D.T1.5.4 – GUIDING DOCUMENT ON THE BENEFITS OF REEF 2W PLANTS, SHOWING HOW TO CONDUCT SUITABLE FEASIBILTY STUDIES

20/11/2018

REMARK:
THIS DOCUMENTS ALSO COVERS THE CONTENTS OF D.T1.5.2 AND D.T1.5.3

1. INTRODUCTION

As indicated in the project proposal, this deliverable integrates not only contents related to D.T1.5.4 but to D.T1.5.2, D.T1.5.3 as well. It provides the intended practical approach for implementing an integrated sustainability assessment (ISA) of REEF 2W plants in the intended feasibility studies. Due to the integration of three deliverables a description of draft procedures (as indicated in D.T1.5.2, D.T1.5.3) is consciously avoided and the focus of this document just lays on the final version.

It describes the different steps of the assessment procedure, the (1) analysis of energetic efficiency (EE) of a wastewater treatment plant (WWTP) for identifying optimization potentials, (2) the selection of technologies for generation of renewable energy (RES) at a WWTPs, the (3) definition of potential energy supply scenarios including and urban compatibility assessment (UCA), the (4) evaluation of the economic feasibility of the intended supply scenarios and (5) the evaluation of the environmental benefits related to the different supply scenarios.

Introductory, the deliverable also presents different REEF 2W models and highlights the environmental and economic benefits of related applications.

2. RELEVANT MODELS OF REEF 2W (D.T1.5.4)

REEF 2W relevant models are those models that will be implemented in each pilot site as described in the Application Form. These models, according to the needs of each utility involved in the project, want to demonstrate that the decrease of the energy consumption in the waste and wastewater plants is feasible and sustainable from the environmental and economic point of view.

Each model takes in consideration the specific need of each utility involved and they will try to minimize the energetic impact of the treatment platforms. Each utility involved has suggested a specific model designed according to the business model that they are developing, the actual legal and social barrier present in each country site.

As it is possible to see below in this paragraph the different models describe a variety of strategies and technologies applicable that can represent a good scenario of available technologies and interlinked possibilities of integration.

A further evaluation that will be done in the tool, that was not proposed in the models is the recovery of available heat from the different heat streams available in a treatment platform and the possibility to recovery and use RES further than the biogas and biomethane.

The five suggest models in the application form are:

MODEL A: PP 11 Zagreb Holding Ltd

"Modification of WWTP to accept Organic Fraction of Urban Waste to recovery more energy, stabilize and lower the treatment costs in the circular economy view"

This treatment plant that is quite modern and already produce biogas from sludge would like to increase its production of biogas to lower the costs of the treatments. As PP11 manage also the collection of solid wastes and they already are developing the sotring of the waste collection the idea it to use the organic fraction of the municipal solid waste to increase the biogas production of the biogas. At the same time in this way they can decrease the impact of GHG due to the actual practice of landfilling of the organic fraction.

Model C for PP3 Montefeltro Servizi

"Revamping of the sludge line of the WWTP to receive the organic fraction of urban waste and public green waste in order to improve biogas production for energy recovery as biomethane to feed existing grid to make more profitable waste and wastewater management". As PP3 is a quite small utility and the first evaluations of the model suggest that the transformation of available biomasses in biogas could be not convenient also the evaluation of thermochemical processes have been considered and implemented the technical evaluations in the REEF 2W Tool.

MODEL E PP9 VEOLIA CESKA REPUBLIKA

"Transformation a WWTP in a plant for water treatment and biomethane production"

In this case the treatment plant of Praha will be analysed to evaluate the cost and the economic advantages of its upgrading to recovery biogas from wastewater treatment sludge and upgrade it to biomethane.

MODEL F for PP5 Berlin Centre of Competence for Water

"Improvement of a WWTP for generating a mix of energetic output: Implementation of a pre-treatment in the sludge process of a WWTP to improve the biogas production as well as to maximize energy production, use of the excess heat to dry sludge, and also application of new cleaning technologies for the extraction of biomethane".

In this case the model is very complex as almost all the EE and RES technologies will be analysed to be implemented in the pilot plant. A further complex evaluation that shoud be done is the availability of RES during the functioning of the power to gas process, without which it is not possible to work the process according to the German legislation

MODEL G for PP7 RHV Trattnachtal

"Treating sewage and urban waste in a fermentation plant: different approaches in legal/technical questions".

In this pilot site the main aspect analysed is the possibility to improve the energy efficiency of the plant, that already produce biogas where it seems not much convenient to upgrade in biomethane, but instead it is very interesting evaluate the possible advantages deriving from the use of waste heat in the nearby municipality.

3. BENEFITS OF REEF 2W (D.T1.5.4)

3.1. Economic

Economic evaluation of REEF 2W is based on a variation of Life Cycle Cost (LCC) analysis. LCC is a tool for assessing the total cost performance of an asset over time, including the acquisition, operating, maintenance, and disposal costs. The evaluation is in case of REEF 2W economic tool based on simple comparison of initial state and state after application of innovative REEF 2W technology using cost analysis and possible incomes resulting from application of REEF 2W technology. General benefits arising from the implementation of this evaluation tool are:

- Transparency of possible future operational cost
- Ability to plan possible future expenditure and manipulate/optimize future cost
- Improved awareness of total costs of new technology
- Evaluation of cost vs environmental performance

Looking closer to REEF 2W implementation, the technology will influence the operation of WWTPs in several directions and therefore the economic benefits of these can be divided into 3 main ranges:

- Energy benefits
- Waste disposal benefits
- Social/environmental benefits

Energy benefits

The REEF 2W technologies are mainly focused to energy production and possible energy savings. The energy is produced through the anaerobic digestion in WWTPs in form of biogas which can be transformed into thermal or electric energy. Addition of REEF 2W steps show possibility of increase energy production (biogas) or utilization of produced biogas into more energy-dense biomethane. Biomethane have similar properties like natural gas and can be substituted in to the grid. The examples of possibilities how to gain benefits from increased energy production into economic cost evaluation are displayed in Table 1.

Table 1: Examples of energy benefits from implementation of REEF 2W

Technology	Benefit description	Price
Electricity production – CHP	Sale to grid	0,036 EUR/kWh
Electricity production – CHP	Own consumption - savings of external electricity	0,06 EUR/kWh
Heat production – CHP, boiler	Sale to customers (local grid)	14 EUR/GJ
Heat production - CHP, boiler	Own consumption - savings of heat	14 EUR/GJ
Biomethane production	Sale to grid	0,4 EUR/Nm3
Biomethane production	Sale as bioCNG to vehicles	0,8 EUR/Nm3
P2G electrolysis	Hydrogen sale	2 EUR/kg (liquid)
P2G electrolysis + methanation	Biomethane sale	0,4 EUR/Nm3

Waste disposal benefits

Implementation of REEF 2W technologies can lead to the significant lowering of sludge (waste) production. Decreasing the amount of sludge has a big impact on the overall cost of sludge management due to the sludge disposal price.

Another possible benefit is generated by implementation of waste co-digestion to AD system due to the receiving fees from accepting received waste (compare Table 2).

Table 2: Waste disposal benefits from implementation of REEF 2W

Benefit	Technology	Method	Price
Waste amount decrease	Anaerobic digestion of raw sludge Hydrolysis installation	Save for waste disposal costs – decreasing of WWTP sludge production	40 EUR/t
Income for waste processed (co-digested)	Co-digestion	Income per ton of waste	20 – 80 EUR/t

Social/environmental benefits

Application of REEF 2W technologies will have even effect on economy of surrounding area in terms of social and environmental benefits. Adding new technology to WWTP will provide new direct and indirect employment opportunities. Supplying surroundings of WWTP with heat and electricity will produce income for WWTP and reduce carbon footprint from fossil fuel. Injection of biomethane into gas grid can help with more independency in future. In case of production bioCNG from biomethane there will be benefits of reduction emissions and lower price for fuel (approximately half the cost of gasoline and diesel).

3.2. Environmental

The utilization of REEF 2W technologies entails various environmental benefits. The overview is based on the project partners input given in previous deliverables.

One basic opportunity is to enhance the biogas yield by co-digesting other available organic material. This can represent a big advantage in both cases that this material would be composted or simply be landfilled (e.g. in some eastern European countries). In the first case the recovery of energy from this material is much higher than the energy consumption during the composting phase. In the second case, direct landfilling. this constitutes an improvement regarding greenhouse gas emissions and water pollution during landfilling of the organic material and also here the recovery of the contained energy. The increased volume of generated digestate is beneficial if the sludge can be used as soil improver or fertilizer. Another option to increase the biogas yield, as well as the recovery of heat from the processes available in a WWTP, is the thermal hydrolysis of excess sludge before digestion. In this case the amount of dry mass sludge is reduced due to enhanced digestion which would be beneficial regarding emissions during transports of the digestate.

The produced biomethane during biogas upgrading is a gas from renewable resources with the same quality as natural gas and can replace it by providing a carbon-neutral form of energy. It is possible to produce fuel quality biomethane for an existing CNG fleet. The additional supply has the potential to increase the total number of CNG vehicles. Producing the biomethane and biofuel can enhance the image of the operator and may set trends for a main biogas utilization with higher technology standard than simply burning biogas in CHPs.

An additional biomethane stream is created during methanation of CO_2, originating from the biogas upgrading, and hydrogen from the Power-to-Gas module A Power-to-Gas module can use the surplus of renewable electric energy peaks generated in the grid by the unpredictable production from RES instead of them simply being wasted. The gas generated by this process can be stored in the natural gas grid so the production and consumption of the renewable energy can be decoupled. Additional energy can be saved by utilizing the oxygen stream of the electrolyzer to produce ozone for the disinfection of the WWTP effluent.

A significant reduction of the environmental impact can be achieved by using wastewater as thermal energy source. Heat pumps require electrical energy, the energy mix is essential regarding the impacts. The use of heat pumps benefits strongly from energy mixes containing high levels of renewable energy. A heating grid is needed to accept and distribute the recovered thermal energy.

4. ISA IMPLEMENTATION - FEASABILTY STUDY PROCEDURE (D.T1.5.2, D.T1.5.3, D.T1.5.4)

In this chapter the procedure for ISA implementation and the related working steps will be presented. Where suitable and already possible, the theoretical explanations will be supported by examples of practical application (specific situations).

4.1. Procedure overview

Figure 1 provides an overview of the different working steps of the designated feasibility study procedure (implementation of ISA).

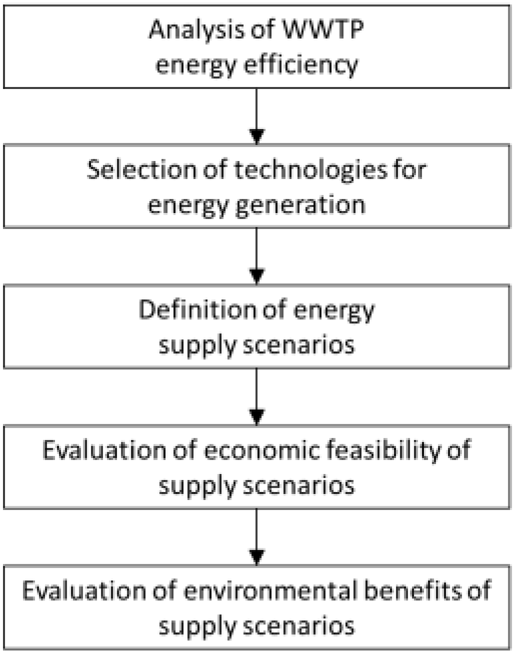

Figure 1: Working steps of the feasibility study procedure

4.2. Analysis of energy efficiency (EE)

The analysis of the energy efficiency of a WWTP is based on the comparison between the current electric and/or thermal energy consumption of an investigated WWTP and pre-defined standard ranges for related energy consumption. If the total energy consumption of the WWTP or, depending on the available data, of the different energy consuming installations (treatment steps, infrastructure) is within or even below the pre-defined standard ranges the energetic performance of the WWTP can be considered as efficient. In contrary, an energy consumption beyond the pre-defined ranges gives indication on potential for energetic optimization (for the sake of completeness it is mentioned, that the elaboration of concrete optimization recommendations is not in the scope of the project). The following table (**Errore. L'origine riferimento non è stata trovata.**) and Table 4 give show the current electric and thermal energy consumption of a designated REEF 2W WWTP in comparison to the related standard ranges of energy consumption.

Table 3: Analysis of the electric energy consumption and performance of a designated REEF 2W WWTP

			standard range	
WWTP total	**43,3**	**kWh/PE$_{120}$/a**	*20*	*50*
1) inflow pumping station and mechanical pre-treatment	**4,2**	**kWh/PE$_{120}$/a**	*2,5*	*5,5*
1.1 pumping stations	0,0	kWh/PE$_{120}$/a	*1,5*	*3,5*
1.2 screening	4,2	kWh/PE$_{120}$/a	*0,5*	*1*
1.3 sand trap and primary clarifier	0,0	kWh/PE$_{120}$/a	*0,5*	*1*
2) mechanical-biological treatment	**18,4**	**kWh/PE$_{120}$/a**	*14,5*	*33*
2.1 aeration	10,6	kWh/PE$_{120}$/a	*11,5*	*22*
2.2 stirrers	0,0	kWh/PE$_{120}$/a	*1,5*	*4,5*
2.3 return sludge pumps	7,8	kWh/PE$_{120}$/a	*1*	*4,5*
2.4 miscellanious (sec. clarifier)	0,0	kWh/PE$_{120}$/a	*0,5*	*2*
3) sludge treatment	**0,0**	**kWh/PE$_{120}$/a**	*2*	*7*
3.1 thickening	0,0	kWh/PE$_{120}$/a	*0,5*	*1*
3.2 digestion	0,0	kWh/PE$_{120}$/a	*1*	*2,5*
3.3 dewatering	0,0	kWh/PE$_{120}$/a	*0,5*	*3,5*
4) infrastructure	**0,0**	**kWh/PE$_{120}$/a**	*1*	*4,5*
4.1 heating	0,0	kWh/PE$_{120}$/a	*0*	*2,5*
4.2 misc. infrastructure	0,0	kWh/PE$_{120}$/a	*1*	*2*

From the above table one can see, that not for all potential energy consumers (processes, infrastructure) data on electric energy consumption are available (e. g. sludge treatment and infrastructure). However, the comparison of the total energy consumption show that the WWTP is within the standard range. Same can be said for the mechanical pre-treatment and the mechanical-biological treatment (energy consumption of screening might be further checked). Consequently, in regard to electrical energy the WWTP can be considered as efficient.

The table below refers to the thermal energy consumption of the investigated WWTP. Here one can see, that the current values are far beyond the given standard ranges. This gives clear evidence for existing optimization potential concerning the use of thermal energy.

Table 4: Analysis of the thermal energy consumption and performance of a designated REEF 2W WWTP

			standard range	
WWTP total	**48,1**	**kWh/PE/a**	***0***	***30***
sludge heating	26,9	kWh/PE/a	***8***	***12***
transmission loss, digester tower heating	10,9	kWh/PE/a	***0***	***4***
generation, storage and distrivution loss	3,8	kWh/PE/a	***0***	***2***
heat for buildings	6,6	kWh/PE/a	**0**	**2**
heat for supply air unit	0,0	kWh/PE/a	***0***	***10***

Summarizing the above said, the analysis of energy efficiency provides information regarding possible optimization potential at the investigated WWTP. This information is only of qualitative nature, quantitative data (saving potentials) can only be derived from detailed investigations which are not in the scope of this project.

4.3. Selection of energy generation technologies (RES)

Basically, at a WWTP different sources of energy can be made available. REEF 2W applications consider the following components and aspects (technologies) in regard to energy supply:

- Digester gas
  - Utilization
    - Application in combined heat and power plants (CHP) to provide electricity and heat
    - Technical upgrading to meet quality requirements for feed-in to natural gas grids and, where appropriate, subsequent power-to-gas application (to further process the CO_2 removed during the upgrading)
  - Output increase
    - Application of co-substrate (organic fraction of urban solid and liquid waste, sewage sludge from other WWTPs)
    - Thermal hydrolysis to improve digestion quality of secondary sludge
- Other renewable energy sources
  - Wastewater heat recovery in the effluent of a WWTP to provide heat (and cool)
  - Photovoltaics and solar thermal (also by using hybrid collectors to optimize the output per collector area) installations at the premises of a WWTP to provide electricity and heat
  - Hydropower installation in the effluent of a WWTP to provide electricity

- (Wind power installation at the premises of a WWTP to provide electricity)

The following Figure 2 summarizes and links the different components and aspects the above list in a graphical way.

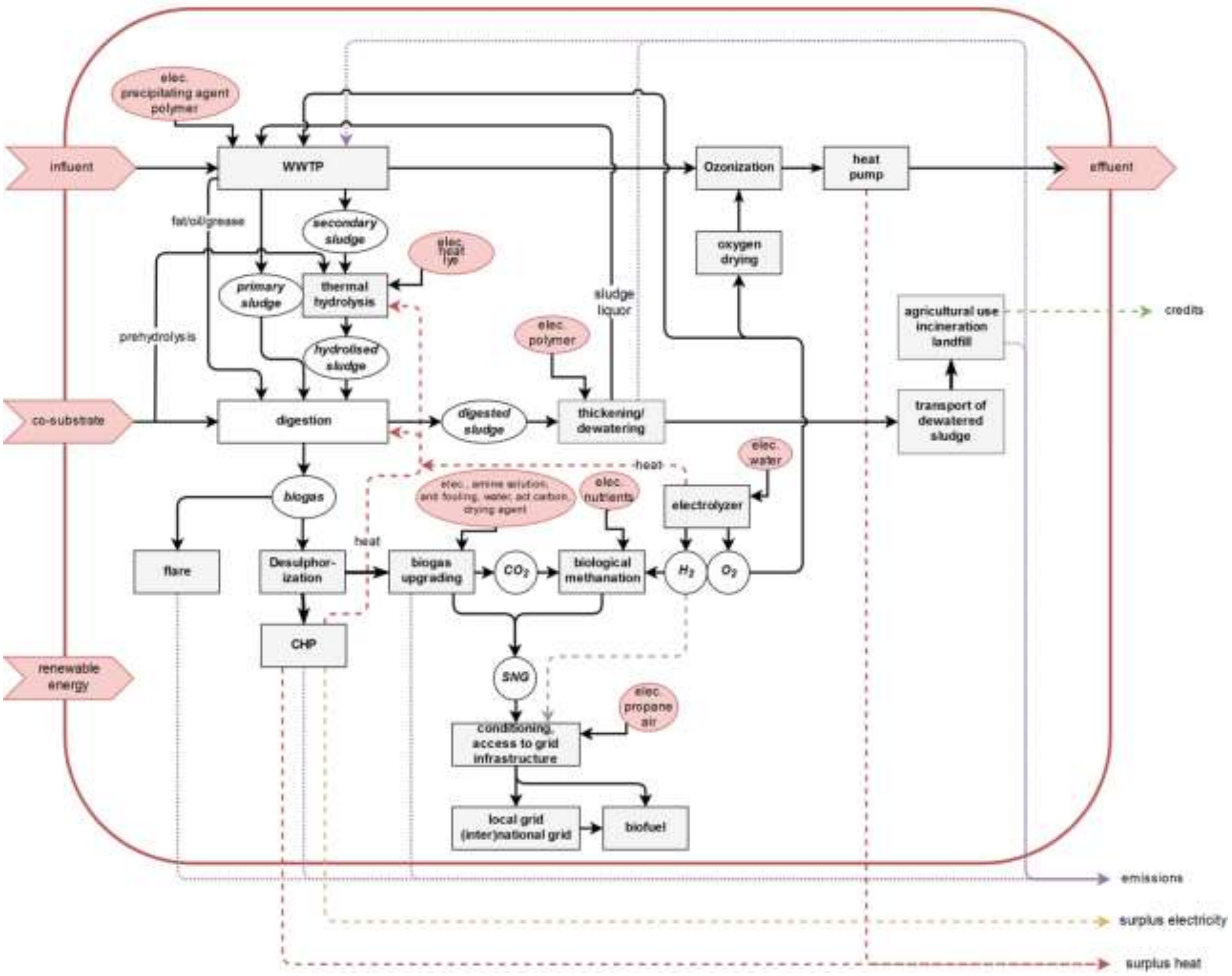

Figure 2: Components and aspects regarding REEF 2W energy supply

The selection of technologies for energy generation at a REEF 2W plant also includes an estimation of the related energy potentials (e. g. increase of digester gas output, electricity and heat generation).

In the following the assessment of potentials for thermal energy from waste water, sewage gas, hydropower and solar power is addressed. The potential for windpower is will not be considered due to very specific and local data requirements.

Digester gas

The monthly potential in kWh of energy from digester gas (thermal and electrical) can be calculated using the formulas:

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

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

- SG_{total} = monthly amount of sewage gas in m³/mo (depends on the wastewater flow)
- SG_{grid} = monthly part of sewage gas fed into the grid in m³/mo (default value 0)
- c_{CH4} = methane content in % (around 60%)
- e_{cont} = energy content of methane in kWh/m^3 (11,1 kWh/m³)
- eff_{el} = electric efficiency of the CHP unit in % (35-40% using a micro CHP)
- eff_{th} = thermal efficiency of the CHP unit in % (40-45% using a micro CHP)

Table 5 shows the necessary input values.

The CH_4 content of the digester gas as well as the thermal and electric efficiencies of the CHP plant can be set constant throughout the year.

For the amount of digester gas and the fraction that is directly put into the grid, monthly values can be inserted.

Table 5: Calculation scheme for assessing the energy potential from sewage gas with given amounts of sewage gas per month

Energy from sewage gas		
CH4 content digester gas	CHP el. eff	CHP th. eff.
0,6	0,37	0,43
	sewage gas m³/mo.	fraction grid injection m³/mo
Jan	100.000	20.000
Feb	100.000	20.000
Mar	100.000	20.000
Apr	100.000	20.000
May	100.000	20.000
Jun	100.000	20.000
Jul	100.000	20.000
Aug	100.000	20.000
Sep	100.000	20.000
Oct	100.000	20.000
Nov	100.000	20.000
Dec	100.000	20.000
year	1.200.000	240.000

Additionally the amount of sewage gas fed into the grid (SG_{Grid}) is an energy source that can be used at another site in the gas grid. The efficiency ranges are the same – if it used only thermally, thermal efficiencies around 80-90 % can be reached.

Wastewater heat recovery

Wastewater is typically at a temperature between 10 and 20 °C. With heat pumps it can be transferred to a higher temperature level. Depending on the actual wastewater temperature and the electricity price, temperatures up to 60 °C are economically feasible.

As the temperature and in some cases also the flow will vary between summer and winter, a monthly calculation makes sense (also with respect to the different demands).

To calculate the monthly energy potential from wastewater, the following calculations can be used:

$P_{th} = 1{,}16 * Q_{WW} * f_{TW} * (T_{WW} - T_{min})$

- 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}: minimum temperature of wastewater after heat recovery in °C (default value 5; alternatively a fixed deltaT of 4K can be set)

In order to calculate the coefficient of performance per month of the heat pump the following formula applies:

$COP = CF*(273+T_{heat})/(T_{heat} - T_{WW})$

- 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)

The needed monthly electric energy is:

$P_{el} = P_{th}/(COP - 1)$

and the monthly available total thermal potential from the heat pump system is the sum of electric consumption and thermal potential:

$P_{total} = P_{th} + P_{el}$

The following Table 6 shows the calculation scheme based on the values of the Austrian pilot plant. The yellow values are input parameters. For each month the amount of effluent wastewater, the wastewater temperature and the temperature to which the wastewater is cooled down are needed.

Furthermore for the calculation of the COP and the needed electric energy (and subsequently the system output which is the sum of electric consumption and thermal potential) the desired temperature level (depends on the needs of the consumers) and the Carnot-grade of the heat pump system (real COP vs. maximum possible COP based on the temperature levels) are necessary (see Table 7). From the temperature levels and the Carnot-grade the COP can be calculated.

Table 6: Calculation of the monthly energy potential from the effluent wastewater from the WWTP (Tmin, allowed is a default value)

Wastewater energy			
	m³ effluent waste water	T effluent °C	T min allowed
Jan	505.787	9,6	6,0
Feb	468.334	10,3	6,0
Mar	542.247	11,4	6,0
Apr	555.607	12,9	6,0
May	647.611	15,0	6,0
Jun	444.780	18,3	6,0
Jul	472.397	19,2	6,0
Aug	451.656	19,4	6,0
Sep	417.945	17,1	6,0
Oct	460.046	15,0	6,0
Nov	455.621	12,4	6,0
Dec	602.284	10,6	6,0
year	6.024.315	14,3	
in m³/h	687		
in l/s	191		

Table 7: COP calculation for the heat pump with source wastewater (50 °C is a default value, 0,45 is a typical value for heat pumps)

COP calculation	
T needed for supply	50
Carnot-Gütegrad	0,45
resulting COP	
Jan	3,60
Feb	3,66
Mar	3,77
Apr	3,92
May	4,15
Jun	4,58
Jul	4,72
Aug	4,74
Sep	4,42
Oct	4,15
Nov	3,87
Dec	3,69

Solarpower:

The solar energy can be used thermally and/or electrically. PV only makes electrical energy available, solarthermal collectors provide heat at a temperature up to 100 °C depending on the site and mode of operation. Hybrid collectors can deliver both in a quantity equivalent to separated PV and solarthermal collectors each with the same size, making hybrid technology around double area efficient.

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

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

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

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

- W_{sol}: solar irradiance per month in kWh/m²*mo (varies from month to month and is site-dependent)
- A_{PV}: PV collector surface in m²
- $eff_{el,PV}$, $eff_{el,hyb}$: electric efficiency of the PV resp. the solar hybrid plant in %
- $eff_{th,sol.th.}$, $eff_{th,hyb}$: thermal efficiency of the solar thermal resp. the solar hybrid plant in %
- $E_{el,PV}$, $E_{el,sol.th.}$: monthly electric energy generated by the PV resp. solar hybrid plant at the WWTP in kWh/mo
- $E_{th,sol.th.}$, $E_{th,hyb}$: monthly thermal energy generated by the solar thermal resp. solar hybrid plant at the WWTP in kWh/mo

When calculating A_{PV} it must be considered that the angle of the solar device plays an important role. Angles of around 30 to 40 °C and orientation to south are optimal. Other direction can lead to a lower effective area and therefore to a lower energy output.

For the Austrian pilot plant of RHV Trattnachtal the values for the solar irradiation apply as given in the following (Table 8).

Regarding the area separate values for the three technologies PV, solar thermal and hybrid can be inserted – the potential will be summed up, separated for thermal and electrical potential.

Table 8: Needed input values for calculating the energy output from solar collectors; the solar irradiation on the left side are real values from a weather station near the Austrian pilot plant, the rest are default values

Solar energy				
solar kWh/m²/mo.				
28				
50				
88		**area for solar energy**		
130		m²	el. efficiency	th. efficiency
165	PV	70	0,175	
172	solar thermal	50		0,5
166	hybrid collectors	50	0,185	0,5
141	source for efficiency: http://www.photovoltaik.org/wissen/photovoltaik-wirkungsgrad			
100				
62				
25				
21	source for monthly values: http://doris.ooe.gv.at			
1.148				

Hydropower

If there is a height difference between the exit of the WWTP and the attached water body, a small hydropower plant can be erected.

The energy potential in kWh/mo can be assessed as follows:

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

- Q_{WW}: monthly average of wastewater flow at the WWTP in m³/mo
- h: drop height at the effluent of the WWTP in m
- eff_{hpp}: efficiency of turbine and generator in % (around 90%)

The needed input parameters are the monthly wastewater flow, which was already asked during the calculation of the thermal potential of the effluent wastewater, a usable height (e. g. 3 meters) and the efficiency of the turbine/generator system of the hydropower plant.

Table 9: Values necessary only for assessment of the water power potential at the WWTP, default values are used

Water power	
usable height [m]	3,0
eff. turbine + generator %	90

Monthly renewable energy balance of a WWTP

The monthly energy balance can be seen in the following table (Table 10). In the column 'amount' the different contributions are listed. In the column 'energy content' all the values are transferred to kWh-values. In the column 'utilisable electric energy' the electric output and also the consumptions of the different energy sources are displayed. In the column 'utilisable thermal energy' the thermal output of the different energy sources are displayed.

The energy content of the sewage gas not used on-site is given at the bottom of the column 'energy content'. Additionally the overall electricity output is given at the bottom of the column 'utilisable electric energy'. It can be negative as for the provision of heat using the effluent wastewater electricity for the heat pump system is needed which is subtracted in the balance. At the bottom of the column 'utilisable thermal energy' the monthly sum of heat is given. It does not say anything about the temperature level at which this amount is available, but the main contribution, the effluent wastewater, is set by the user in Table 6.

Table 10: Monthly renewable energy balance of a WWTP

January								
Energy sources	amount		energy content		utilisable electric energy		utilisable thermal energy	
digester gas fed into the grid	20.000	m³/mo	**133.200**	kWh/mo	0	kWh/mo	0	kWh/mo
digester gas energetically used	80.000	m³/mo	532.800	kWh/mo	197.136	kWh/mo	229.104	kWh/mo
wastewater heat recovery	2.103.746	kWh/mo	2.103.746	kWh/mo	-810.225	kWh/mo	2.913.971	kWh/mo
solar power (solar thermal)	1.400	kWh/mo	1.400	kWh/mo			1.400	kWh/mo
solar power (photopholtaics)	602	kWh/mo	602	kWh/mo	602	kWh/mo		
windpower	0	kWh/mo	0	kWh/mo	0	kWh/mo		
hydropower	3.793	kWh/mo	3.793	kWh/mo	3.793	kWh/mo		
total electric and thermal energy generation at WWTP					**201.531**	***kWh/mo***	**3.144.475**	**kWh/mo**
energy necessary for renewable production					810.225	***kWh/mo***	0	**kWh/mo**
energy provision at WWTP			**133.200**	kWh/mo	**-608.694**	**kWh/mo**	**3.144.475**	**kWh/mo**

The following table (Table 11) is just a compilation of all 12 monthly balances (last line from the above table (Table 10) can be seen in the first line of the table below (Table 11)).

Table 11: Annual renewable energy balance of a WWTP

	in kWh per month		
	energy content (feed-in to gas	utilisable electric energy	utilisable thermal energy
January	133.200	-608.694	3.144.475
February	133.200	-670.814	3.423.706
March	133.200	-1.027.447	4.868.692
April	133.200	-1.322.125	6.217.069
May	133.200	-1.937.791	9.136.539
June	133.200	-1.563.716	8.335.976
July	133.200	-1.739.434	9.404.611
August	133.200	-1.665.700	9.101.709
September	133.200	-1.372.244	7.191.358
October	133.200	-1.318.477	6.541.455
November	133.200	-986.069	4.825.414
December	133.200	-991.257	4.631.667

Based on the available energy potential, in a next step, supply scenarios could be defined.

4.4. Defintion of supply scenarios (UCA)

The energy available can be used in two ways, for the supply of WWTP internal and/or external demand. From a WWTP operator point of view, the former option will be a primary task as it helps to reduce energy purchase and thus operational costs. However, from a municipality perspective external supply of the adjacent infrastructure might be a promising option as well. In the case, excess energy is available at a WWTP internal and external supply scenarios could both be considered.

Consequently, the basis for the scenario development must be a (1) comparison of available internal energy demand (from EE) and renewable energy generation potential (from RES). Based on this comparison the (2) available excess energy can be quantified. This quantification considers (a) electric energy, (b) thermal energy and (c) digester gas to be treated for grid feed-in. Finally, the (3) WWTP external demand conditions and existing infrastructure have to be considered. In this context, an urban compatibility assessment (UCA) for the potential external supply of electricity, bio gas and/or thermal energy provides the final input for scenario development.

Excess electrical energy can be fed into the grid. Against the background that WWTPs count among the largest municipal energy consumers, network capacity is generally not a limiting factor. With regard to the feeding in of excess gas, the investigation is limited to the query of the distance to the next possible feed-in point. In the case of excess heat, the distance to the nearest feed-in point is also of interest in the case of an existing heat network in the vicinity of the WWTP. If there is no heat network, a detailed spatial analysis of the heat demand is required, since thermal energy cannot be transported across large distances without losses and potential energy consumers have to be identified in the vicinity of the WWTP. The respective urban compatibility assessment follows a three-step approach (Figure 3):

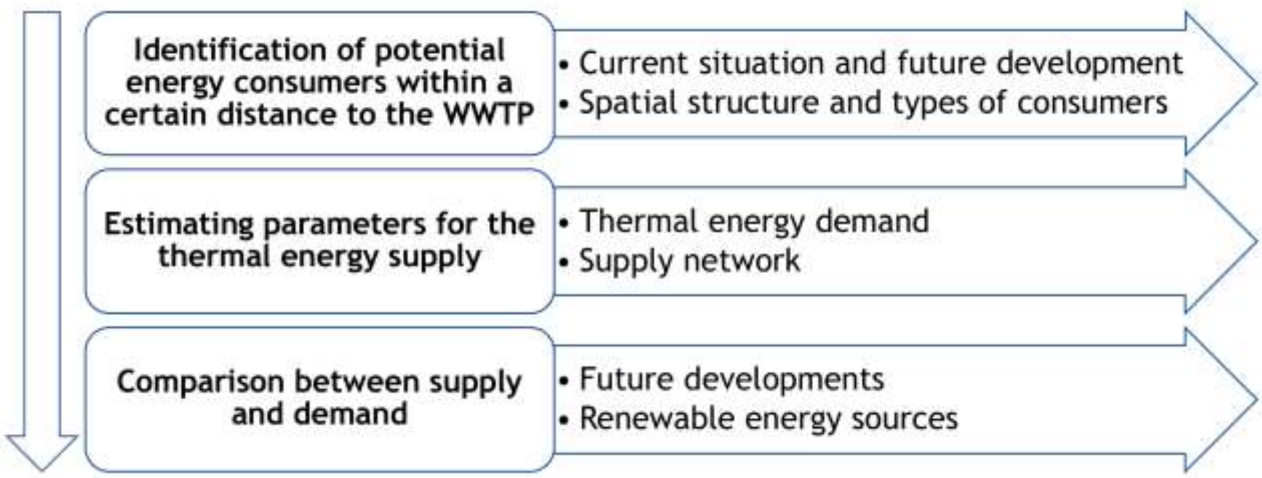

Figure 3: Urban compatibility assessment with regard to thermal energy demand

A first step towards an optimal use of location-bound waste heat from a wastewater treatment plant is a detailed consideration of the WWTP's surrounding area with the aim of identifying potential heat consumers, who are characterised by a relatively high capacity and energy demand. A realisation is worth investigating for larger buildings with a thermal capacity of around 100 kW or more, which corresponds to around 30 existing residential units. Potential heat consumers can be multi-storey buildings, commercial and industrial areas, areas with high density such as village cores or town centres, but also agricultural and forestry uses (greenhouses, drying plants).

In a second step, the heat demand and a corresponding network configuration shall be estimated for a potential heat supply area in the WWTP's vicinity. Depending on the available data basis, the estimation of the heat demand can be carried out using a settlement or building-related approach (see D.T1.4.1). With this step parameters (e. g. heat demand density, heat demand in relation to supply area as well as network length, network losses, etc.) are determined for the assessment of whether a grid-bound heat supply makes sense from an economic and ecological point of view.

In a third step, the thermal energy supply potential from the WWTP is compared with the estimated heat demand in the WWTPs surroundings. In order to check also the future feasibility of a potential heat supply system starting from the WWTP, the following future scenarios are to be considered: On the one hand, the development of previously unused areas (e.g. gaps between buildings) or subsequent increasing densities by adding additional storeys to already existing buildings creates additional heat demand. On the other hand, future heat requirements will be reduced by renovation measures (e.g. thermal insulation) and the increased use of renewable energy sources (e.g. solar thermal systems).

4.5. Evaluation of economic feasibility (LCC)

In a next step, the economic feasibility of the designated supply scenarios has to be carried out.

Economy of REEF 2W project consist of 3 main chapters:

- Economic analysis based on EE & RES and UCA
- Investment costs of REEF 2W technologies
- Operational costs of REEF 2W technologies

4.5.1. Initial economic analysis based on EE & RES and UCA

Evaluation of economic feasibility proceeds in accordance to the previous chapter. The comparison of EE and RES will quantify the amount of excess energy in form of (a) electric energy, (b) thermal energy and (c) digester gas. The UCA identifies potential energy requirements for excess energy in the vicinity and in case of existing or possible future energy demand the economic assessment for this demand will be done. Economic analysis will calculate with predefined averages values of prices to obtain a first insight on potential profits/expenses. For more accurate results, it will be recommended to use current actual data entered by the operator.

If demand for energy supply is not met and the operator will decide to extend WWTP by REEF 2W technologies the investment and operating cost described in next sub-chapters will be included.

4.5.2. Investment costs of REEF 2W technologies

The estimation of investment cost is not easy due to the wide range of REEF 2W technologies. Main issue is difference in scale and capacity of projects, where the price of technologies not depends on capacity with simple coefficient. Therefore, it will be strongly recommended to users of the tool to use data from manufacturer of current technology based on local conditions. For REEF 2W one can evaluate following technologies (with examples of individual technology pricing):

- Biogas production unit at WWTP (sludge + biowaste digestion)
- Co-fermentation technology for existing anaerobic sludge (new input and processing technology)
- Biomethane units
- Power 2 gas technology

<u>Biogas production unit</u>

In case of WWTP without sludge stabilization, there is a possibility to build the new technology of sludge digestion. The technology consists of a thickening centrifuge, fermenters equipped with mixers and heating system and gas technology (no CHP or other gas utilization). For presumed technology design with sludge production 0,58 m3/PE, sludge DM 5 % (thickened by primary centrifuge) and hydraulic retention time of 25 days is the estimated investment cost summarized in Table 12.

Table 12: Estimated investment cost for biogas production unit

PE of WWTP	Sludge production (digestion input) t/year	AD installation investment EUR/PE	AD investment EUR/t of input sludge
150000	65000	€ 10,4	€ 23,7
250000	100000	€ 7,2	€ 16,6
450000	200000	€ 5,9	€ 13,5
1000000	500000	€ 5,9	€ 13,4

CHP Price

Common CHP price is 800 EUR/kWh of installed electric output (for units 300 – 1000 kWel) full container installation.

Thermal hydrolysis price

There are 2 main thermal hydrolysis systems – continual system, for example, Kruger – Exelys hydrolysis and semi continual, for example, CAMBI process. Investment costs are similar about 20 EUR/t of processed material.

Co-fermentation technology

There are various technologies for co-digestion input. In case of REEF 2W technologies there are 4 possible options:

- Input of liquid co-digestion materials
- Input of solid materials
- Input of solid contaminated materials (biowaste, gastro-waste)
- Hygienisation

Table 13: Examples of prices for different options of co-fermentation technology

	Capacity t/year	Price	
Liquid (Input tank + pumping system)	10000 – 35000	200000	EUR
Solid (Vogelsang/Huning solution) contains	10000 – 20000	350000	EUR

no buildings			
Solid (Huning/Wackelbauer solution) contains no buildings	10000 – 20000	650000	EUR
Hygienisation	10000 – 20000	200000	EUR
Building – technology – storage hall		400000	EUR

Biomethane units

For biomethane upgrading units, there is possible to use Patruska´s data (Patruska et al. 2015) which are in accordance to Veolia data displayed in Table 14.

Table 14: Examples of biomethane unit investment cost depending on flowrate

Biogas upgrading method	Biogas input flowrate, m^3/h				
	250	*500*	*700*	*1000*	*1400*
Water scrubbing, EUR/(m^3/h)	5000	2000	1000	1000	1000
Amine scrubbing, EUR/(m^3/h)	5400	3000	2357	2000	1607
Membrane separation, EUR/(m^3/h)	4400	2900	2286	2000	1786
Physical scrubbing, EUR/(m^3/h)	5000	2000	1000	1000	1000
Pressure swing adsorption, EUR/(m^3/h)	-	3000	2200	1750	1500

Power to gas units

Power to gas (P2G) systems are still in development. Most of the installations are at pilot scale and some technologies are only at lab scale testing phase. Therefore, data for full-scale application will need to be extended.

Currently there are data about water electrolysis technologies (first step of P2G units). There are 3 main technologies: Alkaline electrolysis, Membrane electrolysis, and Solid-oxide electrolysis.

By project MEGASTACK (Smolinka et al., 2016) investment cost per electrolysis unit are shown in Table 15.

Table 15: Investment cost of electrolysis unit and predicted future price development

System cost [1]			Today	2015	2020	2025	2030
EUR/kW	Alkaline	Central	**1,100**	**930**	**630**	**610**	**580**
		Range	1,000 - 1,200	760 - 1,100	370 - 900	370 - 850	370 - 800
	PEM	Central	**2,090**	**1,570**	**1,000**	**870**	**760**
		Range	1,860 - 2,320	1,200 - 1,940	700 - 1,300	480 - 1,270	250 - 1,270

[1] incl. power supply, system control, gas drying (purity above 99.4%). Excl. grid connection, external compression, external purification and hydrogen storage

But this is only the first step. Second is transforming produced hydrogen to methane which is possible via synthesis with CO_2 by Sabatier process or biologically. In case of REEF 2W there is possible to use digesters for biological methanation by hydrogenotrophic methanogens.

This bacteria in common AD process is responsible for about 30 % of methane production and can produce methane more quickly than acetate processing methanogens. Now there is strong research about the enrichment of AD biomass by hydrogenotrophic methanogens and produce high methane-content biogas.

Full-scale technology is still not developed. Price should be similar or equal to AD technologies with anaerobic biofilters reactors.

3.3.3. Operational cost of REEF 2W technologies

The operational cost of REEF 2W technologies is not easily determined and predict due to variable costs which can change over time with the number of consumables. Therefore, there will be strongly recommended, like in case of investment cost, use data based on information from manufacturer and experiences of Operator. Economic evaluation of operational costs will be focused only on add-on technology implemented by REEF 2W. As the base for its evaluation will serve data obtained from experience with the technology or survey of available literature. The economics evaluation of the operational cost will also consider the size of the technology.

Biogas upgrading

Table 16 provides examples of operating parameters from which operation costs for different biogas upgrading technologies can be estimated.

Table 16: Example of operating parameters for different Biogas upgrading technologies

	water scrubbing	amine scrubbing	membrane separation	physical scrubbing	pressure swing adsorption
Water consumption, m^3/m^3 of biogas	$22(10^{-5})$	$3(10^{-5})$	-	-	-
Electricity consumption, kWh/m^3 of biogas	0.265	0.1	0.22	0.25	0.23
Thermal energy consumption, kWh/m^3 of biogas	-	0.55	-	-	-

P2G costs

Table 17 shows examples for operational parameters and costs of hydrogen production the most important part "power to gas" technologies. Other operational cost will be estimated as similar to AD process.

Table 17: Example of operational parameters and costs of hydrogen production

Max Capacity (Nm^3/h of H_2)	**485**
Electrical energy consumption (kWh/Nm^3 H_2)	**4.1-4.75**
Electrical energy consumption (kWh/kg H_2)	**49.0**
Power consumption (MW)	**2.2**
Operating range (%)	**20-100%**
Start up time (min)	**<10**
Expected parts lifetime (electrodes and membrane)	**10 years**

4.6. Evaluation of environmental benefits (LCA)

If the economic feasibility of the designated supply scenarios was proved, in a last step the related environmental benefits will be evaluated.

A life cycle assessment (LCA) is an environmental protocol of a product or a process and provides knowledge about their impact on the environment.

The goal of LCA is to analyse the potential environmental impacts of different products or process configurations and to compare them with each other. Consequently, LCA can help to develop more environmental-friendly products. (Yoshida & at el., 2014)

The following Figure 4 illustrates the framework of LCA according to ISO14040.

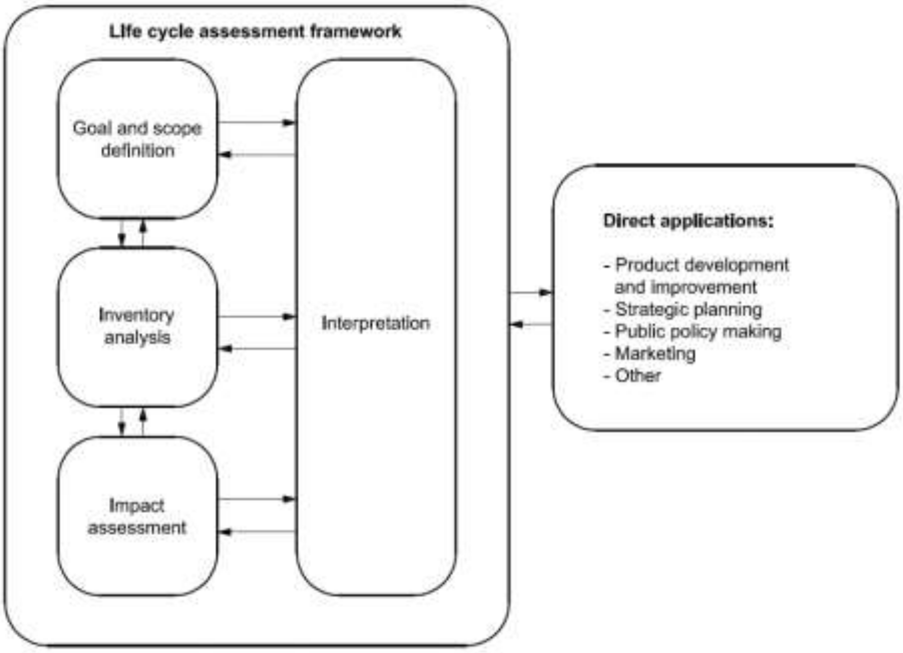

Figure 4: the framework of LCA according to ISO14040

Different dedicated commercial as well as open source software can be used for the LCA. One of the well-known software is Umberto that is also used in Kompetenzzentrum Wasser Berlin gGmbH. With this software, a complex LCA model can be implemented. Figure 5 shows a detail of a complex model containing a combined heat and power unit in the context of a wastewater treatment plant.

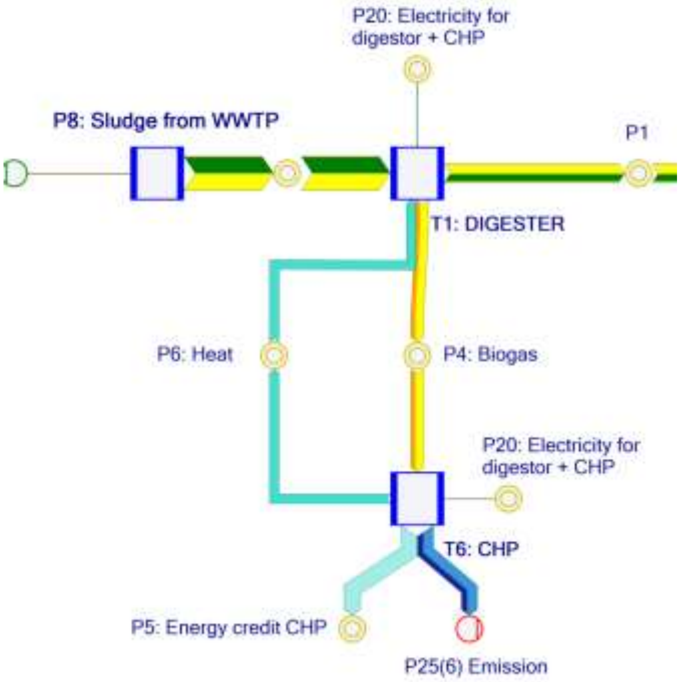

Figure 5: Detail of a LCA model created with Umberto software

The LCA model for the REEF 2W project must be realised with spreadsheet software Excel. However, it is almost impossible to implement such a complex system with a huge database behind in an excel tool. Hence, this tool is simplified enough to be implemented. The focus of the LCA tool is on energy-related environmental impacts, as innovative schemes target the reduction of energy demand from external supply (i.e. grid electricity) by exploiting the internal chemical energy potential of the incoming wastewater and also integrating of renewable energy sources (Remy & al., 2018). For this purpose, the LCA tool for REEF 2W project uses the global warming potential (GWP) of different scenarios. Figure 6 shows an example of the implementation into an Excel spreadsheet.

	Case1 (base case)		
Energy			
Electricity mix for EU	0,390	[kg CO2-eq/kWh]
net_elec_energy_demand	8.500.000	[kWh]
carbon footprint elec. Energy	3.315.000	[kg CO2-eq]
Natural gas	0,234	[kg CO2-eq/kWh]
net_th_energy_demand	57.000	kWh
carbon footprint th. Energy	13.338	[kg CO2-eq]

Figure 6: LCA implementation into a spreadsheet

A prominent impact of energy generation from fossil sources is the emission of greenhouse gases (GHG) such as fossil CO_2. The time horizon for the GWP is 100 years. The target group of the LCA tool primarily includes professionals and decision makers in the water sector (WWTP operators, engineering companies, and regulators) who are related to planning, construction/upgrading, and operation of WWTPs. They should be informed about innovative WWTP schemes and their potential benefits in environmental terms compared to the conventional process.

This LCA tool should enable a simple analysis of relevant effects of the REEF 2W schemes, including GWP impacts of the innovative approach on the life cycle of a WWTP. This perspective can help to identify benefits and drawbacks of different scenarios and reveal potential trade-offs in environmental terms. (Remy & al., 2018)

5. LITERATURE

Yoshida, H., Scheutz, C., & Christensen, T. H. (2014). Life cycle assessment of sewage sludge treatment and its use on land. Kgs. Lyngby: DTU Environment.

Remy, C., Cazalet, D. (2018). Recommendations for eco-efficient new concepts of energy positive WWTP, Deliverable 5.5, H2020 Project POWERSTEPO.

Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, S. Few (2017): Future cost and performance of water electrolysis: An expert elicitation study, International journal of hydrogen energy 42

A. Paturska, M. Repele, G. Bazbauers (2015): Economic assessment of biomethane supply system based on natural gas infrastructure, Conf. proceedings

T. Smolinka, M. Thomassen, A. Oyarce, F. Marchal (2016): Cost benefit analysis and cost and performance target for large scale PEM electrolyser stack – Public Summary, Stack Design for a Megawatt Scale PEM Electrolyser