehrer P, Neugebauer G, Kretschmer F (2019) REEF 2W Machbarkeitsstudie - Fallbeispiel RHV Trattnachtal. Wiener Mitteilungen. In: Abwasserwirtschaft im ländlichen Raum 2019. RSA, Wien.

Chapter 3: REEF 2W application

45. Abart-Heriszt, Erker S., Reichel S., et al. (2019): Energiemosaik Austria. Österreichweite Visualisierung von Energieverbrauch und Treibhausgasemissionen auf Gemeindeebene. EnCO2Web. FFG, BMVIT, Stadt der Zukunft. Wien, Salzburg. Lizenz: CC BY-NC-SA 3.0 AT. https://www.energiemosaik.at/intro (accessed Feb. 13, 2020).

46. Colijn B. (2014) Green Jobs in Europe and the Increasing Demand for Technical Skills. NeuJob working paper No.4.2. - http://www.neujobs.eu/sites/default/files/publication/2014/02/Neujobs_Del4.2_27012014%20.pdf.

47. Hoi-Seong Jeong. (2013) On Environmental Welfare Policy and Its Measurements - https://slideplayer.com/slide/4753205/.

48. Lichtenwoehrer P., Abart-Heriszt L., Kretschmer F., Suppan F., Stoeglehner G., Neugebauer G. (submitted for publication): Evaluating spatial interdependencies of sector coupling using spatiotemporal modelling.

49. Lindtner, S. (2008): Leitfaden fuer die Erstellung eines Energiekonzeptes kommunaler Klaeranlagen (Guideline for the Development of an energy concept for municipal wastewater treatment plants). Austrian Federal Ministry of Agriculture and Forestry, Environment and Water Management (BMLFUW), Vienna.

50. Nussbaumer T., Thalmann S., Jenni, A., Ködel, J. (2017): Planungshandbuch Fernwärme. Bundesamt für Energie, Ittigen.

51. Statistik Austria: Gesamtenergiebilanz Österreich 1970 bis 2018 (Detailinformation). https://www.statistik.at/web_de/statistiken/energie_umwelt_innovation_mobilitaet/energie_und_umwelt/energie/energiebilanzen/index.html (accessed May 07, 2020).

Chapter 4: REEF 2W strategy

52. Bodík, I. et al. (2011) Biogas production in municipal wastewater treatment plants - Current status in EU with a focus on the Slovak Republic. Chemical and Biochemical Engineering Quarterly, 25(3), pp. 335-340.
53. CORINE land cover (2018) Available online: https://land.copernicus.eu/pan-european/corine-land-cover (accessed in Apr. 2020).
54. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast).
55. Directive - reported data. Online in the Internet: https://www.eea.europa.eu/data-and-maps/data/waterbase-uwwtd-urban-waste-water-treatment-directive-6 (accessed in Apr. 2020).
56. EEA - European Environment Agency (s. a.): Waterbase - UWWTD: Urban Wastewater Treatment
57. European Commission (s. a.): A European Green Deal, Online in the Internet: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed in Aug. 2020).
58. Eurostat (s.a.) © EuroGeographics for the administrative boundaries. Available online: https://ec.europa.eu/eurostat/de/web/gisco/geodata/reference-data/administrative-units-statistical-units (accessed in Apr. 2020).
59. Hutnan, M. et al. (2015) State of Biogas Production in the Slovak Republic. Journal of Biotechnology & Biomaterials, 05(04). doi: 10.4172/2155-952x.1000206.
60. Igliński, B., Buczkowski, R. and Cichosz, M. (2015) Biogas production in Poland - Current state, potential and perspectives. Renewable and Sustainable Energy Reviews, 50(2015), pp. 686-695. doi: 10.1016/j.rser.2015.05.013.
61. Kovac, K. (2015) Potential of 800 biogas plants in Hungary. Online in the internet: https://www.biogaschannel.com/en/video/market/12/potential-800-biogas-plants-hungary/1004/ (accessed in April 2020).
62. Kretschmer, F., Lichtenwoehrer, P., Stoeglehner, G., Huber, F., Neugebauer, G. (submitted for publication): Potentials and Integrated Sustainability Assessment of Wastewater Treatment Plants as Local Energy Cells.
63. Kretschmer, F., Zlonoga, M. (2020): REEF 2W Strategy. Presentation at the REEF 2W Final Conference (Webinar), June 26, 2020.
64. Ligetvári, F. et al. (2015) Wastewater Treatment and Sludge Utilisation in Hungary. doi: 10.17265/2162-5263/2015.03.005.
65. Lindtner, S. (2008): Leitfaden fuer die Erstellung eines Energiekonzeptes kommunaler Klaeranlagen (Guideline for the development of an energy concept for municipal wastewater treatment plants). Austrian Federal Ministry of Agriculture and Forestry, Environment and Water Management (BMLFUW), Vienna.
66. Neugebauer, G.; Kretschmer, F.; Kollmann, R.; Narodoslawsky, M.; Ertl, T.; Stoeglehner, G. Mapping Thermal Energy Resource Potentials from Wastewater Treatment Plants. Sustainability 2015, 7, 12988-13010. https://doi.org/10.3390/su71012988

67. OpenStreetMap contributors. (https://www.openstreetmap.org/copyright)

68. QGIS.org (2020) QGIS Geographic Information System. Open Source Geospatial Foundation Project. (http://qgis.org).

69. Stoeglehner G, Neugebauer G, Erker S, Narodoslawsky M (2016) Integrated Spatial and Energy Planning - Supporting Climate Protection and the Energy Turn with Means of Spatial Planning. Springer International Publishing, Cham

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