D2.2 Economic assessment and cost efficiency analysis of NextGen demo cases solutions

AUTHORS: ANDERS NÄTTORP, VICTOR MISEV

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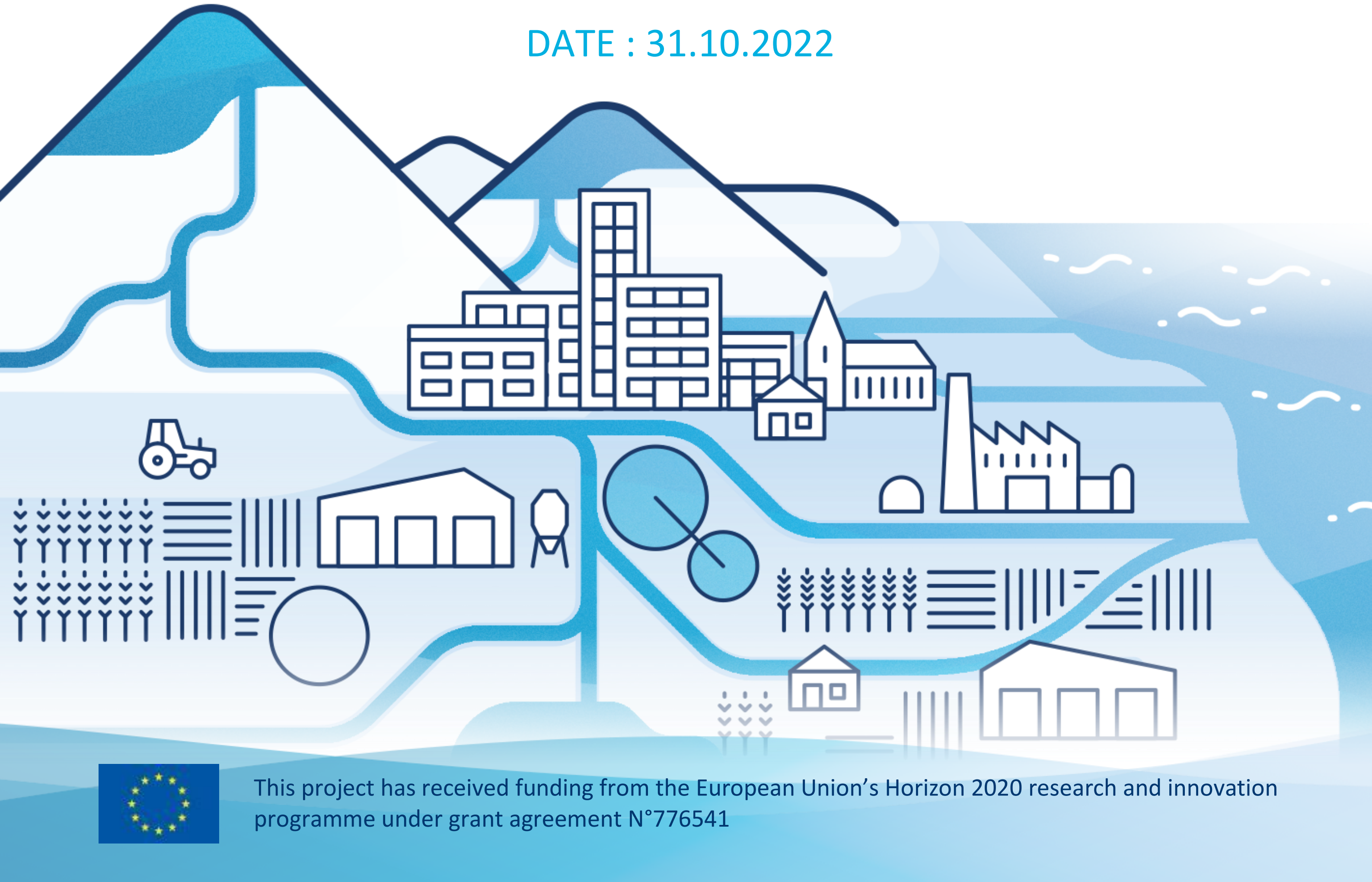

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[1] PU = Public
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Summary

Within NextGen, different innovative approaches for circular economy (CE) in the (waste)water sector were investigated and demonstrated in pilot and full-scale systems. This report presents the cost assessment of 19 scenarios on six selected demo cases in Europe: Braunschweig (DE), Spernal (UK), Athens (GR), La Trappe (NL), Altenrhein (CH), Costa Brava (ES). The comparison of economic impacts between a newly implemented recovery system and its baseline shows the differences and emphasises benefits of the innovative circular solution.

In the Life Cycle Costing (LCC), common cost types were calculated from the perspective of the operators, while in the Cost Effectiveness Analysis (CEA), the life cycle costs of a demo case scenario were put in relation to its environmental benefits.

In all the case studies examined, CAPEX (Capital Expenditure) is the largest cost type. The sensitivity analysis has shown that the depreciation period of the infrastructure has a correspondingly large influence on TOTEX (Capital Expenditure + Operational Expenditure); doubling the depreciation period leads to mostly around 30%, up to 159% decrease of NextGen TOTEX.

Except for the PK-fertilizer production of Altenrhein, the implementation of NextGen nutrient recovery systems alone is not profitable at this stage, as the revenues from fertilisers are lower than the annual infrastructure costs (CAPEX, insurance and maintenance), personnel costs and additional costs for chemicals. However, these nutrient recovery systems can bring benefits to the WWTP, especially by (1) reducing nutrient loads in the effluent and (2) reducing sludge disposal costs compared to a given baseline, which can help make the whole circular economy approach more economically viable.

All assessed demo cases involve wastewater treatment. The specific cost of wastewater treatment increases with smaller plant size, but this can be compensated by cost savings on energy and infrastructure for transport. Also, organisational aspects might favour local solutions. The scenarios improve circularity and most also reduce climate emissions, but only few are effective also for climate mitigation, i.e. less costly than 100 EUR/CO_2eq. A total of seven scenarios involves upgrading of the wastewater to enable reuse and some can supply water to a lower specific price than the sampled drinking water supplies.

The assessed scenarios are examples for new water techniques valid in their geographical, regulatory and current market context. They can serve as an orientation to identify options, which can be further detailed in feasibility for other sites complemented with experimental data as necessary.

The cost effectiveness of the assessed technologies will change as they are further developed and reach market maturity just as environmental policy and requirements will change. System services such as water reuse, climate mitigation or reduction of pollution are not profitable. Thus, a cost assessment indicates the most cost-effective solution in a given policy framework.

Acknowledgements

The cost assessment presented in this report relies heavily on external input and cooperation with many partners from the NextGen project and also external stakeholders (see also NextGen Deliverables 1.3 and 1.5). In detail, the following persons are highly acknowledged for input, feedback and discussion of data and results:

Braunschweig	Christoph Siemers (SEBS), Janina Heinze (AVB)
Spernal	Ana Soares (UCRAN), Peter Vale (STW)
Athens	Klio Monokrousou (NTUA), István Kenyeres, Erzsébet Poor-Pocsi (BIOPOLUS)
La Trappe	István Kenyeres, Erzsébet Poor-Pocsi, Márton Kenyeres (BIOPOLUS), István Koller, Ruud Schemen, Toon van den Heuvel (Waterboard DeDommel), Ralph Lindeboom (TU Delft/IPSTAR/SeMILLA), Radu Giurgiu (TU Delft), Thomas Exner (TU Berlin)
Altenrhein	Christoph Egli (AVA Altenrhein), Martin Schaub (CTU), Frédéric Gindroz (Alpha), Alexandre Bagnoud, (Membratec)
Costa Brava	Jordi Cros (ADASA), Lluis Sala (CCB), Anna Serra (EURECAT), Queralt Plana Puig (EURECAT)

The environmental and cost assessment scenario development and data collection was made in close collaboration with KWB. All material and energy balances were simulated by KWB in the Umberto software, which gave us a solid basis for estimation of interferences with the wastewater treatment plant. We are also grateful to KWB for writing the scenario descriptions of which we could use large parts in this report.

Disclaimer

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1. Introduction

Thorough cost assessments should be indispensable for potential investment and future policymaking. In the field of circular economy (CE), the comparison of economic impacts between a newly implemented recovery system and its baseline shows the differences and emphasises benefits of the innovative recovery solution. The present report presents the results of Life Cycle Costing (LCC) and Cost Effectiveness Analysis (CEA) of six demo cases of CE application in the water sector within the framework of the EU Horizon 2020 NextGen project.

This study analysis the costs of innovative recovery solutions for sewage-embedded resources jointly developed (and implemented) by authorities, learning institutions and industrial plant owners within the NextGen consortium. It involves solutions for the following dimensions:

- **Water (Spernal, Athens, La Trappe, Costa Brava)**

Itself with reuse at multiple scales supported by reused membranes (Costa Brava), advanced treatment technologies (Spernal), engineered ecosystems (La Trappe) and compact/mobile/scalable systems (Athens).

- **Energy (Braunschweig, Spernal, Athens, Altenrhein)**

Treatment plants as energy factories, water-enabled heat transferfor internal energy reuse (Braunschweig, Spernal, Athens) and/or producing energy surplus (Athens).

- **Materials (Braunschweig, Spernal, Athens, Altenrhein, Costa Brava)**

Such as nutrient mining and reuse (Braunschweig, Spernal, Athens, Altenrhein), repurposing membranes to reduce water reuse costs (Costa Brava) and producing activated carbon from sludge to minimise costs of micro-pollutant removal (Altenrhein).

An upscaling to a potential full scale is done for demo cases, where trials were being performed at pilot scale in the project (Spernal, Athens, La Trappe, Altenrhein, Costa Brava).

Two basic questions we seek to answer are:

1. How much more or less money is spent by the operator per year compared to the baseline? (LCC)
2. How much more or less money is spent per unit of environmental benefit or impact? (CEA)

2. Methodology

2.1 Life Cycle Costing (LCC)

Common cost types were calculated from the perspective of the operators based on 2021 net costs (VAT excluded) for the operation of one year:

- Capital expenditure (CAPEX) for infrastructure
- Energy
- Materials
- Personnel
- Disposal of waste
- Insurance and maintenance of infrastructure
- Revenues/savings (e.g. by selling materials, reducing emissions or material demand)

Figure 1 shows a flow chart with the cost types considered for the comparison between a given NextGen scenario and its baseline in the form of input and output flows. Cost benefits and drawbacks can be determined when comparing the baseline with the NextGen scenario. In the Spernal demo case a full LCC considering all above-mentioned cost types was performed for both baseline and NextGen scenarios (Figure 1a). In some demo cases actual cumulative costs for water, market fertiliser and pruning waste disposal (Athens), wastewater (La Trappe) or drinking water (Costa Brava) from the operators' perspective were considered as baseline costs (Figure 1b). In other demo cases, where the NextGen solutions represent additional recovery stages in an existing wastewater treatment plant (Braunschweig, Altenrhein), the NextGen scenarios were considered as "add-on" to their respective baseline WWTP considering the differences in material and energy balance (Figure 1c).

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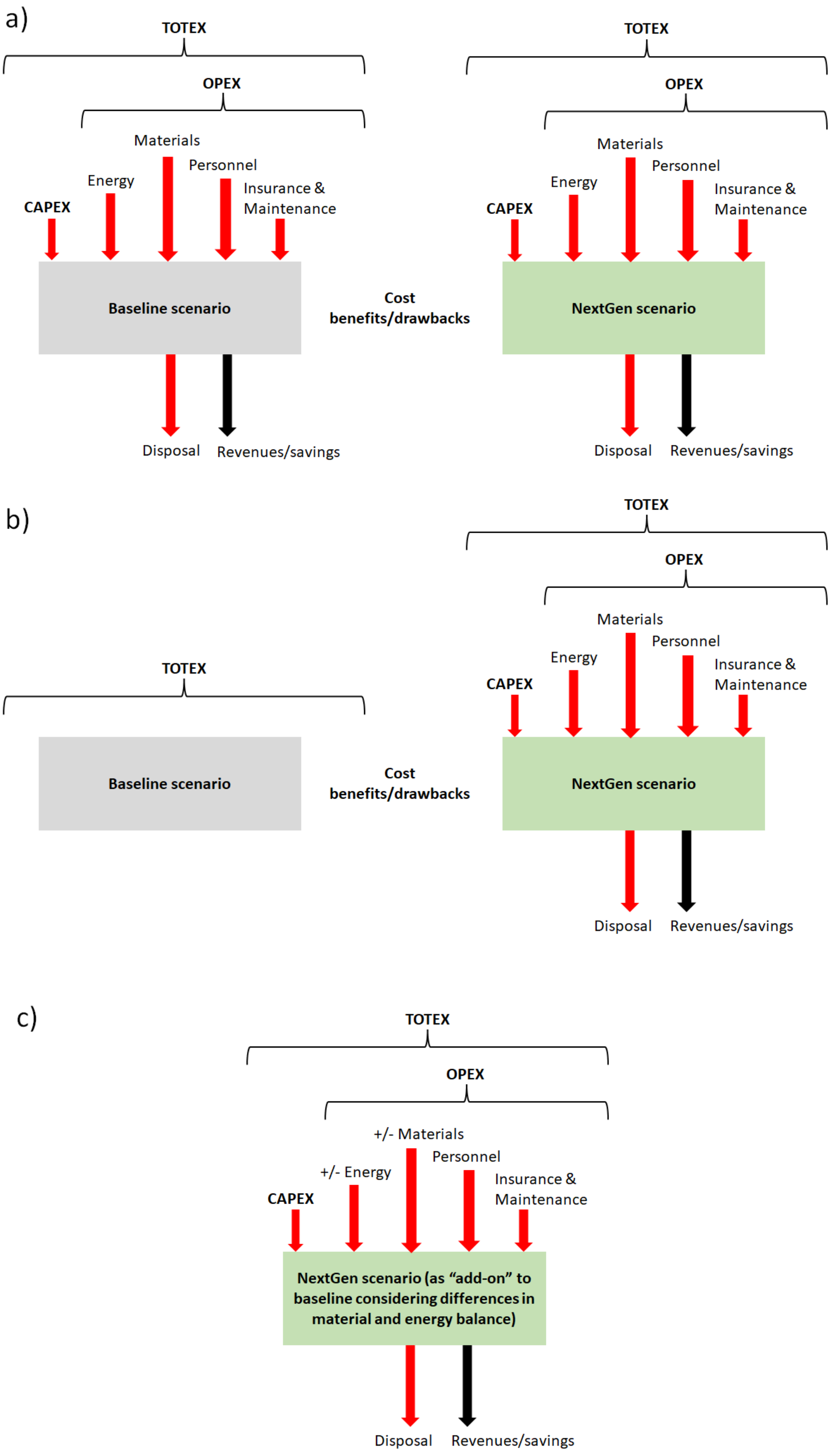

Figure 1 Overview on cost types considered in the baseline and NextGen scenarios

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CAPEX

Data on investments in infrastructure (technology equipment, piping, tanks and buildings, groundwork, excavation) with lump sums for planning costs and risks were collected from operators or from estimations by technology providers in consultation with the plant owners. In all cases full-scale costs were compared to allow comparison between the baseline and NextGen scenarios.

We consider the operation for one year, annualising the NextGen investment cost with an amortisation period of 10 years for technology and 30 years for buildings. Considering an estimated interest rate for capital expenditure of 3%, the annuity factor was calculated to be 12% and 5% for process equipment and building/construction, respectively. The NextGen technologies are new. Therefore, it can be expected that the processes are not yet optimised, leading to higher wear of equipment. Also, the probability that the equipment will have to be (partly) replaced or modified once the operators gain more experience is high. Thus, a rather short depreciation period of 10 years is justified, in contrast to typical baseline WWTP (20 years).

In some cases, without standard WWTP as baseline, the corresponding cost was comparatively simple to evaluate (Athens, La Trappe). But often the standard WWTP (baseline) involves long-time operation with continuous and mostly depreciated investments. CAPEX on total investment is difficult to determine and not meaningful, the standard cost from branch averages is more practicable. Instead of systematically comparing baseline cost and NextGen scenario cost for the whole system, either a comparison of additional costs (Braunschweig, Altenrhein, Costa Brava) or (additional) OPEX (Spernal) was used. Where useful and possible, baseline for certain parts (e.g. tertiary treatment) was compared to the scenarios (Altenrhein, Costa Brava).

The calculation of cost types could be applied, but due to availability and quality of data it was adapted. Water supply and wastewater treatment has a very long lifetime and investment history and cannot be calculated using amortisation of a global cost. Therefore, either the additional cost (Braunschweig, Altenrhein, Costa Brava) or absolute cost compared to a simplified baseline (Athens monetised water supply, La Trappe monetised wastewater treatment cost, Spernal estimated OPEX) was used.

Energy and materials costs

Specific costs for material and energy were provided by stakeholders or drawn from statistics and literature. We used prices of 2021 or earlier, representing a stable market before the Ukraine crisis. Considering that the scope of the technology also depends to some extent on the specific prices in the respective country, prices for energy and raw materials were not standardised between case studies. As the NextGen systems are spread across Europe, there are differences in electricity prices. Raw materials (e.g. chemicals, polymers) were purchased from different providers. Such price variations and their influence on the result were considered in the cross-comparison of the systems. When necessary price quotes were adapted to the price level of other countries using the Big Mac index (Economist, 2022).

Personnel costs

The cost for operating personnel required to run the plant was estimated by the technology providers or plant owners responsible for the demo case based on local typical wages for technicians.

Insurance and maintenance costs

Annual insurance against breakdown, damage, fire, etc. was estimated to be 0.5% of the sum of investment costs (process equipment + building/construction), while annual maintenance was estimated to be 2% of the process equipment costs.

Disposal costs

A standardised price for the transport of dewatered sludge (to farm or incineration plant) was assumed, considering an average transport distance of 50 km.
Prices for sludge valorised in agriculture, co-incineration and mono-incineration were approximated based on experience of technology providers and published offers..

Fertiliser revenues

In all case studies, solid and liquid fertilisers with concentrated nutrient concentrations were counted as revenues compared to the corresponding baseline. In the demo cases of water reuse, we assume that the value of nutrients with the reclaimed water for irrigation of arable fields is negligible due to the untargeted application and uncertain crop availability.

Cost benefits and drawbacks

All systems mass and energy balances were modelled by KWB in Umberto for the environmental assessment and kindly provided also as a basis for the cost assessment. A NextGen scenario was compared to its baseline. The performance of a scenario is not just the sum of the performance of the individual technologies. The technologies of one scenario interact with each other and influence each other's economic performance. Implementing new solutions has an impact on mass and energy flows and corresponding costs of existing wastewater and sludge treatment systems upstream or downstream (e.g. lowered polymer consumption (and costs) for sludge dewatering).

2.2 Cost Effectiveness Analysis (CEA)

The Cost Effectiveness Analysis (CEA) puts the difference of life cycle costs in relation to the difference of environmental performance (GWP impact or product recovery) between a given NextGen scenario and its baseline. Data on GWP impact (LCA) were generated and kindly provided by our colleagues from KWB.
As NextGen provide recovery solutions for water, energy and material from wastewater, typical cost effectiveness units are:

1. Euro/PE*a (PE= population equivalent)
2. Euro/m^3 of recovered water
3. Euro/kWh of recovered energy
4. Euro/kg of recovered phosphorous/nitrogen
5. Euro/kg CO_2eq savings[1]

Definition of the ceiling cost effectiveness
Figure 2 shows an example of a CEA result diagram relating the cost-effectiveness of random systems to their CO_2eq emissions, with the CO_2eq balance on the x-axis and the cost balance on the y-axis. Since both the costs and environmental impact can potentially have both positive and negative signs, there are a total of four possible result ranges. Systems in the range bottom left always can be considered cost effective since both CO_2eq and money can be saved compared to their respective baseline. Systems in the range top right always can be considered not cost-effective since more money is spent and more CO_2eq is emitted compared to their respective baseline. The remaining two result areas are trade-off areas. Systems in the top left range can save CO_2eq, but require more money, while systems in the bottom right range can save money but emit more CO_2eq compared to their respective baseline. There are different kind of trade-offs for systems 2 and 4. The decision as to which of these two technologies performs better depends on the point at which the environmental savings can compensate for the expenditure, or the point at which the monetary savings can compensate for the additional environmental emissions – as the money saved could potentially be reinvested in other mitigation measures. Therefore, a ceiling cost effectiveness must be defined to rank options. This line can be defined by sectorial KPIs or market prices (e.g. for CO_2 credits). The technologies with lower cost/environmental impact ratio (on the left of this line) are improvement options for environmental efficiency. The further away perpendicular to the line downwards and leftwards, the better they perform.

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[1] In the Athens demo case the difference in GWP impact is not directly transferable to the difference in life cycle costs since the LCA performed by KWB considered a full baseline WWTP, while this LCC only considered the cumulative cost of potable water from the operator's perspective.

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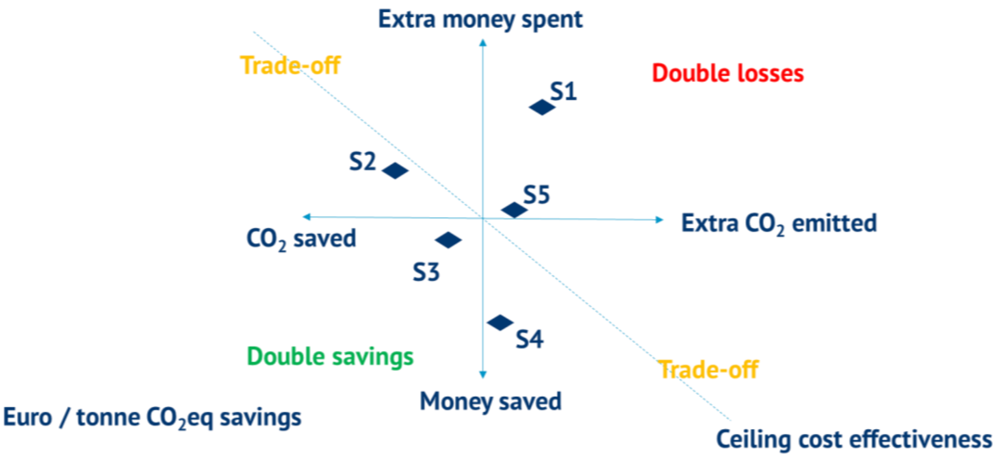

Figure 2 Exemplary CEA result plot showing the relationship between cost balance and CO_2eq balance for random systems with the CO_2eq balance on the x-axis and the cost balance on the y-axis

2.3 Step-by-step approach

Since both KWB for LCA and FHNW for LCC used the same basic data for energy and mass balance, we were in joint exchange with the relevant partners, technology providers and plant operators, who were able to provide us with the data based on tests or best estimates.

These were our work steps for the cost analyses:

1. Define scenarios with partners
2. Collect data from partners & statistics (specific costs if not provided by partners)
3. Crosscheck collected data in terms of plausibility
4. Transfer primary data into scenarios
5. Make LCC and CEA calculations
6. Validate results with partners
7. Write report
8. Validate report with partners

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3. Results & Discussion

3.1 Demo cases

3.1.1 Braunschweig (DE): nutrient and energy recovery in municipal wastewater treatment

The cost analysis for the Braunschweig demo case was carried out on the basis of (1) the annual NextGen infrastructure related costs and personnel costs, and (2) the annual changes between the baseline (former WWTP Braunschweig–Steinhof prior to NextGen implementation) with activated sludge treatment and anaerobic sludge treatment and NextGen scenarios in the mass balance, whereby all changes were assigned to the NextGen scenarios.

The *Hydrolysis & N, P recovery scenario* adds excess sludge digestion, pre-dewatering and thermal-pressure-hydrolysis of pre-dewatered digested excess sludge followed by digestion of hydrolysed excess sludge and primary sludge. Both sludge waters (e.g. filtrate from pre-dewatering and centrate from final dewatering) are mixed and fed into nutrient recovery containing struvite precipitation/harvesting and ammonia stripping/scrubbing. The steam needed for the thermal-pressure-hydrolysis is generated by a steam generator using biogas (about 10 % of the entire biogas from the digesters) as energy source.

The *Hydrolysis & N, P recovery scenario* is supplemented with two deviations:

- In the *+ High temperature CHP scenario*, the steam for the thermal-pressure-hydrolysis is generated via water boiling using the high temperature heat from the combined heat and power (CHP), meaning that the entire biogas from the digesters is valorised in the CHP, resulting in higher electricity recovery compared to the *Hydrolysis & N, P recovery scenario*.
- In the *+ Max Struvite recovery scenario*, a provisional struvite precipitation before final dewatering is removed, to transfer more ortho-phosphate into the centrate and maximise the struvite production. However, this results in a higher dry mass of the dewatered sludge.

In addition, two variants are considered in each case, which differ in the dewatering and utilisation of the sewage sludge:

- In the *mid-term (2020)*, summer sludge is valorised via irrigation and winter sludge is valorised in co-incineration and agriculture, representing sludge management before implementation of the NextGen scheme.
- In the *long-term (2030)*, there will be year-round sludge dewatering resulting in sludge fit for mono-incineration.

Table 1 provides an overview on the different NextGen scenarios considered in the Braunschweig demo case.

Table 1 Overview on scenarios of the Braunschweig demo case considered in the cost assessment

Scenario	**Mid-term (2020)** Summer sludge valorised via irrigation & winter sludge valorised in co-incineration/agriculture	**Long-term (2030)** Year-round dewatering & all sludge valorised in mono-incineration
NextGen **Hydrolysis & N, P recovery**	Thermal-pressure-hydrolysis and nutrient recovery from filtrate and centrate	
NextGen **+ High temperature CHP**	Hydrolysis & N, P recovery, with high temperature valorisation from combined heat and power, without biogas into steam generator	
NextGen **+ Max Struvite recovery**	Hydrolysis & N, P recovery, without Mg-dosing into sludge, with maximum struvite recovery	

System function & functional unit

The function of the system under investigation is to provide wastewater treatment in accordance with legal requirements, including all processes associated with this function. The functional unit of this LCC is one year of operation ("per a"), defined by the annual organic load of the WWTP Braunschweig–Steinhof, which is 350,000 population equivalents (PE).

System boundary

The system boundary of this LCC includes the wastewater and sludge treatment and management system in the WWTP. Production of struvite and ammonium sulphate solution is accounted for as potential fertiliser revenue. Biogas is utilised in a combined heat and power plant, and the electricity is accounted for (Figure 3).

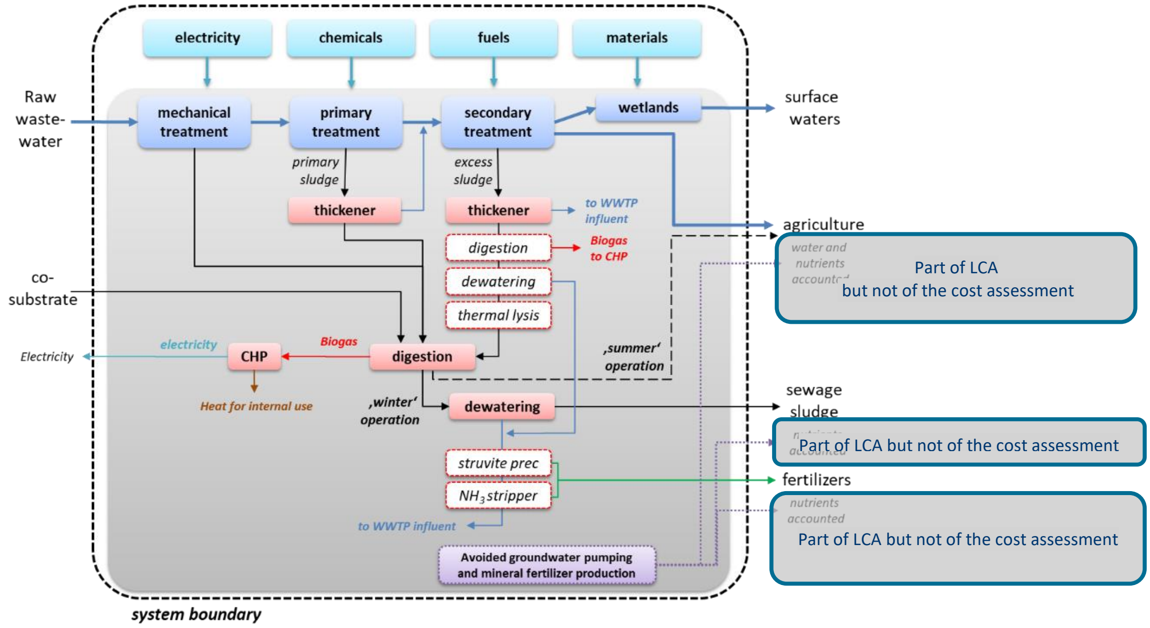

Figure 3 System boundary of the Braunschweig demo case (from KWB)

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Data quality

Table 2 provides an overview of data sources and quality for the Life Cycle Inventory of the Braunschweig demo case. Mass flow data sources and quality were initially indicated by our project partner KWB (See NextGen Deliverable 2.1 for original table). See A.1 Inventory data of the Braunschweig demo case for inventory data of energy and materials and B.1 Cost input data of the Braunschweig demo case for inventory data of investments, personnel costs and specific costs.

Table 2 Overview of data sources and quality for the Life Cycle Inventory of the Braunschweig demo case (adapted from KWB)

Parameter/ Process	Data source	Data quality
Costs		
Investment, insurance, maintenance costs	WWTP operator	very high
Personnel costs	WWTP operator	medium–high
Specific material costs	Market prices	medium–high
Specific energy costs	Market prices	very high
Specific costs for fertilisers	External experts	medium–high
Mass flow – Baseline		
Water quality and quantity	WWTP operator	very high
Measured sludge and sludge liquor quality parameters	WWTP operator	very high
Sludge and sludge liquor quantities (volume & loads)	Calculated	high
Energy and chemical consumption	WWTP operator	very high
Heat balance (CHP, external gas)	Estimated	medium–high
Gaseous emissions from fields/wastewater, heavy metals	Literature	medium
Mass flow – NextGen		
Measured sludge and sludge liquor quality parameters	WWTP operator	high
Sludge and sludge liquor quantities (volume & loads)	Estimated	medium–high
Energy and chemical consumption	WWTP operator	high
Heat balance (CHP, steam generator, external gases)	Estimated	medium–high

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LCC results

Table 3 and Figure 4 show the additional costs for the NextGen mid-term (2020) scenarios in relation to the mid-term baseline, broken down by the main types of operational expenditure and the CAPEX. The mid-term NextGen scenarios add costs of ~1.4–1.6 million Euro/year to the TOTEX of the corresponding baseline. The *+ High temperature CHP scenario* has the lowest TOTEX of all NextGen scenarios, with the higher energy recovery and corresponding savings in total energy consumption more than offsetting the higher CAPEX (waste heat boiler for steam generation).

The CAPEX, the corresponding insurance and maintenance and the personnel make >66%, >12% and >21% of the NextGen scenarios' TOTEX, respectively (sum of >100% possible since cost savings are included in TOTEX).

All NextGen scenarios increase the cost for chemicals (+30% in cost) compared to the baseline. However, the higher costs for chemicals can be offset (*Hydrolysis & N, P recovery*) or more than offset (*+ High temperature CHP & + Max struvite recovery*) by the revenues and cost savings of the circular solutions: (1) Energy costs can be lowered via energy recovery in all NextGen scenarios, in particular in the *+ High temperature CHP scenario*, which is primarily geared towards high energy recovery. (2) With improved sludge dewaterability, the amount of sludge and corresponding costs for transport and valorisation can be reduced with all NextGen scenarios. The *+ Max struvite recovery scenario* leads to less savings in sludge disposal compared with the other NextGen scenarios as dewatering efficiency is decreased. (3) Revenues from ammonium sulphate solution (ASL: 7.7% N) and struvite (5.7% N & 12.6% P) lead to cost savings for all NextGen scenarios. We have assumed a typical 7.7% N in the ASL solution, even though the proportion is potentially different from the actual concentration in the Braunschweig case, as we have the best cost estimate for this N content. The ~4% higher fertiliser revenues of the *+ Max Struvite recovery scenario* – due to a higher struvite yield – cannot compensate the higher cost of sludge transport and valorisation compared to the other NextGen scenarios.

Table 3 Additional annual costs of NextGen scenarios compared to the mid-term baseline in the Braunschweig demo case

Cost type (annual values)	Hydrolysis & N, P recovery	+ High temperature CHP	+ Max Struvite recovery
CAPEX	1,040,000 €	1,120,000 €	1,070,000 €
Insurance & Maintenance	195,000 €	205,000 €	195,000 €
Personnel	350,000 €	350,000 €	350,000 €
Energy	–119,000 €	–370,000 €	–141,000 €
Chemicals	420,000 €	420,000 €	420,000 €
Sludge disposal	–190,000 €	–190,000 €	–108,000 €
Fertiliser revenues	–151,000 €	–151,000 €	–153,000 €
TOTEX	**1,570,000 €**	**1,382,182 €**	**1,630,000 €**

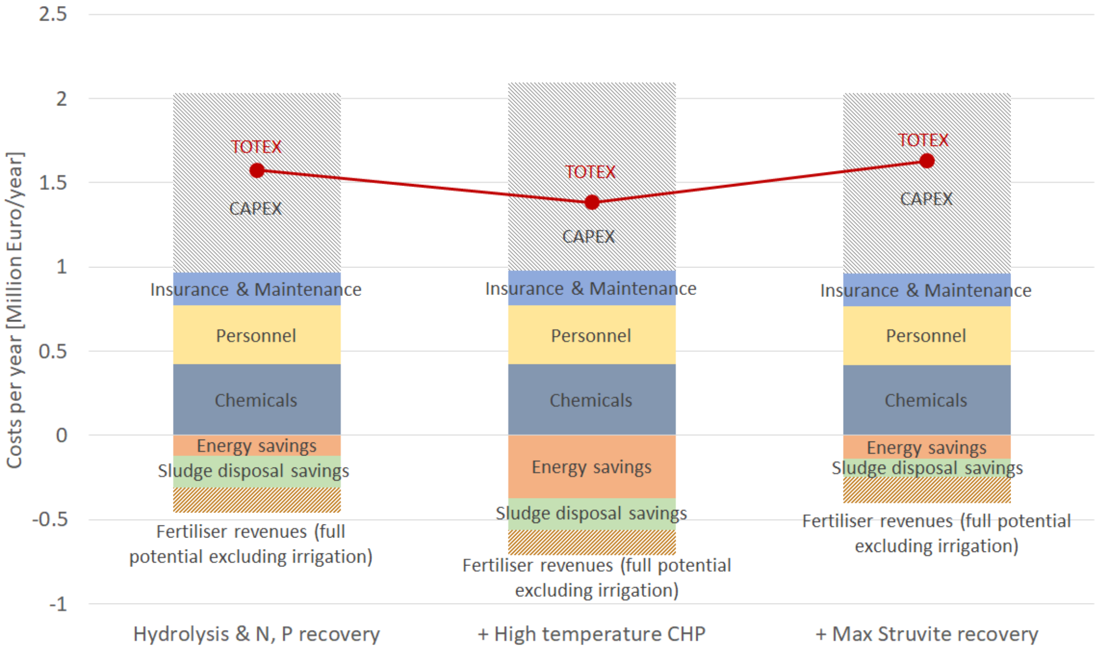

Figure 4 Additional cost of the NextGen scenarios in relation to the mid-term baseline in the Braunschweig demo case

Table 4 and Figure 5 show the LCC results for the NextGen long-term (2030) scenarios. Additional costs for NextGen decrease with rising sludge disposal costs, as savings from sludge reduction are getting more important. In fact, savings from sludge disposal are now the major factor for savings in all scenarios. The additional TOTEX of the long-term NextGen scenarios is “only” ~1.1–1.4 million Euro/year.

Table 4 Additional annual costs of NextGen scenarios compared to the long-term baseline in the Braunschweig demo case

Cost type (annual values)	Hydrolysis & N, P recovery	+ High temperature CHP	+ Max Struvite recovery
CAPEX	1,070,000 €	1,120,000 €	1,070,000 €
Insurance & Maintenance	195,000 €	205,000 €	195,000 €
Personnel	350,000 €	350,000 €	350,000 €
Energy savings	–137,000 €	–390,000 €	–171,000 €
Chemicals	450,000 €	450,000 €	440,000 €
Sludge disposal savings	–480,000 €	–480,000 €	–285,000 €
Fertiliser revenues	–191,000 €	–191,000 €	–193,000 €
TOTEX	**1,250,000 €**	**1,060,000 €**	**1,410,000 €**

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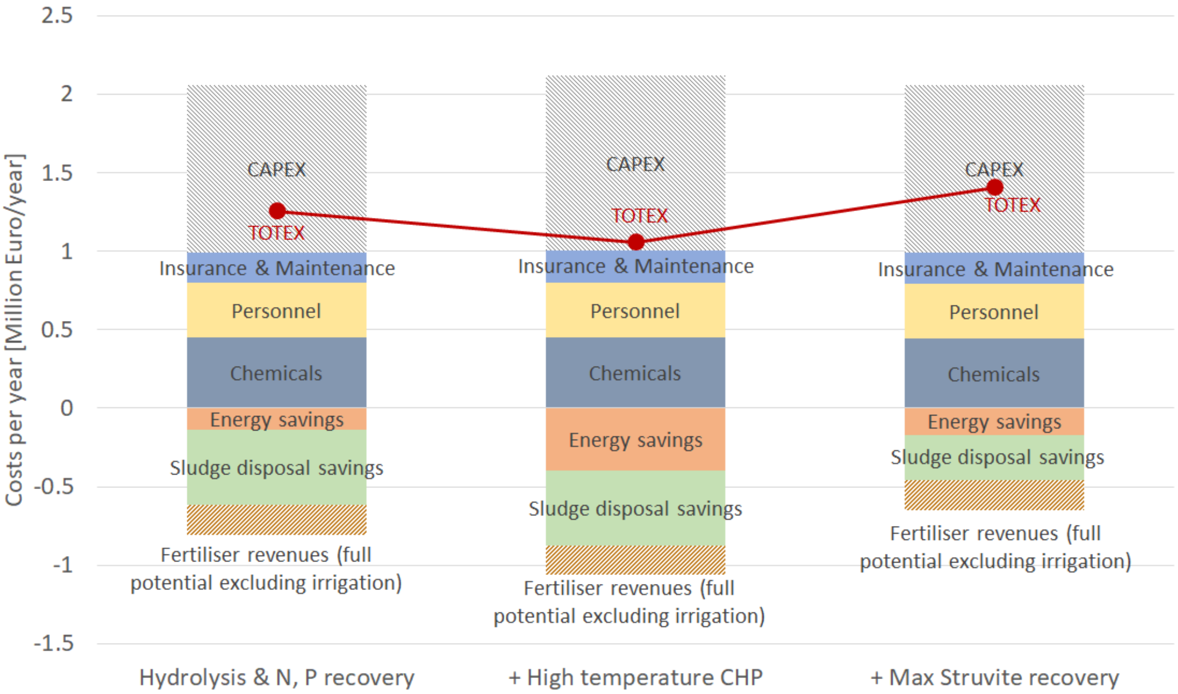

Figure 5 Additional cost of the NextGen scenarios in relation to the long-term baseline in the Braunschweig demo case

The sewage treatment plant in Braunschweig has a load of 350,000 PE but is actually only designed for 275,000 PE. The effluent limit values for phosphorus and nitrogen cannot be reliably met, especially in the winter months. Relieving the sewage treatment plant is therefore a necessary goal to ensure compliance with the discharge limits (Abwasserverband Braunschweig 2019). The NextGen scenarios are associated with higher costs but can help to achieve this goal.

Sensitivity analysis

When assuming a depreciation period of 20 years (instead of 10 years) for the process investments, the additional TOTEX of the mid-term NextGen scenarios are decreased by 21–26% and the additional TOTEX of the long-term NextGen scenarios are decreased by 24–34%.

Considering 2022 prices for energy, chemicals, and fertilisers, which are a factor ~2.2, ~1.3 and ~1.3 higher, respectively, compared to 2021 prices (eurostat 2022), the costs for the baseline increase significantly with 2022 prices compared with 2021 prices, primarily due to higher energy costs. In contrast, the additional costs of the NextGen scenarios are smaller due to the higher savings of energy and the higher revenues for recycled fertiliser. The additional TOTEX of mid-term NextGen scenarios are decreased by 4–26% and the additional TOTEX of the long-term NextGen scenarios are decreased by 7–37% considering 2022 instead of 2021 prices.

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Specific costs of environmental services

Considering the additional life cycle costs and the GWP impact reductions of the NextGen mid-term scenarios compared to the mid-term baseline, specific costs of ~15T, ~2T and ~16T Euro per tonne of CO_2eq savings are calculated for the *Hydrolysis & N, P recovery scenario*, *+ High temperature CHP* and *+ Max Struvite recovery scenario*, respectively. Consequently, the *+ High temperature CHP scenario* has the lowest specific cost/t CO_2eq savings, which equals the highest cost effectiveness of the NextGen mid-term scenarios (Table 5).

Table 5 Specific cost of NextGen mid-term scenarios GWP savings compared to the mid-term baseline in the Braunschweig demo case

Scenario	Life cycle cost compared to baseline	GWP impact compared to baseline	Specific costs
2020_ Hydrolysis & N, P recovery	+1,570,000 Euro/a	–105 t CO_2eq/a	15,000 Euro/t CO_2eq savings
2020_+ High temperature CHP	+1,380,000 Euro/a	–665 t CO_2eq/a	2,100 Euro/t CO_2eq savings
2020_+ Max Struvite recovery	+1,630,000 Euro/a	–105 t CO_2eq/a	15,500 Euro/t CO_2eq savings

The same calculation was done for the NextGen long-term scenarios compared to the long-term baseline. This results in a higher cost effectiveness of the *+ High temperature CHP scenario* and a lower cost effectiveness of the *Hydrolysis & N, P recovery scenario* and *+ Max Struvite recovery scenario* compared to their respective mid-term scenarios (2020). The *long-term + Max Struvite recovery scenario* is the only *scenario* without CO_2eq savings compared to its baseline (Table 6).

Table 6 Specific cost of NextGen mid-term scenarios GWP savings compared to the long-term baseline in the Braunschweig demo case

Scenario	Life cycle cost compared to baseline	GWP impact compared to baseline	Specific costs
2030_ Hydrolysis & N, P recovery	+ 1,250,000 Euro/a	–35 t CO_2eq/a	36,000 Euro/t CO_2eq savings
2030_+ High temperature CHP	+ 1,060,000 Euro/a	–595 t CO_2eq/a	1,780 Euro/t CO_2eq savings
2030_+ Max Struvite recovery	+ 1,410,000 Euro/a	+70 t CO_2eq/a	No GWP savings

Conclusions

The following conclusions can be drawn from the results of this cost assessment:

- The implementation of the NextGen nutrient recovery schemes in the WWTP Braunschweig–Steinhof is not profitable at this stage as the revenues of fertilisers are much lower than the annual infrastructure related costs (CAPEX, insurance and maintenance), personnel costs and additional costs for chemicals.
- However, the NextGen nutrient recovery schemes are a solution to ensure that the discharge limits for nitrogen and phosphorus are met.
- The application of thermal pressure hydrolysis is more favourable in situations where sludge disposal costs are high (long-term scenarios in the Braunschweig demo case).
- Doubling depreciation period of infrastructure and using 2022 instead of 2021 prices would considerably reduce the additional TOTEX of the NextGen scenarios.
- The *+ High temperature CHP scenario* has the highest cost effectiveness regarding GWP impact reduction.

3.1.2 Spernal (UK): energy, nutrient and water recovery in municipal wastewater treatment

In the Spernal demo case, the baseline is a typical 100,000 PE WWTP in the UK. After a primary clarifier, the secondary treatment consists of biological P and N removal combined with P removal by iron dosing. For tertiary treatment to remove P to very low limits, a second stage of iron dosing in combination with a sand filter is applied. Sludge treatment (thickening, digestion, dewatering) takes place on-site at the WWTP, and dewatered sludge is applied in agriculture.

In NextGen, a new concept is tested with anaerobic treatment of municipal wastewater in a membrane bioreactor (AnMBR), followed by nutrient recovery by ion exchange. The AnMBR consists of an upflow anaerobic sludge blanket reactor (UASB) and an ultrafiltration membrane system (UF). The UASB combines two energetic benefits: 1) low energy consumption for organics (COD/BOD) removal because no aeration is needed and 2) biogas production in the biological stage of the WWTP. The UF delivers a pathogen/solids free effluent which can be further treated/reused in several applications (e.g.: ion exchange for nutrient recovery, farming and industrial use). A degasser is located downstream to recover the dissolved methane.
The IEX stage first removes ammonium (N-IEX) using a specific zeolite resin, and then phosphate (P-IEX) with a hybrid anionic ion exchange resin. The nutrients can be recovered from the regenerant solution by membrane stripping (N) and precipitation as a mineral salt (P).

Three NextGen scenarios are considered in the analysis. All of them include an AnMBR for BOD and total solids (TS) removal, without targeted nutrient removal (i.e. without nitrification/denitrification and without Fe dosing):

- *AnMBR/Degasser/IEX scenario*: The AnMBR is supplemented by a membrane degasser, to recover the dissolved biogas in the UF effluent. A two-stage IEX system for NH^{4+} and PO_4^{3-} removal is used to reach the defined effluent standards. A large share of the nutrients can be recovered from the regenerant with stripping or precipitation processes.
- *AnMBR/Aerobic stage/IEX scenario*: The energy-intensive membrane degasser in the previous scenario is replaced by an aerated biofilm reactor (MABR). Residual CH_4 is thus converted into biogenic CO_2 to prevent the direct emission of the greenhouse gas methane.
- *AnMBR/Degasser/Irrigation scenario*: This scenario considers the AnMBR configuration and degassing without an IEX for nutrient removal. The UF effluent is directly used for irrigation in agriculture, assuming that water can be utilised for the whole year, e.g. in greenhouse farming.

Table 7 provides an overview on the different baseline and NextGen scenarios considered in the Spernal demo case.

Table 7 Overview on scenarios of the Spernal demo case considered in the cost assessment

Scenario	
Baseline	• Biological N/P removal + low Fe • Post-treatment with Fe and sand filtration • Sludge treatment by digestion • Sludge valorisation in agriculture
AnMBR/Degasser/IEX	• Anaerobic membrane bioreactor (AnMBR) including UASB and UF for BOD removal and additional biogas production • Methane recovery with membrane degassing • IEX for post-treatment and N/P recovery to ultimately produce recycling fertilisers • Sludge treatment by digestion • Sludge valorisation in agriculture
AnMBR/Aerobic stage/IEX	• Anaerobic membrane bioreactor (AnMBR) including UASB and UF for BOD removal and additional biogas production • Aerobic stage • IEX for post-treatment and N/P recovery to ultimately produce recycling fertilisers • Sludge treatment by digestion • Sludge valorisation in agriculture
AnMBR/Degasser/Irrigation	• Anaerobic membrane bioreactor (AnMBR) including UASB and UF for BOD removal and additional biogas production • Methane recovery with membrane degassing • Water valorisation by fertigation • Sludge treatment by digestion • Sludge valorisation in agriculture

System function & functional unit

The function of the system under investigation is to provide wastewater treatment in accordance with legal requirements, including all processes associated with this function. The functional unit of this LCC is one year of operation (“per a”), defined by the annual organic load of the WWTP, calculated in population equivalents of the WWTP. A wastewater treatment plant with a capacity of 100,000 PE was considered for both the baseline and the NextGen scenarios in this LCC, corresponding to a wastewater inflow of 9,110,400 m^3 per year (~25,000 m^3 per day).

System boundary

The system boundary of this LCC includes the wastewater and sludge treatment and management system in the WWTP. Costs from the reuse of nutrients in fertilisers are accounted for. Biogas is utilised in a combined heat and power plant, and the electricity is accounted for (

Figure 6).

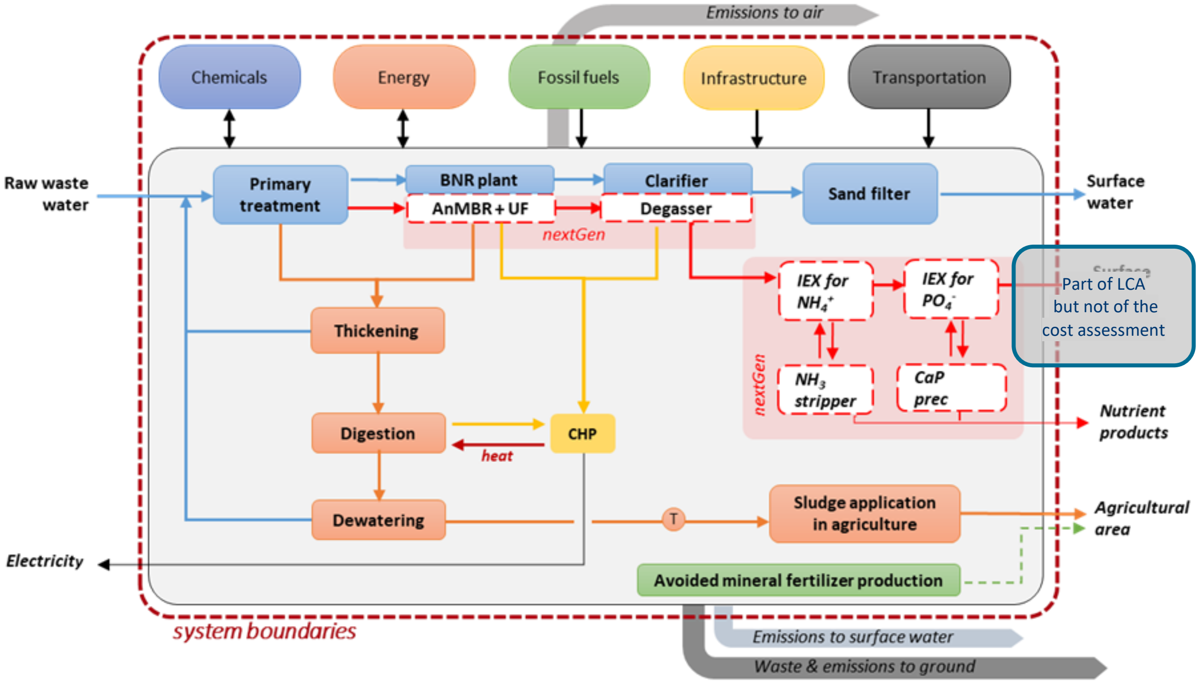

Figure 6 System boundary of the Spernal demo case (from KWB)

Data quality

Table 8 provides an overview of data sources and quality for the Life Cycle Inventory of the Spernal demo case. Mass flow data sources and quality were initially indicated by our project partner KWB (See NextGen Deliverable 2.1 for original table). See A.2 Inventory data of the Spernal demo case for inventory data of energy and materials and B.2 Cost input data of the Spernal demo case for inventory data of investments, personnel costs and specific costs.

Table 8 Overview of data sources and quality for the Life Cycle Inventory of the Spernal demo case (adapted from KWB)

Parameter/ Process	Data source	Data quality
Costs		
Investment, insurance, maintenance costs	WWTP operator	medium
Personnel costs	Estimated	low
Specific material costs	Market prices	medium–high
Specific energy costs	Market prices	high
Specific costs for fertilisers	External experts	medium–high
Mass flow – Baseline		
WWTP reference system: influent, effluent, sludge, energy and chemical demand	WWTP operator	high
Mass flow – NextGen		
Operational data of sludge line in NextGen schemes	WWTP operator	medium–high
UASB and UF	Cranfield University	medium
Degasser	Cranfield University	low
Aerated stage	Cranfield University	medium
N-IEX and P-IEX layout and operation, including regenerant	Cranfield University	medium–high
Ammonium recovery from regeneration solution + Calcium phosphate recovery from regeneration solution	Cranfield University	low–medium
Irrigation	Estimated	low

LCC results

CAPEX calculations based on equipment cost estimates in NextGen are higher than previous literature data for the same system (Huang et al. 2020). CAPEX of the baseline and the *AnMBR/Degasser/IEX scenario* can be situated in the range of 1.5– 4.5 million Euro per year. Due to the high uncertainty of data, the CAPEX and insurance/maintenance costs (based on CAPEX) were not included in this cost assessment.

Table 9 and Figure 7 show the OPEX for personnel, energy, chemicals, disposal and revenues for the Spernal demo case scenarios: The NextGen scenarios *AnMBR/Degasser/IEX*, *AnMBR/Aerobic stage/IEX* and *AnMBR/Degasser/Irrigation* can reduce this sum of costs by <1%, ~16% (170,000 EUR/a) and ~43% (460,000 EUR/a) compared to the baseline, respectively. The fertiliser revenues, the lower energy input and the lower sludge amount to be transported and applied in agriculture can more than offset the higher costs for chemicals in the NextGen scenarios *AnMBR/Degasser/IEX* and *AnMBR/Aerobic stage/IEX* compared to the baseline. All NextGen scenarios can reduce the net energy input compared to the baseline when considering the generated energy to be reused in the process. The *AnMBR/Degasser/Irrigation scenario* has the lowest sum of costs of all NextGen scenarios since the avoided incremental cost of IEX inputs of materials, energy, and chemicals to recover nutrients (ultimately fertilisers) is higher than the calculated credits for the fertilisers.

Table 9 Additional annual costs of NextGen scenarios compared to the baseline in the Spernal demo case

Cost type (annual values)	AnMBR/Degasser/IEX	AnMBR/Aerobic stage/IEX	AnMBR/Degasser/ Irrigation
Personnel	0 €	0 €	0 €
Energy	–19,000 €	–186,000 €	–274,000 €
Chemicals/Materials	540,000 €	540,000 €	–87,000 €
Sludge disposal	–97,000 €	–97,000 €	–97,000 €
Fertiliser revenues	-430,000 €	-430,000 €	0 €
SUM	0 €	**–168,000 €**	**–460,000 €**

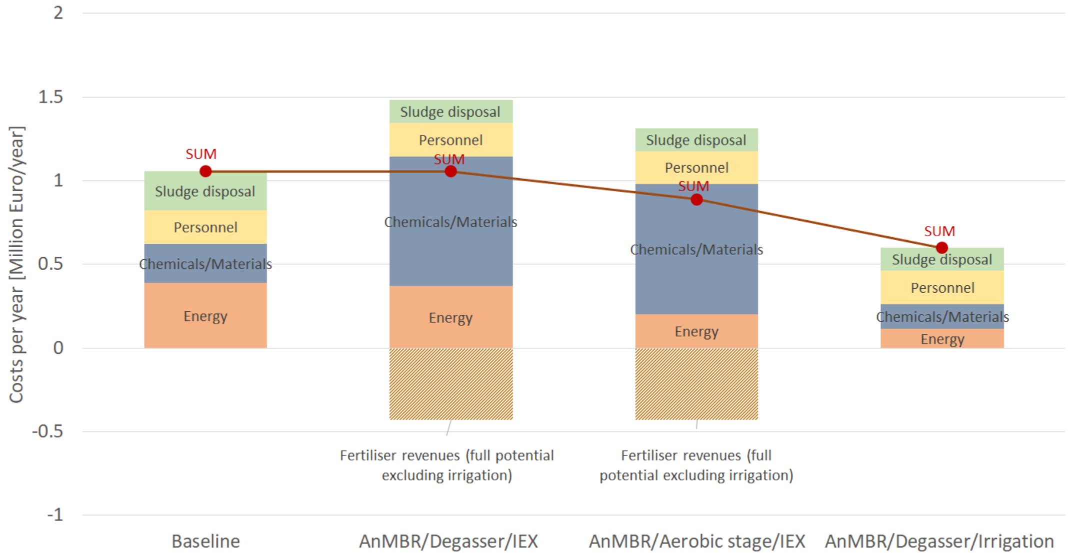

Figure 7 OPEX results of the Spernal demo case scenarios (excluding insurance/maintenance)

Sensitivity analysis

Considering 2022 prices for energy, chemicals, and fertilisers, which are a factor ~2.2, ~1.3 and ~1.3 higher, respectively, compared to 2021 prices (eurostat 2022),the *AnMBR/Aerobic stage/IEX* and the *AnMBR/Degasser/Irrigation scenario* still reduce the sum of costs by ~22% and ~51%, respectively, compared to the baseline. The *AnMBR/Degasser/IEX scenario* has still about the same costs as the baseline (<1% higher costs).

Specific costs of environmental services

Considering lower life cycle costs (excluding CAPEX and insurance/maintenance) and GWP impact reductions of the NextGen scenarios compared to the baseline, no specific costs of the NextGen scenarios could be calculated regarding GWP impact reduction (double savings). The *AnMBR/Degasser/Irrigation scenario* has the highest cost effectiveness of the NextGen scenarios with both highest cost reduction and highest GWP reduction (Table 10, see also Figure 20).

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Table 10 Comparison of life cycle cost savings and GWP reduction of the Spernal demo case NextGen scenarios compared to the baseline

Scenario	Life cycle cost compared to baseline (excluding CAPEX and insurance/maintenance	GWP impact compared to baseline
AnMBR/Degasser/IEX	–0 Euro/a	–1,100 t CO_2eq/a
AnMBR/Aerobic stage/IEX	–170,000 Euro/a	–1,300 t CO_2eq/a
AnMBR/Degasser/Irrigation	–460,000 Euro/a	–2,900 t CO_2eq/a

Conclusions

The following conclusions can be drawn from the results of this cost assessment:

- The implementation of combined NextGen nutrient and energy recovery schemes can reduce OPEX as the revenues of fertilisers, energy cost savings and sludge disposal savings are much than the additional costs for chemicals.
- The application of IEX is not profitable regarding OPEX for nutrient recovery only, as related chemical costs are higher than fertiliser revenues.
- Using 2022 instead of 2021 prices would further increase the OPEX reductions of the NextGen scenarios *AnMBR/Aerobic stage/IEX* and *AnMBR/Degasser/Irrigation* compared to the baseline, as they require much less energy input.
- The *AnMBR/Degasser/Irrigation scenario* – considering OPEX – has the highest cost effectiveness regarding GWP impact reduction.

3.1.3 Athens (GR): sewer mining for water and nutrient reuse

The Athens urban tree nursery is located in the Goudi park in the city of Athens. The Athens demo case baseline represents the status quo of linear water and nutrient management:

- Potable water is imported from reservoirs over more than 250 kilometres for irrigation of the tree nursery.
- Market fertiliser is purchased for the tree nursery: ~60 t/a organic fertiliser enriched with peat (>60% dry matter content) plus ~700 kg/a mineral fertiliser (12N–12P–17K), which could be substituted by ~60 t peat, ~450 kg mineral N fertiliser and ~150 kg mineral P fertiliser.
- 6,000 t/a of pruning waste from the Goudi park is disposed of in a landfill.

The Athens *NextGen scenario* represents the future situation of circular water, nutrient (and energy) management. The three systems are installed and tested at the tree nursery in pilot scale:

- 62,250 m^3/a of municipal wastewater is recovered locally by the Sewer Mining Unit (SMU), which includes a membrane bioreactor (MBR) to treat wastewater drawn from the local sewer system, followed by a UV treatment for water disinfection. The produced irrigation water is then stored and used to irrigate the plants at the tree nursery.
- Heat is recovered with an in-line heat exchanger and heat pump, which extracts heat from the MBR effluent. This heat is used internally at the composting unit to accelerate the composting process, and surplus heat can be used for other purposes. The heat exchanger is sized according to the total effluent volume of the SMU and an extraction of 5°C, resulting in a maximum heat output of 50 kW.
- A rapid composting system – accelerated by the heat recovered from the sewage – is introduced to transform excess sludge (140 m^3/a with 5% TS) from the MBR plus shredded pruning waste (105 t/a) to nutrient rich compost, with the aim of fully replacing the market fertiliser from the baseline. Only the marginal fraction (~2%) of total Goudi park pruning waste, which can be reused in the *NextGen scenario*, is considered for both scenarios (baseline and *NextGen scenario*) in the LCC comparison.

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Table 11 provides an overview on the baseline and *NextGen scenario* considered in the Athens demo case.

Table 11 Overview on scenarios of the Athens demo case considered in the cost assessment

Scenario	Water line	Energy line	Material line
Baseline	Potable water for irrigation	No energy recovery	Market fertiliser used for tree nursery & pruning waste to landfill
NextGen	Municipal wastewater locally recovered by sewer mining unit (SMU) for irrigation	Heat recovery from sewage by heat exchangers	Recycling compost used for tree nursery, produced by rapid composting unit using sludge from SMU, pruning waste and recovered heat

System function & functional unit

The function of the systems under study is multi-dimensional. It comprises of a) the delivery of irrigation water and nutrients to the tree nursery and b) the disposal of pruning waste. The LCC includes all relevant processes related to these two functions. However, it is very difficult to identify a dedicated functional unit, as the system functions cover different input materials and services. Hence, it was decided to define an overarching functional unit as the operation of the systems fulfilling these functions for a period of one year. Based on the findings in the pilot trials, the system is evaluated in its costs compared to the status quo (baseline) of water and nutrient management at the tree nursery. Therefore, the performance and scale of the systems is extrapolated from the pilot trials to a suitable full-scale size for the tree nursery. The driving factor here is the actual water demand of the tree nursery (i.e. 62,250 m^3/a or ~170m^3/d), which defines the required size of the SMU unit and then also the downstream processing of compost and the unit for heat extraction.

System boundary

This cost assessment includes all relevant processes for water and nutrient management in the two scenarios from the tree nursery's point of view: the cost for potable water, market fertiliser and pruning waste disposal in the baseline and the demand of electricity and chemicals for the operation of the NextGen scenario with SMU, rapid composting, and heat exchanger. The cost savings of fertiliser due to recovery of nutrients and organics via compost of SMU sludge and pruning waste – considering both substituting only actual demand and selling surplus compost in a full potential scenario) – and the surplus heat are accounted for in the NextGen scenario (

Figure 8).

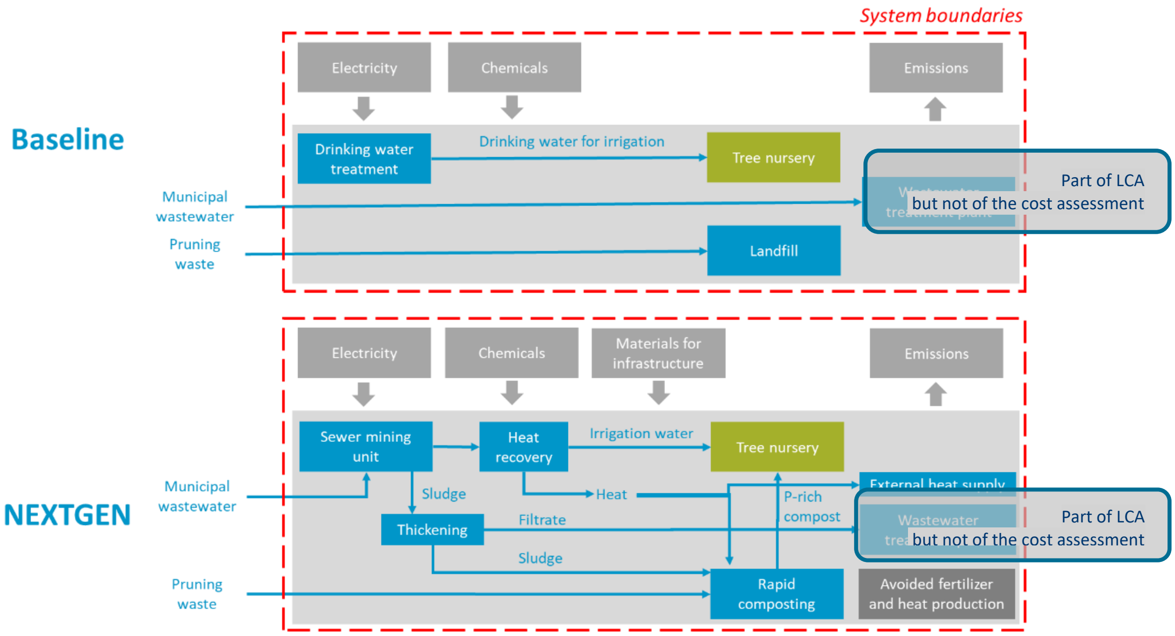

Figure 8 System boundary of the Athens demo case (from KWB)[2]

Data quality

Table 12 provides an overview of data sources and quality for the Life Cycle Inventory of the Athens demo case. Mass flow data sources and quality were initially indicated by our project partner KWB (See NextGen Deliverable 2.1 for original table). See A.3 Inventory data of the Athens demo case for inventory data of energy and materials and B.3 Cost input data of the Athens demo case for inventory data of investments, personnel costs and specific costs.

Table 12 Data sources and quality for Life Cycle Inventory of Athens demo case (adapted from KWB)

Parameter/ Process	Data source	Data quality
Costs		
Investment, insurance, maintenance costs	NTUA, BIOPOLUS	high
Personnel costs	NTUA, BIOPOLUS	medium–high
Specific material costs	Market prices	medium–high
Specific energy costs	Market prices	very high
Specific costs for fertilisers	External experts	medium–high
Mass flow – Baseline **Irrigation water, fertiliser demand, sludge and pruning waste quantities**	NTUA: Data from the tree nursery	very high
Mass flow – NextGen		
SMU (MBR + UV + storage and irrigation)	NTUA: results from pilot trials for water quality and chemicals, up-scaling for electricity demand and infrastructure	medium–high
Rapid composting unit	BIOPOLUS: estimate from mass balance, KWB: emissions estimate	medium
Heat exchanger	BIOPOLUS: supplier data	medium–high

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[2] Electricity/chemicals as inputs for drinking water treatment in the baseline can be considered as foreground processes included in the price for potable water, which is used in our cost assessment. Cost for wastewater treatment in the WWTP is not considered since LCC is performed from the perspective of the nursery operator.

LCC results
Table 13 and

Figure 9 show the LCC results for the Athens demo case scenarios broken down by the main types of operational expenditure and the CAPEX. The individual recovery lines for water, material (i.e. compost) and energy with the corresponding investments, operational costs and credits shown, work jointly and add up to the total of the NextGen circulation system. The heat credits in total are smaller than in the individual *energy line* because a third of the energy recovered in the *energy line* can be reused for rapid composting, reducing the energy input in the overall *NextGen scenario*. We assume revenues for all compost produced by this system. Only ~45% (when excluding nutrients in irrigation water) is needed for substituting the current nutrient demand in the tree nursery, the rest is considered to be sold at market prices to local gardens or farmers.

Considering these sales, the *NextGen scenario* still has a ~16% higher TOTEX (+17,000 EUR/a) compared to the baseline. Capital expenditure (~60%) and process energy (~31%) are the major cost types in the *NextGen scenario*. The membranes and chemicals for wastewater treatment and the inoculum for rapid composting have only minor shares of TOTEX (<2%).

Independent from energy and material recovery, the *NextGen water line* can reduce the total expenditure on irrigation water by ~8,000 EUR/a (11%) compared to the cost of imported drinking water in the *baseline*: less infrastructure cost (no piping, no transport) of the decentralised, direct reuse option can more than compensate for the higher energy input compared to conventional central wastewater treatment. The conventional WWTP removes most nutrients to fulfil effluent limits with additional effort and corresponding costs. This is not necessary for the irrigation of the nursery, and the remaining nutrients in the SMU recycled water can be absorbed by the trees, thus reducing the amount of nutrients that have to be removed compared to the *baseline*.

The *NextGen material line* alone (compost production with rapid composting unit) increases the cost of fertilisation threefold (+ 30,000 EUR/a) compared to the *baseline* (market fertiliser and disposal of pruning waste, which is used for compost production in NextGen).

The *NextGen energy line* alone can generate cost savings in the amount of ~5,500 Euro/a.

Table 13 Additional annual costs of NextGen scenarios compared to the baseline in Athens demo case

Cost type (annual values)	Total	Water line	Material line	Energy line
CAPEX	60,0000 €	32,000 €	24,000 €	4,100 €
Insurance & Maintenance	11,700 €	5,700 €	5,100 €	900 €
Personnel	10,287 €	3,600 €	6,700 €	
Energy	31,000 €	20,000 €	9,300 €	7,800 €
Heat	−12,200 €			−18,300 €
Chemicals/Materials	3,800 €	3,600 €	170 €	
Potable water	−73,000 €	−73,000 €		
Pruning waste disposal	−1,000 €		−1,000 €	
Fertiliser savings	−14,000 €		−14,000 €	
TOTEX	**17,300 €**	**−7,700 €**	**30,000 €**	**−5,500 €**

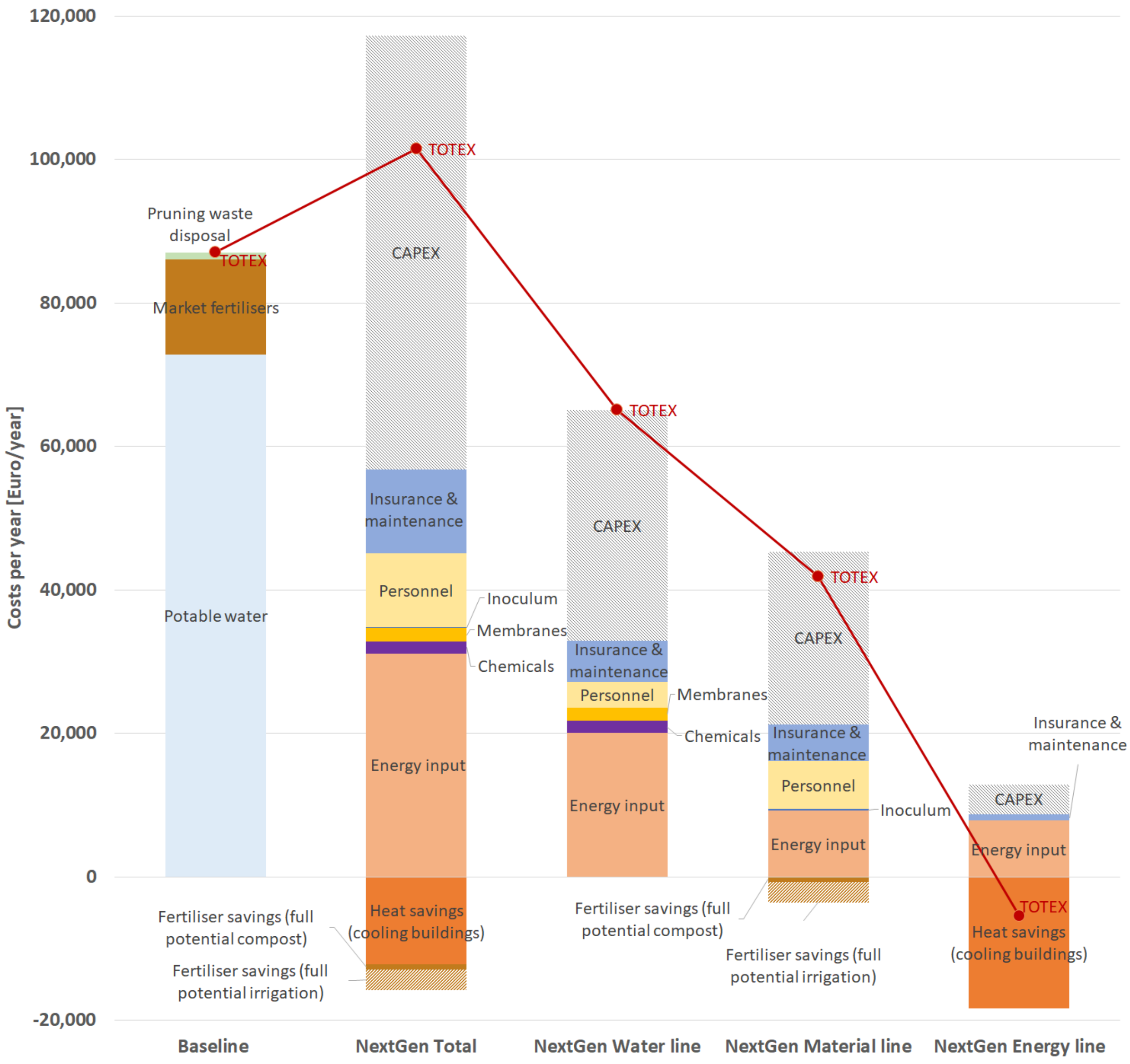

Figure 9 LCC results for the Athens demo case scenarios

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Sensitivity analysis

When assuming a depreciation period of 20 years (instead of 10 years) for the technology investments, the *NextGen scenario* would no longer increase, but reduce the TOTEX by ~14% compared to the *baseline*.
Considering 2022 prices for potable water, energy, chemicals, and fertilisers, which are a factor ~1.3, ~2.2, ~1.3 and ~1.3 higher, respectively, compared to 2021 prices (eurostat 2022), the *NextGen scenario* would increase the TOTEX by ~25% compared to the *baseline*. The total costs for the *NextGen scenario* would increase to a higher extent, primarily due to the higher share of energy costs in the total system, compared to the *baseline*. The higher credits for heat and fertiliser couldn't offset the higher costs for energy inputs in the *NextGen scenario*.

Specific costs of system services

Considering the cost for purchased potable water in the *baseline* (73,000 Euro/a) and the life cycle costs of the *NextGen scenario* recovery of irrigation water (65,000 Euro/a) related to the annual irrigation demand of the tree nursery (62,000 m^3/a), specific costs of 1.17 and 1.05 Euro/m^3 irrigation water can be calculated for the baseline and *NextGen scenario*, respectively. Consequently, the *NextGen scenario* can reduce the specific cost of irrigation water by ~10% (0.12 Euro) compared to the *baseline*, which equals a higher cost effectiveness (Table 14).

Table 14 Calculation of specific costs of irrigation water for the baseline and NextGen scenario

Scenario	Life cycle costs	Irrigation demand	Specific cost
Baseline	73,000 Euro/a	62,000 m^3/a	1.17 Euro/m^3
NextGen	65,000 Euro/a	62,000 m^3/a	1.05 Euro/m^3
Specific cost savings with NextGen			**0.12 Euro/m^3**

Conclusions

The following conclusions can be drawn from the results of this cost assessment:

- The implementation of NextGen water and energy recovery schemes is profitable while the nutrient recovery scheme (compost production) is not profitable at this stage.
- Doubling the depreciation period of infrastructure would favour the implementation of NextGen schemes. In contrast, using 2022 instead of 2021 prices would not favour the NextGen, mainly due to the high share of energy costs.

3.1.4 La Trappe (NL): water recovery from brewery wastewater

This case study investigates different options for treatment of brewery wastewater from a brewery at Koningshoven Abbey close to Tilburg in the Netherlands. As it is a Trappist monastery since the 19th century, the site is called “La Trappe” brewery. Both the treatment of wastewater from the brewery with innovative technology and a further treatment step for water reuse in the brewery are investigated in NextGen.

The *baseline* represents the past wastewater treatment, where the brewery paid a specific cost per volume of brewery effluent discharged to the local WWTP.

Two *NextGen scenarios* were assessed:

- *MNR/DAF/MF scenario*: A metabolic network reactor (MNR) as a modular reactor system where 2,000–3,000 different types of organisms, ranging from bacteria to plants in an integrated system biologically treat the influent from the brewery. Dissolved air flotation (DAF) and microfiltration (MF) further purify the water. The effluent is used for irrigation of farmland. The sludge from DAF and MF is treated with a belt filter, treated in a nearby digestor and then applied to farmland.
- *MNR/DAF/MF/NF scenario*: Adding a nanofiltration (NF) step following microfiltration could further improve the water quality. It was assumed that 25% of the 450m^3/d water flow in the NextGen system could be recycled for cleaning purposes in the brewery. The retentate (75% of water), with a slightly higher COD is reused for irrigation of farmland.

The original intention to integrate a photobioreactor (PBR) into the system to ultimately produce recycling-fertiliser or -fodder could not be realised for LCA and LCC due to the following reasons:

- PBR was tested in a small open pond system, but this setup would require too much space to be feasible at the brewery at full-scale.
- Closed systems for PBR work with artificial lighting (= high energy input), so the input stream should be optimised to make the system efficient and the product of high value. The brewery wastewater does not seem ideal.
- PBR was tested at low TRL and is theoretically possible on brewery wastewater, but it couldn’t be up-scaled at this site into an efficient process at that time.
- Consequently, no solid and reasonable process data for an LCA or LCC of a full-scale PBR on brewery wastewater at this site could be generated.

Table 15 provides an overview on the different baseline and NextGen scenarios considered in the La Trappe demo case.

Table 15 Overview on scenarios of the La Trappe demo case considered in the cost assessment

Scenario	
Baseline	• Brewery effluent discharge fee to local WWTP
MNR/DAF/MF	• Metabolic network reactor (MNR) • Dissolved air flotation (DAF) • Microfiltration (MF) • Treated water is fully reused for irrigation in agriculture • Sludge treated with belt filter, transported to digestor • Digested sludge applied to farmland
MNR/DAF/MF/NF	• Basic MNR + DAF + MF wastewater treatment • Nanofiltration (hollow fibre membrane) • 25% of water recycled for cleaning purposes in brewery • 75% of water is reused for irrigation in agriculture

System function & functional unit

In the *baseline* brewery effluent is discharged with a fee corresponding to this wastewater with high organic content. The function of the NextGen system under investigation is to provide a circular water solution for the treatment of brewery effluent in accordance with the water quality standards for irrigation in agriculture (*MNR/DAF/MF scenario*) or cleaning purposes (*MNR/DAF/MF/NF scenario*).

The functional unit of both the baseline and the NextGen scenarios is one year of operation ("per a") based on the volume of brewery effluent, which a full scale MNR is designed for, i.e. 450 m^3/d or 164,000 m^3/a.

System boundary

Since this LCC analyses the entire wastewater and sludge treatment and management system, the system boundary includes the internal brewery effluent treatment system, external sludge digestion and the application of dewatered sludge to farmland (Figure 10).

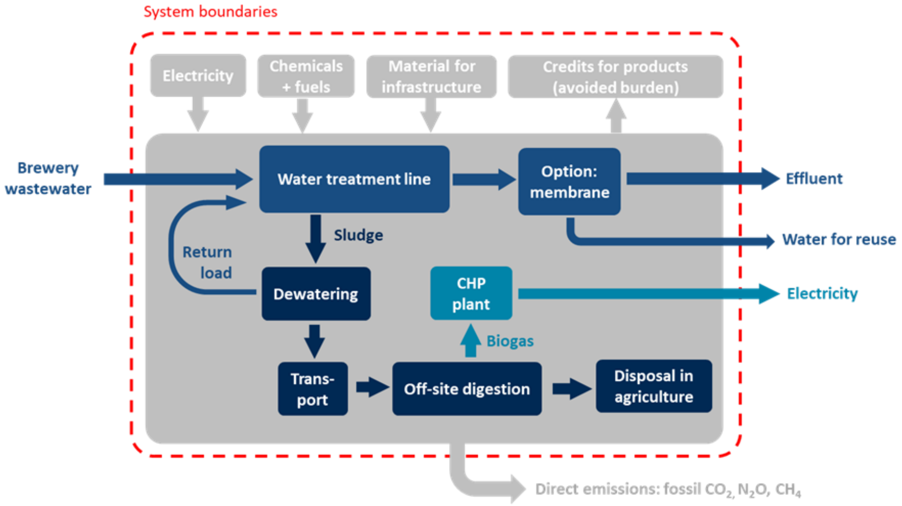

Figure 10 System boundary of the La Trappe demo case (from KWB)

Data quality

Table 16 provides an overview of data sources and quality for the Life Cycle Inventory of the La Trappe demo case. Mass flow data sources and quality were initially indicated by our project partner KWB (See NextGen Deliverable 2.1 for original table). See A.4 Inventory data of the La Trappe demo case for inventory data of energy and materials and B.4 Cost input data of the La Trappe demo case for inventory data of investments, personnel costs and specific costs.

Table 16 Overview of data sources and quality for the Life Cycle Inventory of the La Trappe demo case (adapted from KWB)

Parameter/ Process	Data source	Data quality
Costs		
Investment, insurance, maintenance costs	BIOPOLUS (MNR/DAF/MF)	high
	NF calculated based on SEMiLLA and efficiency	medium
Personnel costs	BIOPOLUS, SEMiLLA	medium–high
Specific material costs	Market prices	medium–high
Specific energy costs	Market prices	very high
Mass flow – NextGen		
MNR		
Water quality + sludge	SUMO model (BIOPOLUS)	medium–high
Electricity	BIOPOLUS design data	medium–high
Chemicals	Supplier data + KWB estimates	medium
Infrastructure	Design data for existing system	High
MNR + NF		
Electricity + chemicals	SeMilla design based on literature	medium
Infrastructure	KWB estimate for NF	medium
Sludge disposal for all scenarios		
Electricity + chemicals	KWB estimate	medium–high
Credits for electricity and nutrients	KWB estimate	medium–high

LCC results

Table 17 and

Figure 11 show the LCC results for the La Trappe demo case scenarios broken down by the main types of operational expenditure and the CAPEX. The *MNR/DAF/MF scenario* can reduce the TOTEX of wastewater treatment compared to the *baseline* by ~8,500 EUR/a (2%). The major cost shares of the *MNR/DAF/MF scenario* are CAPEX (~60%), insurance & maintenance (~12%) and energy (~11%). The nanofiltration step using the MF effluent adds ~10% of cost to the TOTEX in the *MNR/DAF/MF/NF scenario*. The recycled water savings (0.02 EUR/m^3 avoided groundwater pumping) cannot compensate for the additional costs of NF, in particular not the CAPEX (~44% of NF TOTEX). The *MNR/DAF/MF/NF scenario* thus increases the TOTEX of wastewater treatment compared to the *baseline* by ~52,000 EUR/a (9%).

Table 17 Additional annual costs of NextGen scenarios compared to the baseline in the La Trappe demo case

Cost type (annual values)	MNR/DAF/MF	NF
CAPEX	300,000 €	23,000 €
Insurance & Maintenance	61,000 €	5,000 €
Personnel	30,000 €	12,000 €
Energy	55,000 €	7,100 €
Chemicals/Materials	31,000 €	5,400 €
Sludge disposal	22,000 €	
Wastewater discharge fee	–510,000 €	
Recycling washing water		–820 €
TOTEX	**–8,400 €**	**52,000 €**

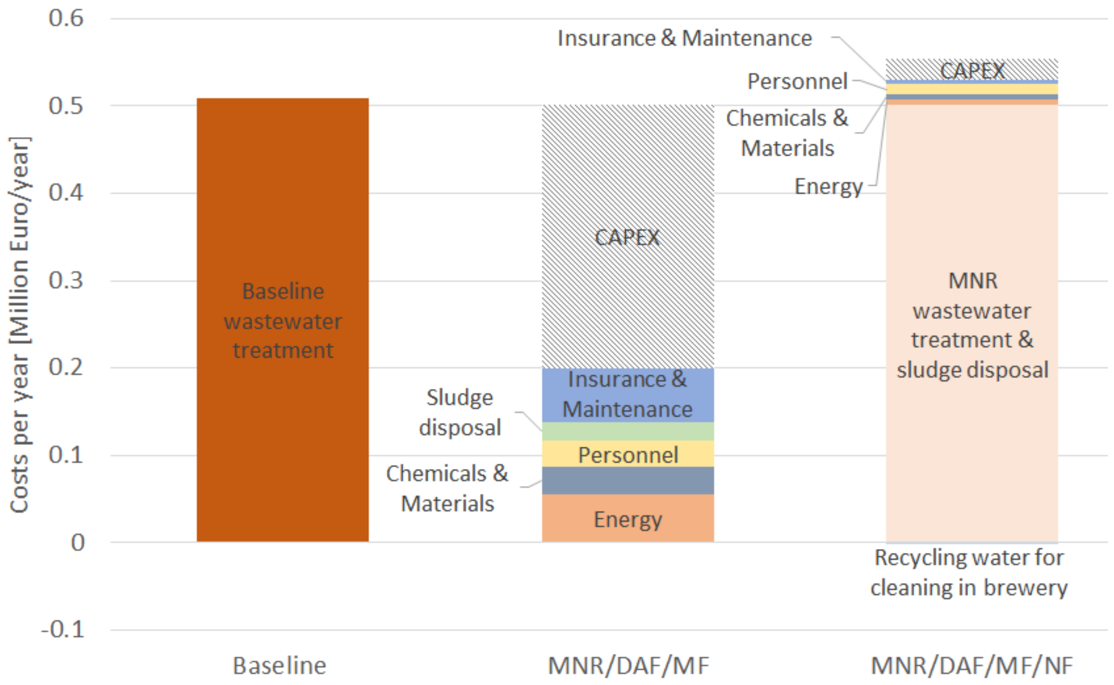

Figure 11 LCC results for the La Trappe demo case scenarios

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Sensitivity analysis

When assuming a depreciation period of 20 years (instead of 10 years) for the technology investments, the TOTEX of the NextGen scenarios *MNR/DAF/MF* and *MNR/DAF/MF/NF* would be reduced considerably by ~31% and ~30%, respectively. The *baseline* TOTEX (without change) would be higher than the NextGen TOTEX of both scenarios in this case. Considering 2022 prices, which are assumed a factor ~1.3, ~2.2, and ~1.3 higher for effluent discharge fee (*baseline*), energy and chemicals, respectively, compared to 2021 prices (eurostat 2022), the TOTEX of the *baseline* would increase by ~30% while the TOTEX of both NextGen scenarios would "only" increase by ~15%.

Specific costs of system services

Considering the cost for brewery effluent discharge in the *baseline* (510,000 Euro/a) and the life cycle costs of the NextGen scenarios *MNR/DAF/MF* (500,000 Euro/a) and *MNR/DAF/MF/NF* (550,000 Euro/a) related to the annual brewery effluent calculated based on the potential of a full scale MNR (450 m^3/d or 164,000 m^3/a), specific costs of 3.10, 3.05 and 3.37 Euro/m^3 treated brewery effluent can be calculated for the *baseline*, *MNR/DAF/MF* and *MNR/DAF/MF/NF scenario*, respectively. Consequently, the *MNR/DAF/MF scenario* can reduce the specific cost of brewery effluent treatment by ~2% (0.05 Euro/m³) compared to the *baseline*, which equals a higher cost effectiveness. The *MNR/DAF/MF/NF scenario* increases the specific cost of brewery effluent treatment by ~9% (0.27 Euro) compared to the *baseline*, which equals a lower cost effectiveness. Thanks to the additional purification by nanofiltration, ¼ of the water can be recycled for bottle washing in the brewery (avoided costs for groundwater pumping are considered) (Table 18).

Table 18 Calculation of specific costs of brewery effluent treatment for the baseline and NextGen scenarios

Scenario	Life cycle costs of brewery effluent treatment	Brewery effluent (full MNR potential)	Specific cost
Baseline	510,000 Euro/a	164,000 m^3/a	3.10 Euro/m^3
MNR/DAF/MF	500,000 Euro/a	164,000 m^3/a	3.05 Euro/m^3
MNR/DAF/MF/NF	550,000 Euro/a	164,000 m^3/a including 41,000 m^3/a recycled water for bottle washing in the brewery	3.37 Euro/m^3

Conclusions

The following conclusions can be drawn from the results of this cost assessment:

- The implementation of the *MNR/DAF/MF scenario* is profitable while the *MNR/DAF/MF scenario* (i.e. further treatment for recycling purposes) is not profitable at this stage.
- Doubling depreciation period of infrastructure and using 2022 instead of 2021 prices would favour both NextGen scenarios.
- Considering brewery effluent treatment as the main system service of the La Trappe demo case, the *MNR/DAF/MF scenario* can be considered cost effective compared to the *baseline*. Recycling water for use as washing water should only be considered as secondary system service.

3.1.5 Altenrhein (CH): nutrient recovery and renewable activated carbon

This case study investigates new approaches for the recovery of nitrogen and phosphorus from wastewater treatment and sewage sludge, and also for the production of activated carbon from renewable raw materials. These innovative processes are tested for the wastewater treatment plant (WWTP) Altenrhein, which is located close to Lake Constance in Eastern Switzerland (Figure 12).

The WWTP Altenrhein treats municipal and industrial wastewater from the surrounding municipalities, handling a capacity of around 105,000 population equivalents (PE). After primary settling, the wastewater is treated in an activated sludge process (70% of inflow) or a fixed bed biofiltration system (30% of inflow). After final clarification, the water is further treated with sand filtration, ozonation, and filtration using granular activated carbon (GAC) to remove residual phosphorus and organic micropollutants. Sludge is digested on-site, then dewatered and dried before disposal in a nearby cement kiln. Biogas is used in a CHP plant to generate electricity and heat for internal use. On top, a large heat pump is operated at Altenrhein which extracts heat from the WWTP effluent to be used for sludge drying. Surplus heat of the entire system can be fed to the local district heating network.

Figure 12 Aerial view of WWTP Altenrhein

Apart from the primary and excess sludge of wastewater treatment, WWTP Altenrhein also receives high amounts of external sludge (~200,000 PE) and co-substrates. Acting as a local “sludge center”, the WWTP processes raw sludge, digested sludge, and dewatered sludge from other WWTPs in the area. This leads to a high amount of centrate from dewatering, and consequently a high return load in nitrogen, which is currently recycled to the WWTP inlet. The additional N load to the WWTP from centrate amounts to 22% of the total N load to the biological stage.

In NextGen, different options have been explored to recycle both nitrogen and phosphorus from wastewater and sludge, and also to produce renewable GAC for the final treatment step of the WWTP. In particular, the following processes have been tested:

- Stripping nitrogen from centrate with a membrane process: After extensive pre-treatment to remove suspended solids, the centrate is heated and pH is increased by dosing of NaOH to shift the chemical equilibrium from NH_4-N to gaseous NH_3. Using a gas-permeable membrane, NH_3 can then be extracted from the centrate and collected in a solution of concentrated sulfuric acid. The produced ammonium sulfate solution can be further concentrated and sold as a ready-to-use fertiliser to local service providers. The process is realised in full-scale at WWTP Altenrhein and was assessed and optimised during the NextGen project.
- Production of renewable GAC from dried sludge: to replace conventional GAC made from fossil resources (hard coal), FHNW investigated the production of renewable GAC using dried sludge as organic input. Performance of the material in an ozone + GAC system for removal of organic micropollutants was assessed in pilot columns to determine maximum standing time until regeneration compared to conventional GAC. Regeneration of renewable GAC was also tested to estimate material losses and regeneration efficiency of the innovative material.
- Production of a PK fertiliser from dried sludge using a combination of pyrolysis and fluidised bed incinerator (Pyrophos® process). Sewage sludge is mixed with a potassium source and thermally treated. A reductive phase eliminates heavy metals, an oxidative phase generates an inorganic PK-fertiliser in which the phosphorus has been made plant available. It also generates electricity and heat for drying and district heating. The Pyrophos® process was piloted in a project with Swiss national funding[3] by the NextGen partners FHNW, CTU and AVA Altenrhein. In NextGen these data were extrapolated to assess a full-scale implementation. Laboratory tests in the frame of NextGen showed the feasibility of a scenario with meat and bone meal as raw material.

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[3] Projekt-Nr. 25554.1 PFIW-IW   Titel: Pyrophos: Weiterentwicklung der Alkalipyrolyse zur Abtrennung von Schwermetallen und Herstellung eines marktfähigen Phosphor-Kalidüngers aus Klärschlamm.

Table 19 provides an overview on the different baseline and NextGen scenarios considered in the Altenrhein demo case.

Table 19 Overview on scenarios of the Altenrhein demo case considered in the cost assessment

Scenarios	
Baseline **Not calculated. The scenarios except "fertiliser greenfield EU" are calculated as a difference against this baseline.**	Conventional wastewater treatment with activated sludge. Elimination of micropollutants with ozone and granulated active carbon. Water is discharged. Sludge drying using heat pumps and disposal in cement works. In the European scenario dewatered sewage sludge disposal in mono-incineration plant.
Conventional GAC	The baseline micropollutant elimination with ozone and conventional GAC.
Renewable GAC	Conventional GAC is replaced by GAC produced from sewage sludge.
Ammonia stripping	Ammonium sulphate is recovered from the centrate from the sludge dewatering using membrane stripping. The product is further concentrated by forward osmosis.
Fertiliser with sewage sludge and meat and bone meal ash	The dry sludge is mixed with meat and bone meal ash (MBMA) and a potassium source. The mix is converted in a reducing and an oxidating step to a fertilising compound. The excess heat is used for sludge drying and sold in a regional network. In this scenario the fertiliser fulfils the limits[4] for the Swiss Minrec fertiliser category.
Fertiliser with sewage sludge greenfield EU **Greenfield scenario counting all costs for a fertiliser plant starting with dewatered sludge.**	The sludge is dried and mixed with a potassium source. The mix is converted in a reducing and an oxidating step to a fertilising compound. The excess heat is used for sludge drying and sold in a regional network. In this scenario the fertiliser fulfils the limits in the European fertiliser regulation.

The three technologies have been tested for the conditions present at WWTP Altenrhein. Based on the findings in full-scale and pilot trials, the concepts are evaluated in their cost effects compared to the status quo (*baseline*) of WWTP operation in 2020. Therefore, the performance and scale of the pilot systems are extrapolated from the pilot trials to a suitable full-scale size for WWTP Altenrhein.

The goal of this cost assessment is to show the performance of the three technologies. We will analyse the cost difference on implementing each technology separately. The investigated technologies concern different material streams in the WWTP and thus have few interconnections. The cost effects are additive.

This cost assessment serves as an example for upgrading a large WWTP with innovative technologies for nutrient removal or production of renewable GAC. The specific situation of WWTP Altenrhein as a local sludge center with significant input of external sludge has to be considered when extrapolating the results to other sites. The target group of this study consists primarily of professionals dealing with planning and operation of WWTPs, such as plant operators, engineering companies and researchers in this field.

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[4] 814.81 Chemical Risk Reduction Ordinance, ORRChem

System function & functional unit

The function of the systems under study is the treatment of wastewater and sludge according to the quality required for its disposal. The cost assessment includes all relevant processes related to these two functions. The functional unit is defined as “the operation of the systems fulfilling these functions for a period of one year” (“per a”). The amount of raw wastewater and external sludge or co-substrate treated in the system is defined based on information of the WWTP (Table 20).

Table 20 Size of major streams of functional unit and scenarios of the Altenrhein case study

Scenario and system	Size	Remarks
Baseline		
WWTP Altenrhein	9.1 Mio m³/a	Influent data of Altenrhein for 2020
External input for sludge line (sludge + co-substrate)	6,000 t DM/a	
Renewable GAC	122 t/a	More frequent regeneration and higher ozone dose to reach same performance as conventional GAC
Ammonia stripping	67,500 m³/a	Total centrate volume
Fertiliser with sewage sludge and meat and bone meal ash	7,130 t dried sludge + 4,742 t MBM ash	Total mass of dried sludge mixed with MBM ash
Fertiliser with sewage sludge greenfield EU	40,000 t dewatered sludge	Total mass of dewatered sludge

System boundary

We consider investment and operational expenditure of the additional units as well as their influence on WWTP operation (modified nitrogen flows due to stripping) and sludge disposal based on measurements from Altenrhein by the WWTP and by FHNW and simulation in Umberto by KWB. All energy and material flows from sourcing to disposal are considered. Revenue of material sales as well as compensation for CO_2 reduction are evaluated (

Figure 13).

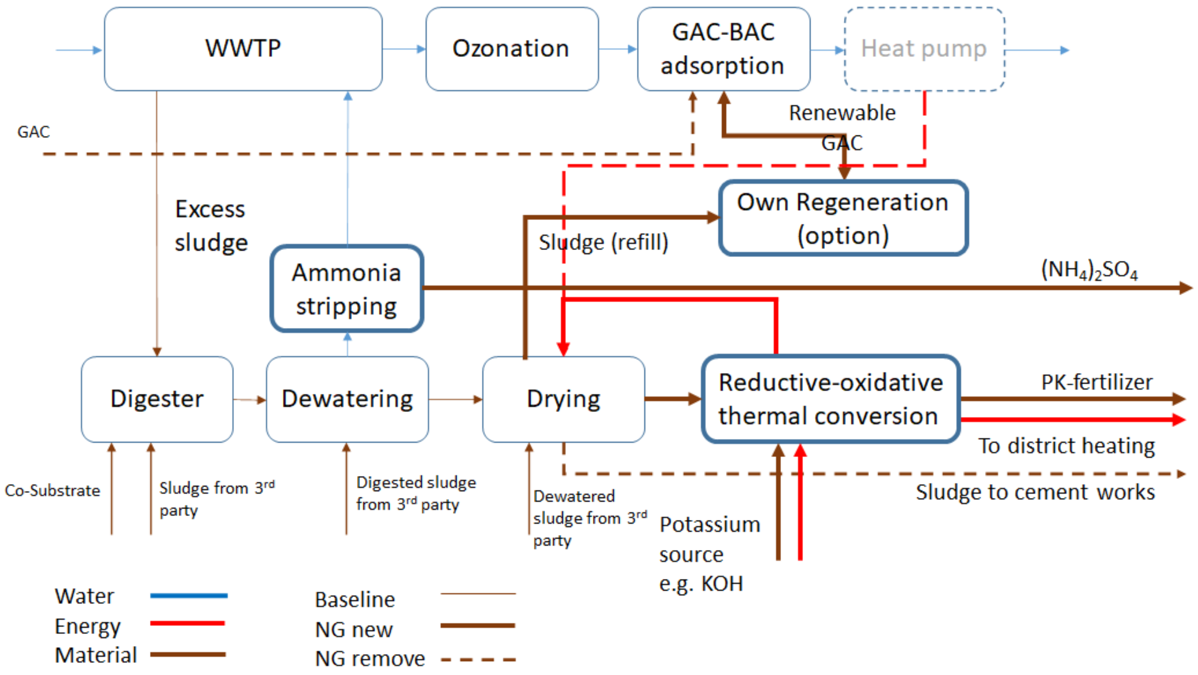

Figure 13 System boundary of the Altenrhein demo case

Data quality

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Table 21 provides an overview of data sources and quality for the Life Cycle Inventory of the Altenrhein demo case. See A.5 Inventory data of the Altenrhein demo case for inventory data of energy and materials and B.5 Cost input data of the Altenrhein demo case for inventory data of investments, personnel costs and specific costs.

Table 21 Overview of data sources and quality for the Life Cycle Inventory of the Altenrhein demo case (Mass and energy data adapted from KWB)

Parameter/ Process	Data source	Data quality
WWTP – Baseline		
Water quality and quantity	WWTP operator[5]	very high
Measured sludge and sludge liquor quality parameters	WWTP operator	very high
Sludge and sludge liquor quantities (volume & loads)	Calculated	high
Energy and chemical consumption	WWTP operator	very high
GAC longevity and consumption	Estimated	medium–high
Renewable GAC		
GAC standing time until regeneration	Pilot results	high
GAC yield and performance after regeneration	Batch results	medium
Specific costs	Market prices	high
Ammonia stripping		
Energy consumption	WWTP operator	high
Yield, product concentration	Estimated from another plant[6]	high
Capacity and runtime	Measured and extrapolated	high
Investment costs	Full scale project	very high
Other cost items (maintenance, personnel)	FHNW standard rate and WWTP operator	medium–high
Specific costs	Market price survey	high
PK fertiliser		
Product quality	Lab results	medium
Energy balance	Upscale from pilot results	high
Investment costs	Upscale from pilot results	medium–high
Other cost items (maintenance, personnel)	FHNW standard rate and WWTP operator	medium
Specific costs	Market prices	medium–high

LCC results

This chapter presents results of the cost assessment, comparing the *baseline* with the NextGen scenarios. Differences in cost types are discussed and analysed regarding important input parameters, and respective conclusions for the analysis.

All NextGen scenarios except PK fertiliser (EU) have an additional cost, the additional cost of PK fertiliser (CH) in Altenrhein being the highest and the transfer from conventional to renewable GAC being the lowest (Table 22 and

Figure 14).

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[5] AVA (2021): Geschäftsbericht 2020 (Business report 2020), Abwasserverband Altenrhein, Altenrhein, Switzerland.

[6] Böhler M., Hernandez A., Fleiner J., Gruber W., Seyfried A. (2018): Powerstep D4.3 Operation and optimization of membrane ammonia stripping

Table 22 Additional annual costs of NextGen scenarios compared to the baseline in the Altenrhein demo case

Cost type (annual values)	Conventional --> renewable GAC	Ammonia stripping	Fertiliser SS & MBMA Altenrhein	Fertiliser sludge greenfield EU
CAPEX		300,000 €	4,100,000 €	2,700,000 €
Insurance & Maintenance		61,000 €	810,000 €	540,000 €
Personnel		17,500 €	1,050,000 €	700,000 €
Energy	67,000 €	43,000 €	–410,000 €	–230,000 €
Chemicals/Materials	290,000 €	270,000 €	2,600,000 €	910,000 €
Sludge disposal		6,200 €	57,000 €	–4,100,000 €
Fertiliser revenues		–240,000 €	–3,500,000 €	–1,460,000 €
TOTEX	360,000 €	460,000€	4,600,000 €	–990,000 €

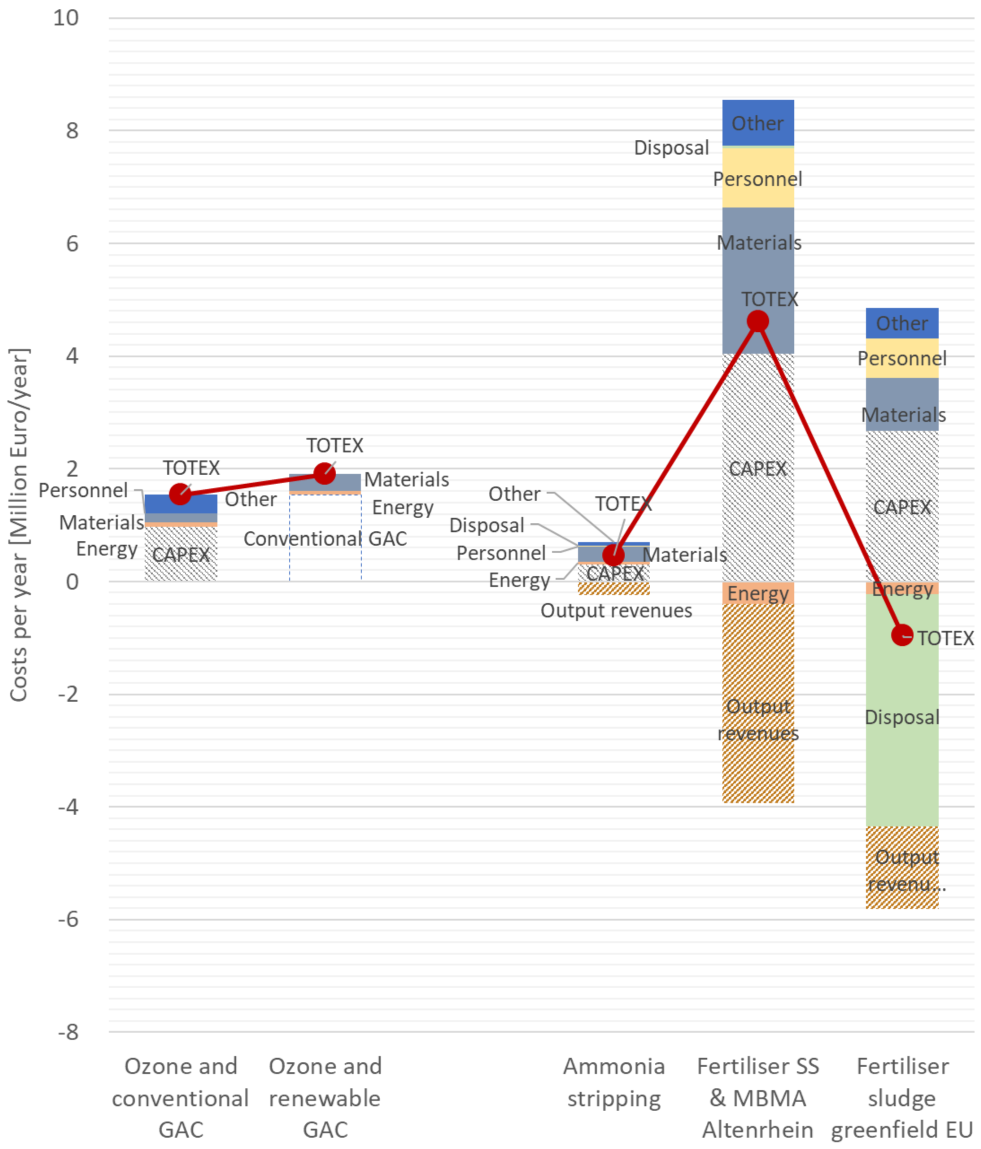

Figure 14 Cost assessment of 1 micropollutant elimination by ozone and conventional/renewable GAC at WWTP Altenrhein 2 ammonia stripping at WWTP Altenrhein 3 PK fertiliser production at WWTP Altenrhein or a greenfield plant in the EU

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

Renewable GAC from sewage sludge requires three times higher ozone dosing and required energy according to the pilot tests. Also, the standing time until regeneration of renewable GAC is at best a third of the standing time of conventional GAC. This leads to higher material and costs for the regeneration. A first estimation made by CTU shows optimisation potential in a regeneration reactor for the Swiss market indicating reduction of the regeneration price by more than half. A regional regeneration and the replenishment with sludge-based GAC would enable a regional cycle. Lower regeneration costs would make the cost difference between conventional and renewable GAC smaller. It is also worth noticing that the type of GAC has no high-cost impact on the full cost of tertiary treatment. The main cost type is the CAPEX and related maintenance for ozone and GAC contactors (70% and 85% for renewable and conventional GAC, respectively;

Figure 14), which shows the importance of choosing a cost-effective technology provider and obtaining a plant with a high longevity.

Ammonia stripping main cost types are the CAPEX and materials, each representing an annual cost of 0.3 M EUR. NaOH alone costs almost 0.2 M EUR annually. They can partly be offset by revenues from product sales and CO_2 credits. The remaining additional cost is after revenues 1.5 EUR/PE.

Two scenarios for *PK fertiliser production* were assessed. The *PK-fertiliser scenario in Altenrhein* uses an input mix of sewage sludge and MBMA in order to fulfil the stringent Swiss fertiliser regulation. Both materials are rendered plant available by the process. MBMA is considered more suited for the Altenrhein site, since MBM as input would require additional safety regulation for category 1 MBM and a larger plant for the additional thermal output. The use of an additional MBM generated thermal output also seems difficult in the area. In this assessment we assumed access to MBMA free of charge. This is not certain and must be verified. Even with this optimistic assumption, the cost for this solution for sewage sludge energy and phosphorus recovery is high (147 EUR/ dew SS) compared to Swiss disposal costs (dry sludge typically free of charge).
The second scenario, a greenfield fertiliser plant in the EU, is less costly in CAPEX and associated maintenance. One reason is the lower cost for equipment, personnel and civil engineering site preparation in the EU compared to Switzerland. Another reason is that the plant throughput is smaller and thus less costly although it includes a dryer for sewage sludge. It processes less phosphorus and consequently has lower costs for raw materials (potassium source), but also less revenue for the PK fertiliser. This is the better option for an operator seeking to fulfil phosphorus recovery requirements under the EU fertiliser regulation. When the *baseline* cost for mono incineration (105 EUR/t) is subtracted, net savings of 955,000 EUR/a or 24 EUR/dewSS result.

Sensitivity analysis
When assuming a depreciation period of 20 years instead of 10 years for the technology investments, the additional cost of the *Renewable GAC*, *Ammonia stripping* and *PK fertiliser Altenrhein* would change by 0%, –27%, –33%, respectively. The savings of the *PK fertiliser EU scenario* would increase by 159%.
Considering 2022 prices, which are assumed a factor ~1.3, ~2.2, and ~1.3 higher for materials, energy and fertiliser revenues, respectively, compared to 2021 prices (eurostat

2022), the additional cost of the *Renewable GAC*, *Ammonia stripping* and *PK fertiliser Altenrhein* would change by +47%, +23%, –17%, respectively. The savings of the *PK fertiliser EU scenario* would increase by 52%. The fertiliser options perform better because of important energy and fertiliser sales.

Specific costs of system services

The driver for Altenrhein scenarios is climate mitigation (renewable GAC), capacity and performance of the WWTP (ammonia stripping) and legislation (PK fertiliser). In Table 23 the specific costs for these services are calculated. Since renewable GAC at present does not reduce climate emissions, no specific cost can be calculated. The specific cost for reduction of nitrogen in the biology of the WWTP is 7,100 EUR/t. For fulfilling phosphorus recovery legislation, the specific cost is 147 EUR/t dewSS and 80 EUR/t dewSS in Altenrhein, Switzerland and in the EU, respectively.

Table 23 Specific costs of system services in case study Altenrhein

Scenario	Additional cost	Service	Specific cost
Conventional --> renewable GAC	360,000 Euro/a	207 t CO_2eq/a	Double losses
Ammonia stripping	460,000 Euro/a	–64 t N/a –1,540 CO_2eq (N_2O)	7,100 Euro/t N
Fertiliser with sewage sludge of meat and bone meal ash	4,400,000 Euro/a	Fulfils legislation	14,7 EUR/PE 147 EUR/t dewSS
Fertiliser with sewage sludge greenfield EU	–990,000 Euro/a	Fulfils legislation	11.8 EUR/PE 80 EUR/t dewSS

Conclusions

The following conclusions can be drawn from the results of this cost assessment:

- Using renewable GAC comes with an additional cost and perhaps more importantly does not contribute to the objective of this technology: climate mitigation. However, a regional regeneration for Swiss GAC users with replenishment of material losses directly from their own sewage sludge is an interesting option for independent circular operation with potentially significant costs reduction making this option economically profitable.
- Ammonia stripping is also not profitable but makes an important contribution to its intended system service of reducing nutrient load in the biological treatment and mitigating climate heating**.**
- A scenario with construction of a greenfield plant for thermal treatment and PK-fertiliser production in the EU shows that this process is economically very attractive: can both treat sewage sludge and recycle phosphorus in a form conform to EU legislation at a cost lower than mono-incineration itself. Fertiliser production by thermal treatment is difficult on the Altenrhein site because of the stringent Swiss regulation for recycled fertiliser. The scenario using a mix of MBMA and sewage

sludge leads to specific treatment cost that are higher than the Swiss average and the procurement of MBMA might be difficult and potentially lead to additional costs. We also see that a longer depreciation period of 20 years and the current higher materials and energy prices strongly both favour the fertiliser scenarios in Altenrhein and the EU.

3.1.6 Costa Brava (ES): water reuse with regenerated membranes

Tossa de Mar is a town located in the south of Costa Brava in the province of Girona in Catalonia, Spain. In this coastal town, the population in the summer months is 5 times higher than the 12,000 permanent residents, resulting in difficulties in terms of seasonal water supply and wastewater discharge.

The city is connected to the water network of the southern zone of Consortio Costa Brava (CCB). Besides local wells in the Tossa Valley (Tossa Wells), a high share (over 50 %) of the freshwater demand is imported via the water network. The imported water is recovered at the Tossa Lloret Drinking Water Treatment Plant (Tossa Lloret DWTP) and the Tordera Seawater Desalination Plant using a reverse osmosis (Tordera SWRO). The water from both plants needs to be pumped via hills into the Tossa Valley, while both plants also producing water for other municipalities. There is an increasing scarcity on available drinking water resources in the region. The drinking water demand of Tossa de Mar is about 1.45 M m³/year. About 0.7 M m³/year are recovered locally from the Tossa Wells, while 0.75 M m³/year are imported via the water network (0.7 Mm³/year from Tossa Lloret DWTP and 0.05 M m³/year from Tordera SWRO) – see Figure 15.

In the Tossa de Mar wastewater treatment plant only 0.81 M m³/year are collected and treated in secondary treatment. The secondary treatment removes solids and COD, while the nitrogen removal is limited due to the low sludge age and a lack of treatment capacity in the summer months. Part of the WWTP effluent is treated by by coagulation, filtration, UV-disinfection and chlorination and distributed by a network to public areas for irrigation in summer. To extend the irrigation towards private purposes a new tertiary treatment using ultrafiltration and regenerated RO membranes was piloted in the NextGen project. Thus, the required higher microbial and chemical water quality can be reached.

However, irrigation is only a small part of the drinking water demand and therefore a future scenario is to infiltrate reclaimed water into the aquifer. An improved secondary treatment removal of ammonium nitrogen would be necessary in order not to pollute the aquifer.

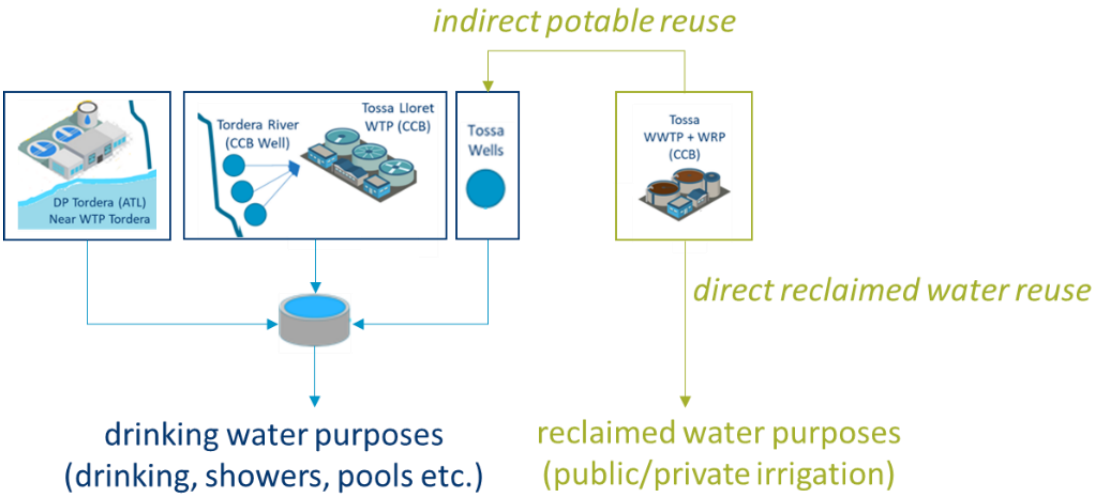

Figure 15 Overview of drinking water and reclaimed water resources and their usage

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

The goal of this cost assessment is to show the performance of two tertiary treatments for water reclamation replacing drinking water:

- A current tertiary treatment with coagulation, filtration, UV-disinfection and chlorination treating a part of the secondary effluent in the summer months for public irrigation
- The tertiary treatment demonstrated within the NextGen project with coagulation, membrane filtration (with regenerated membranes) and chlorination treating a part of the secondary effluent in the summer months for public and private irrigation

Table 24 provides an overview on the different baseline and NextGen scenarios considered in the Costa Brava demo case.

Table 24 Overview on scenarios of the Costa Brava demo case considered in the cost assessment

Scenario	
Baseline **Cost not calculated. The scenarios are calculated as a difference against this baseline.**	Current secondary treatment at the WWTP Tossa de Mar without water recycling. Freshwater is provided via the Tossa Wells, the Tossa Lloret DWTP and the SWRO Tordera.
Current UV tertiary	Current secondary treatment at the WWTP Tossa de Mar. Current tertiary treatment with coagulation, filtration, UV-disinfection and chlorination. The assumed capacity is 62,000 m³/year feed, resulting in 60,000 m³/year reclaimed water. This volume is provided within the month from June to September for public irrigation purposes. A corresponding volume of the drinking water mix from the Tordera valley (Tossa Lloret DWTP & Tordera SWRO) is saved.
NextGen UF/NF tertiary	Current secondary treatment at the WWTP Tossa de Mar. NextGen tertiary treatment with coagulation, UF filtration, (regenerated) RO membrane filtration and chlorination. The assumed capacity is 93,000 m³/year feed, resulting in 74,000 m³/year reclaimed water. This volume is provided within the month from June to September for public & private irrigation purposes. A corresponding volume of the drinking water mix from the Tordera valley (Tossa Lloret DWTP & Tordera SWRO) is saved.

The cost assessment serves as an example for municipalities dealing with the effects of tourism and varying influent volumes and loads during the year and suffering from water scarcity. The target group of this study consists primarily of the WWTP and WRP (Water recycling plant) operators (CCB), but also planers and engineers.

System function & functional unit

The function of the system under study is to provide wastewater treatment according to the legal requirements and the upgrade of effluent for water reuse including all processes related to this function. The functional unit of this cost assessment is defined as “the operation of the systems fulfilling these functions for a period of one year” (“per a”).

System boundary

We consider investment and operational expenditure of the tertiary treatment. All energy and material flows from sourcing to disposal are considered. Savings from replacement of drinking water are considered (see Figure 16).

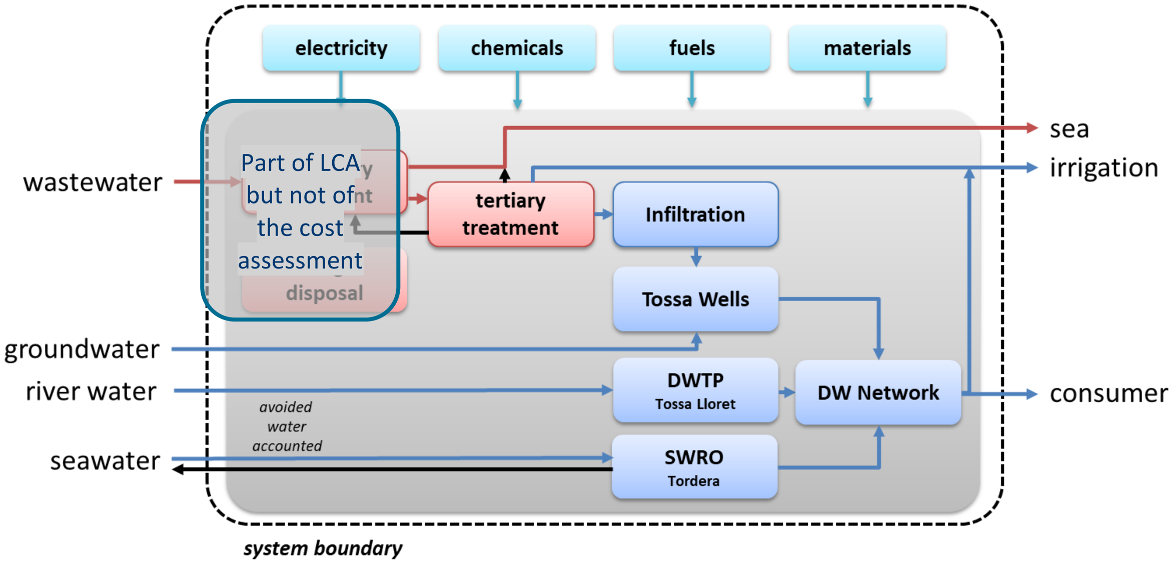

Figure 16 System boundary of the cost assessment in Tossa de Mar

Data quality

Table 25 provides an overview of data sources and quality for the Life Cycle Inventory of the Costa Brava demo case. See A.6 Inventory data of the Costa Brava demo case for inventory data of energy and materials and B.6 Cost input data of the Costa Brava demo case for inventory data of investments, personnel costs and specific costs.

Table 25 Overview of data sources and quality for the Life Cycle Inventory of the Costa Brava demo case (adapted from KWB)

Parameter/ Process	Data source	Data quality
WWTP – Baseline		
Water quality and quantity	WWTP operator	very high
Energy and chemical consumption	WWTP operator	High
Tertiary Treatment		
Energy and chemical consumption UV	WWTP operator	medium
Energy and chemical consumption UF/NF	Pilot results	high
Specific costs	Market prices	high
Investment costs UV	Literature	medium
Investment costs UF/NF	Offer full scale plant	High
Drinking Water Treatment		
Specific costs	Market prices	high

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°776541

LCC results

The cost of the NextGen UF/NF tertiary is five times higher (+ 10,500 EUR/a) than the current UV tertiary (Table 26 and Figure 17). It produces a higher water quality, since UF/NF removes 80% of salinity and micropollutants and probably improves the microbial quality. The main cost type is CAPEX (59%), followed by materials (mainly chlorine for disinfection 11%; membrane costs <2%). The costs saved for water import are also important (15%). The water import cost is the cost that the consortium costa Brava pays for water from the Tordera valley and thus corresponds to the costs that could be saved by water reuse. The distribution network is necessary in both cases, and not part of the comparison.

Table 26 Additional annual costs of NextGen scenarios compared to the baseline in the Costa Brava demo case

Cost type (annual values)	UV tertiary	UF/NF tertiary
CAPEX	3,800 €	79,000 €
Insurance & Maintenance	810 €	12,500 €
Personnel	5,200 €	19,000 €
Energy	370 €	1,830 €
Chemicals/Materials	17,600 €	27,000 €
Savings drinking water	–17,300 €	–21,000 €
TOTEX	10,500 €	117,000€

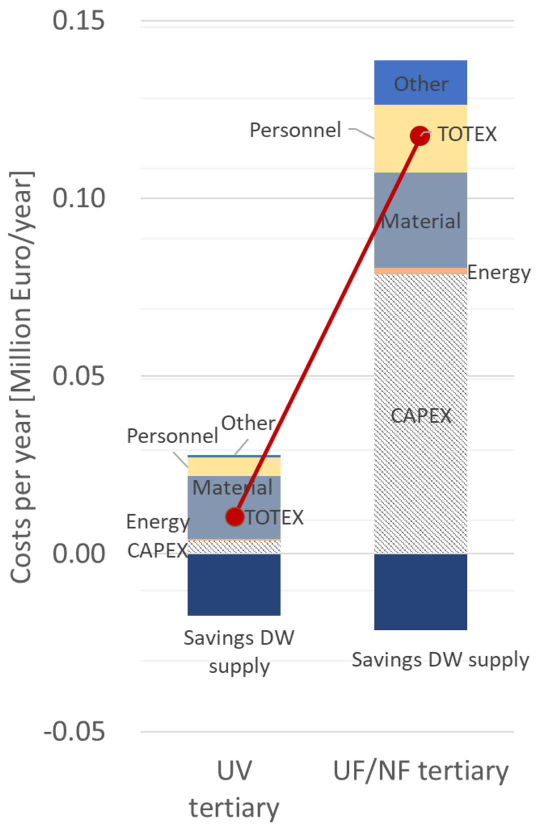

Figure 17 Cost assessment of current UV tertiary treatment and NextGen UF/NF tertiary treatment

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Specific costs of system services

The current water mix of surface and desalinated water imported from the Tordera valley costs 0.29 EUR/m^3 (Table 27). The cost for the reclamation for public irrigation is slightly more costly (0.46 EUR/m^3). An UF/NF tertiary would increase quality and enable private irrigation, but the potential for water reclamation is limited to the summer months and thus not much higher. This leads to high specific costs for water from a plant that can only be run 4–5 months per year (1.87 EUR/m^3). Therefore, an interesting option (see also environmental assessment Deliverable 2.1) is the introduction of N removal in the secondary treatment. Then the tertiary membrane treatment could be run at full capacity, in summer producing for public irrigation and in winter for infiltration into the aquifer. This would lead to lower specific costs, but they would still be at least three times as expensive (0.73 EUR/m^3 without secondary treatment infrastructure) as the current water imports (0.29 EUR/m^3).

Table 27 Quality, volume and price of current water and potential water sources

Water source	Quality	Volume (m^3)	Price/production cost (EUR/m^3)
Tordera valley import	Drinking water	750,000	0.29
UV tertiary	Public irrigation	60,000	0.46
UF/NF tertiary	Private irrigation	74,000	1.87
UF/NF tertiary + N removal in secondary	Indirect potable reuse (winter), public irrigation (summer).	240,000	0.73 (without CAPEX, maintenance & insurance of expanded secondary treatment)

Sensitivity analysis

When assuming a depreciation period of 20 years instead of 10 years for the technology investments, the production cost of water from the UV tertiary, UFNF tertiary and UFNF tertiary with N removal would decrease by –6%, –14% and –11% respectively. Considering 2022 prices, which are assumed a factor ~1.3 and ~2.2 higher for materials and energy, respectively, compared to 2021 prices (eurostat 2022), the production cost of water from the UV tertiary, UFNF tertiary and UFNF tertiary with N removal would increase by 21%, 8% and 17% respectively. The energy cost increase will also increase the current drinking water production cost.

Conclusions

We have assessed costs for three scenarios of reuse: UV tertiary treatment UFNF tertiary treatment and UFNF tertiary combined with upgraded secondary treatment. The following conclusions can be drawn from the results of this cost assessment:

- The three water reuse options are all more expensive than the current imports from the Tordera valley. However, the groundwater tables are under stress and the consortium Brava needs to rely less on groundwater for water supply.
- UFNF tertiary treatment is considerably more costly than UV tertiary treatment. It is chosen to reach sufficient quality for private irrigation/potable reuse.
- UFNF tertiary should be combined with improved secondary treatment of nitrogen to reach sufficient quality for infiltration for potable reuse. Infiltration, in contrast to reuse for irrigation, makes all year water treatment possible with much larger volumes and lower specific cost.

- Membrane costs are a small cost item and membrane regeneration thus leads to small cost savings. Thus, the decision to use regenerated membranes should be carefully considered and only be taken if they have a performance at least equal to virgin membranes (microbial and chemical water quality, energy consumption, membrane safety and integrity).
- The sensitivity of these results to longer equipment depreciation periods or the current higher energy and materials prices is low, less than 20%.

3.2 Discussion

We analysed scenarios' goals varying from fulfilling regulations (Braunschweig, Altenrhein), coping with water scarcity (Costa Brava, Athens) to rethinking wastewater treatment in view of climate change (Spernal) and of urban/industrial wastewaters (La Trappe). Therefore, only a limited cross-comparison of cost-effectiveness towards a function or an environmental impact category was possible.

3.2.1 Life Cycle Costing (LCC)

CAPEX

In all the case studies examined, CAPEX is the largest cost contribution to the annual cost of a NextGen scenario. The sensitivity analysis has shown that the depreciation period of the infrastructure has a correspondingly large influence on TOTEX (mostly around 30%, up to 159% decrease of NextGen TOTEX).

OPEX

The difference in the proportions of OPEX cost items among the NextGen demo cases can be explained with their different system services:

The NextGen scenarios of Braunschweig, Spernal and Altenrhein involve substantial nutrient recovery. For the recovery and concentration of nutrients in the form of solid or liquid fertiliser, they require a larger input of chemicals (Braunschweig, Spernal) or material (Altenrhein) than the *baseline*, but they can also generate income/savings (1) with sale of recycled fertiliser and reduced sludge disposal costs (lower sludge volume or transformation of the sludge to fertiliser or GAC) compared to the *baseline* WWTP and (2) by using sludge energy content to cover their energy demand to an increased extent. Nevertheless, the implementation of NextGen nutrient recovery systems alone in most examples of Braunschweig, Spernal and Altenrhein (only *Altenrhein, PK fertiliser EU* is profitable) is not profitable at this stage, as the revenues from fertilisers are lower than the annual infrastructure costs (CAPEX, insurance and maintenance), personnel costs and additional costs for chemicals. However, these nutrient recovery systems can bring benefits to the WWTP, especially (1) a reduction of nutrient load in the effluent and (2) a reduction in sludge disposal costs compared to a given baseline, which can help make the whole circular economy approach (considering all CE dimensions water, energy, material) of a NextGen scenario more economically viable (Table 28).

Table 28 Relative cost contributions of cost types to annual additional TOTEX of NextGen scenarios compared to baseline for the demo cases Braunschweig, Spernal and Altenrhein

	CAP-EX	Insur. & Maint.	Personnel	Energy	Chemicals / Materials	Sludge disposal	Fertiliser	TOTEX
Braunschweig (mid-term)								
Hydrolysis & N, P recovery	68%	12%	22%	−8%	27%	−12%	−10%	**1,570,000 €**
+ High temperature CHP	81%	15%	25%	−27%	30%	−14%	−11%	**1,380,000 €**
+ Max Struvite recovery	66%	12%	21%	−9%	26%	−7%	−9%	**1,630,000 €**
Braunschweig (long-term)								
Hydrolysis & N, P recovery	85%	16%	28%	−11%	36%	−38%	−15%	**1,250,000 €**
+ High temperature CHP	106%	19%	33%	−37%	42%	−45%	−18%	**1,060,000 €**
+ Max Struvite recovery	76%	14%	25%	−12%	32%	−20%	−14%	**1,410,000 €**
Spernal								
AnMBR/Degasser/IEX			0%	−6703%	191162%	−34275%	−150283%	**0 €**
AnMBR/Aerobic stage/IEX			0%	−111%	324%	−58%	−254%	**−168,000 €**
AnMBR/Degasser/Irrigation			0%	−60%	−19%	−21%	0%	**−450,000 €**
Altenrhein								
Renewable GAC				19%	81%			**360,000 €**
Ammonia stripping	66%	13%	4%	10%	58%	1%	−53%	**460,000 €**
Fertiliser SS & MBMA Altenrhein	88%	18%	23%	−9%	56%	1%	−77%	**4,600,000 €**
Fertiliser sludge greenfield EU	269%	54%	71%	−23%	92%	−415%	−148%	**−990,000 €**

In contrast, the NextGen scenarios of Athens, La Trappe and Costa Brava focus on small scale water reuse for local purposes. Athens and La Trappe include rather high energy and low chemical input technologies. In both cases, costs can be saved compared to the baseline in the scenarios focusing on the main system service water reuse for irrigation, i.e. Athens "water line" and La Trappe *MNR/DAF/MF scenario*. The NextGen scenarios of Costa Brava include high material and low energy input resulting in higher TOTEX compared to the baseline (Table 29). However, with the additional costs, not only is the water kept in circulation, but also emissions are reduced. The recycling schemes can remove micropollutants and salts in the recycled water and if nitrogen removal is implemented the marine eutrophication can be reduced. The cost difference must also be put in relation to the local conditions and the environmental benefits achieved (see CEA).

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Table 29 Relative cost contributions of cost types to annual additional TOTEX of NextGen scenarios compared to baseline for the demo cases Athens, La Trappe and Costa Brava

	CAPEX	Insur. & Maint.	Per-sonnel	Energy	Chemicals & Materials	Disposal (pruning /sludge)	Baseline water manage-ment	Ferti-liser	TOTEX
Athens									
Total	350%	68%	60%	110%	22%	−6%	−422%	−81%	**17,000 €**
Water line	417%	73%	47%	260%	46%		−943%		**−7,700 €**
Material line	79%	17%	22%	31%	1%	−3%		−46%	**30,000 €**
Energy line	75%	16%		−191%					**−5,500 €**
La Trappe									
MNR/DAF/MF	3568%	726%	356%	653%	372%	260%	−6036%		**−8,400 €**
NF	45%	10%	23%	14%	10%		−2%		**52,000 €**
Costa Brava									
UV tertiary	36%	8%	50%	4%	168%		−165%		**10,500 €**
UF/NF tertiary	67%	11%	16%	2%	23%		−18%		**117,000 €**

The sensitivity analysis has shown that price fluctuations of energy and intermediate goods (when comparing prices of 2022 with 2021 or before) can have a large influence on TOTEX (mostly around 10%, up to 52% difference in TOTEX).

3.2.2 Cost Effectiveness Analysis (CEA)

System services

The system services provided by scenarios considered within the six analysed NextGen demo cases Braunschweig, Spernal, Athens, La Trappe, Altenrhein and Costa Brava can be characterised by their water, energy and nutrient recovery/savings. These are summarised together with the corresponding life cycle costs in Table 30.

The NextGen life cycle costs are expressed as TOTEX, except for Spernal (OPEX) and Costa Brava (CAPEX for N recovery missing). For the demo cases Braunschweig, Altenrhein (in general) and Costa Brava the additional TOTEX compared to baseline is given, for the others the absolute value, which is to be compared to the baseline absolute value. The scenario costs indicated in the table always represent the costs for the entire circular solution including the costs for recovery of water, energy and nutrients, depending on which recovery lines are applied in each demo case.

The treatment capacities of the investigated demo cases range from only 510 PE for the local, decentralised recycling solution of the Athens nursery to 350,000 PE for the regional, centralised recycling solution of the Braunschweig WWTP. The range of total costs is correspondingly large, from “only” ten thousand (Costa Brava) to over a million euro per year (Altenrhein, Braunschweig and Spernal).

The direct comparability of the demo studies in terms of total costs is limited due to the different reuse priorities/targets of the treated wastewater (water, energy, nutrient recovery), which naturally result in different costs.

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Table 30 Overview on system services of all scenarios in the six analysed demo cases. Water, energy and nutrient recovery/saving. Life cycle costs and treatment capacity of the WWTP.

Demo case	Scenario	Water savings/recovery [m^3/a]	Energy savings/recovery [MWh/a]	Nutrient savings/recovery as fertilisers [t/a]	NextGen Life cycle costs [Euro/a]
Braunschweig 350,000 PE	Hydrolysis & N, P recovery (mid-term)	Not targeted	9,800 reused in process	149 (N) 18 (P)	1,570,000 additional[7]
	Hydrolysis & N, P recovery (long-term)	Not targeted	9,800 reused in process	189 (N) 18 (P)	1,380,000 additional
	+ High temperature CHP (mid-term)	Not targeted	10,800 reused in process	149 (N) 18 (P)	1,630,000 additional
	+ High temperature CHP (long-term)	Not targeted	10,800 reused in process	189 (N) 18 (P)	1,250,000 additional
	+ Max Struvite recovery (mid-term)	Not targeted	9,800 reused in process	148 (N) 31 (P)	1,060,000 additional
	+ Max Struvite recovery (long-term)	Not targeted	9,800 reused in process	188 (N) 37 (P)	1,410,000 additional
Spernal 100,000 PE	AnMBR/Degasser/ IEX	Not targeted	3,800 reused in process	323 (N) 61 (P)	1,050,000 absolute OPEX excl. insurance/ maintenance
	AnMBR/Aerobic stage/ IEX	Not targeted	3,500 reused in process	323 (N) 61 (P)	900,000 absolute OPEX excl. insurance/ maintenance
	AnMBR/Degasser/ Irrigation	9,110,400 irrigation	3,800 reused in process	Nutrient reuse only by irrigation	600,000 absolute OPEX excl. insurance/ maintenance
Athens 514 PE (COD based)	NextGen	62,250 irrigation	122 heat reused in process + 240 heat surplus	1 (N) 0.3 (P)	101,000 absolute

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[7] Additional costs compared to respective baseline

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Demo case	Scenario	Water savings/recovery [m³/d]	Energy savings/recovery [MWh/a]	Nutrient savings/recovery as fertilisers [t/a]	NextGen Life cycle costs [Euro/a]
La Trappe 12,325 PE (COD based)	MNR/DAF/MF	164,250 irrigation	Not targeted	Only by irrigation	500,000 absolute
	MNR/DAF/MF/NF	123,190 irrigation (¾) 41,060 washing (¼)	Not targeted	Only by irrigation	550,000 absolute
Altenrhein 100,000 PE water 300,000 PE sludge	Renewable GAC	8,760,000	Not targeted	10 (coal)	360,000 additional
	Ammonia stripping	Not targeted	Not targeted	64 (N)	460,000 additional
	Fertiliser with sewage sludge of meat and bone meal ash	Not targeted	900 electricity 14,000 heat	1030 (P)	4600,000 additional
	Fertiliser with sewage sludge greenfield EU	Not targeted	2,300 electricity	340 (P)	–990,000 additional
Costa Brava 12,000 permanent residents	UV tertiary	60,225	Not targeted	Not targeted	10,500 additional
	UFNF tertiary	73,000	Not targeted	Not targeted	117,000 additional
	N removal secondary, UFNF tertiary	240,900	Not targeted	Not targeted	106,000 additional, not counting infrastructure cost secondary treatment upgrade

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Scale effect on cost
The specific cost of wastewater treatment itself varies with the plant size as illustrated in

Figure 18. A small plant of 510 PE (Athens) has a specific cost of 130 EUR/PE, 20 times higher than a WWTP of 100,000 (Spernal, not counting CAPEX). Most of the NextGen scenarios of La Trappe and Spernal can reduce costs (by providing cost efficient wastewater treatment or other functions). Still, they have a small influence compared to the scale effects.
On the one hand, the increased costs of small-scale plants are often compensated by cost savings on energy and infrastructure for transport. Also, organisational aspects might favour local solutions. Therefore, despite the high specific cost for water reuse in the Athens tree nursery, the monetary cost is slightly lower than buying water from the network. There is also a considerable stakeholder interest in the sewer mining system making this possible.
On the other hand, the economies of scale are often high. The most favourable scenario for these three case studies reduces OPEX in Spernal by 43% compared to baseline. A similar effect can be expected from doubling the plant size, so such options should always be kept in mind.

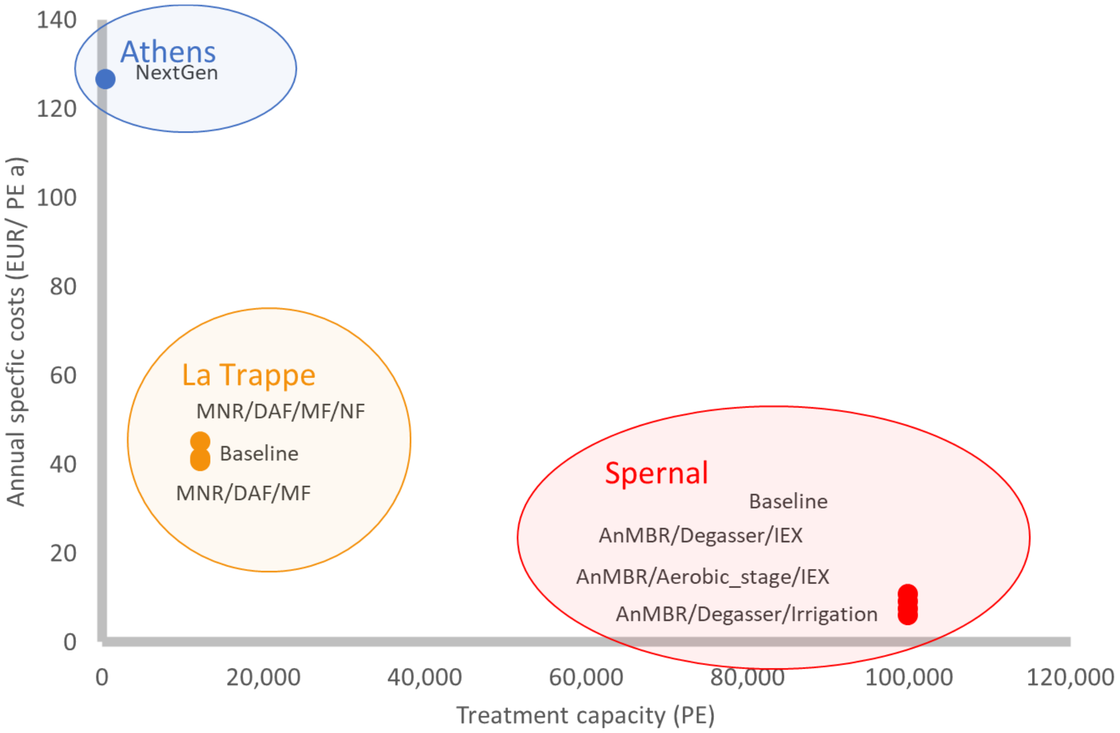

Figure 18 Specific cost of wastewater treatment as a function of WWTP treatment capacity in population equivalents (PE). NextGen solutions are compared to their respective baseline scenario.

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Scale effect on GWP impact

Also, the environmental impact is often improved by economies of scale. As an example, we compare AnMBR in Spernal and in Athens keeping in mind the different CO_2 impact of the the power mix in the two countries (Figure 19). As can be seen for the case study Spernal, GWP can be decreased by up to 52%. But most importantly, the large plant in Spernal has 13 times smaller GWP emissions per PE than the one in Athens. Hence, for GWP and many other environmental indicators, we need to keep in mind that larger plants have not only lower specific costs, but also lower specific environmental impacts.

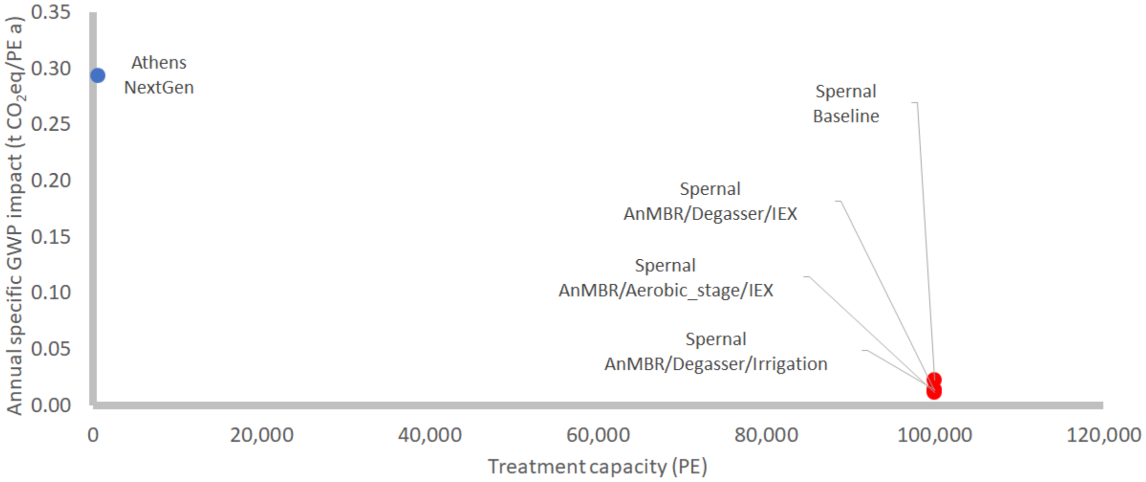

Figure 19 Specific GWP impact of wastewater treatment as a function of WWTP treatment capacity in person equivalents (PE). NextGen solutions are compared to their respective baseline scenario.

Cost effectiveness with regards to GWP impact of NextGen scenarios

Figure 20 and Figure 21 indicate the cost effectiveness of the NextGen scenarios compared to their respective baseline regarding GWP impact reduction, with the difference of GWP impact on the x-axis and the difference of annual costs on the y-axis. A ceiling cost effectiveness of 100 Euro/t CO_2eq was considered, based on the carbon price in the EU ETS, which was around 100 Euro per tonne in the EU at the time of writing this report (statista.com 2022).

In terms of cost-effective saving of GWP, the *Braunschweig 2030 max struvite scenario*, *Altenrhein renewable GAC*, Athens and the *Costa Brava UFNF tertiary* are the least attractive since they neither save costs nor GWP (double losses). Under the GWP-saving scenarios, the remaining five scenarios of Braunschweig have considerable gains, but also high costs. In comparison, the *Altenrhein ammonia stripping scenario* has a more favourable cost effectiveness. Also, the *Costa Brava scenario of N elimination followed by UFNF tertiary* has a better cost effectiveness[8] although much smaller in scale and thus in impact (better visible in Figure 21). All Spernal scenarios show double gains, both in GWP and cost. Interestingly no *NextGen scenario* has higher GWP but lower cost. Not shown in the figure is the Altenrhein scenario *PK fertiliser from sludge and meat and bone meal ash* with huge advantage in GWP (–5500 CO_2eq/a) and a cost effectiveness somewhat better than the Braunschweig scenarios.

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[8] The CAPEX for the secondary treatment modification and associated maintenance/insurance is not included in this scenario. It will lead to higher cost and lower GWP cost efficiency.

Only the three Spernal scenarios show a better cost effectiveness than the carbon pricing. Thus, only these can be motivated only on the grounds of climate mitigation. The others have a poor climate mitigation efficiency compared to other measures. Consequently, the circular solutions demonstrated in NextGen are in general not efficient for climate mitigation. This also means that the implementation of the scenarios cannot be motivated by climate mitigation alone, except for Spernal if their effectiveness considering TOTEX is just as good.

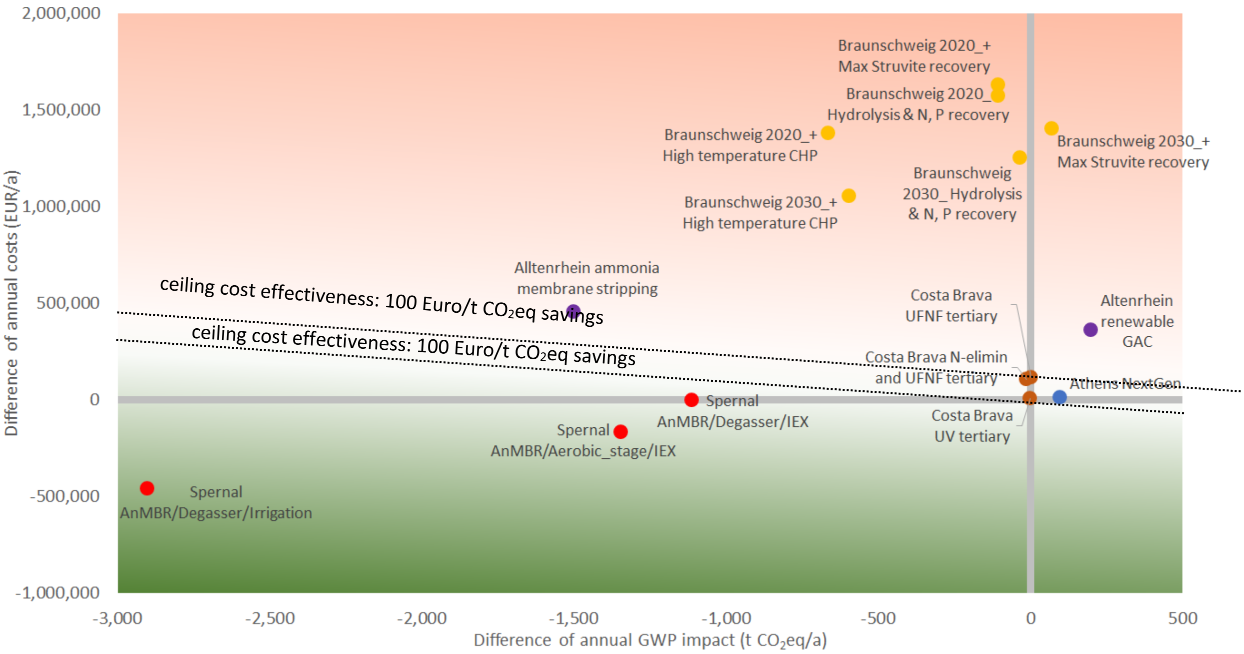

Figure 20 NextGen scenarios difference to their respective baseline regarding cost and GWP impact

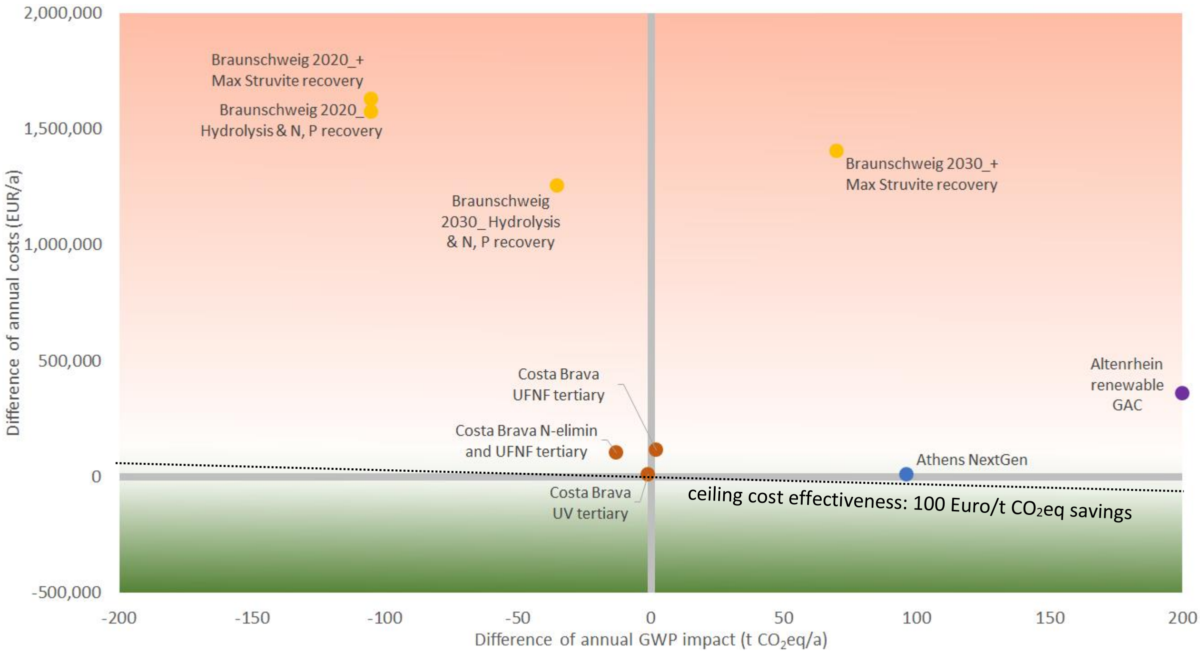

Figure 21 Zoom in on the smaller scale NextGen scenarios difference to their respective baseline regarding cost and GWP impact

Cost effectiveness and quality of water recovery

All assessed case studies involve wastewater treatment. A total of seven scenarios involves upgrading of the wastewater to enable reuse (Table 31). Costa Brava scenarios use secondary effluent as input whereas the others treat raw urban/brewery wastewater. The output water has a reduced nutrient content (TN 2–29 mg/L) and microbial activity (*E. coli* between <1 to 2; not all determined). All cases seem technically feasible, but not all have sufficient long-term quality monitoring to prove it.

Nitrogen in treated wastewater is mostly readily available (ammonium, nitrate). When water is reused for irrigation two factors are important to avoid groundwater pollution. On the one hand the nutrient content should not be too high. The N limits required for irrigation (e.g. 15 mg/L in Greece) can easily be reached with denitrification. Secondly, the application of the embodied nutrients should closely match plant nutrient demand/uptake. Typically, more than 90% of nitrogen is supplied by mineral and organic fertilisers in areas with water reuse. Since nutrient content in reuse water is in general not useful, only revenue for nutrients in the fertilisers were counted in the assessment.

The economic viability for water reuse is strongly dependent on the site-specific costs in the baseline differing among the demo cases: In the Athens *baseline*, the nursery is irrigated with potable water. Potable water has a higher price (1.17 EUR/m^3) and is at the same time less appropriate than the less purified water kept in the local circuit (1.05 EUR/m^3), which contains even more N and P that can be absorbed by the trees. In the La Trappe demo case, the profitability differs in the different water reuse scenarios: The La Trappe scenario *MNR/DAF/MF* which only aims to treat the brewery effluent to irrigation water quality is profitable (3.05 EUR/m^3) compared to the baseline situation with direct brewery effluent discharge (discharge fee of 3.10 EUR/m^3).

In contrast, the La Trappe scenario *MNR/DAF/MF/NF* including the nanofiltration step for the recovery of wash water is not profitable (3.37 EUR/m^3) since the recycled wash water is accounted as avoided groundwater pumping, which comes at very low cost for the brewery (0.02 EUR/m^3). In Costa Brava lower specific cost can only be achieved if the best of the scenarios (range: 0.46–1.87 EUR/m^3) is compared to the most expensive baseline source (range: 0.29-0.83 EUR/m^3). However, the cost difference must always be put in relation to the local conditions and the environmental benefits achieved. Costa Brava has the urgent objective of addressing water scarcity and is thus not seeking a profitable technology but the most cost-effective technology providing this system service.

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Table 31 Case study, technology and targeted reuse quality, input, specific cost, resulting nutrient content (TN) and disinfection (E. coli). All NextGen water upgrade scenarios except Spernal (no TOTEX data) compared with specific drinking water supply costs.

Case study, technology and targeted reuse quality	Input	Specific cost (EUR/m^3)	TN (mg/L)	*E. coli* (cfu/100 ml)	Comment
Costa Brava UV for irrigation	Secondary with COD removal	0.46	29	1	Limited operation only in summer
Costa Brava UFNF for irrigation	Secondary with COD removal	1.87	29	<1	Limited operation only in summer
Costa Brava N removal/UFNF indirect potable reuse	Secondary with COD removal	0.73	n.d.	<1	CAPEX extension N removal not included. TN should be comparable to Athens.
Athens MBR/UV for urban reuse/recharge	Raw urban wastewater	1.05	5.5	2	Greek standards for urban reuse/recharge fulfilled.
La Trappe MNR/DAF/MF irrigation	Raw brewery wastewater	3.05	2	n.d.	Disinfection deemed sufficient for use based on previous experience
La Trappe MNR/DAF/MF/NF washing water	Raw brewery wastewater	3.37	2	n.d.	Disinfection deemed sufficient for use based on previous experience
Athens DWT to site	-	1.17	-	-	
Costa Brava bank filtration to reservoir	-	0.29	-	-	
Costa Brava desalination to reservoir	-	0.83	-	-	

4. Conclusion

Cost and cost effectiveness of 19 scenarios based on solutions tested were assessed from an operator's perspective, taking into account all relevant side-effects on the sludge treatment or the WWTP in the six selected NextGen demo cases. The different cost types (capex, materials cost and revenue, energy cost and revenue and personnel) all contribute to the cost of the different processes. Taking into account also the associated changes in environmental impact, the cost effectiveness with regards to GWP and water savings was calculated. The cost of the scenarios could thus be assessed. The scenarios' goals varied from fulfilling of regulations (Braunschweig, Altenrhein), coping with water scarcity (Costa Brava, Athens) to rethinking wastewater treatment in view of climate change (Spernal) and of urban/industrial wastewaters (La Trappe). Therefore, only a limited cross-comparison of cost-effectiveness towards a function or an environmental impact category was possible.

With the exception of PK fertilizer production in the EU setting the implementation of NextGen nutrient recovery systems alone is not profitable at this stage, as the revenues from fertilisers are lower than the annual infrastructure costs (CAPEX, insurance and maintenance), personnel costs and additional costs for chemicals. However, these nutrient recovery systems can bring benefits to the WWTP, especially by (1) reducing nutrient loads in the effluent and (2) reducing sludge disposal costs compared to a given baseline, which can help make the whole circular economy approach more economically viable.

The scenarios ranged in size from 500 PE to 350,000 PE. Thus, both their absolute and specific cost and environmental effects varied widely. Many of them had positive cost effects (up to -46% on OPEX for Spernal resp. -990,000 EUR/a for PK fertilizer Altenrhein), and most reduce climate heating (up to -126% resp. -2,900 CO2eq/a both for Spernal). However, the circular solutions as investigated in NextGen are not targeting climate mitigation. Only three of the investigated solutions are potentially cost effective compared to measures in other sectors.

Water quality improvement can only be achieved in the water sector and seven scenarios target water reuse for irrigation, industry/urban or indirectly potable use. Almost all could show the needed disinfection and reduction of nutrient quality in long term operation, in two cases verifying conformity with national standards (Costa Brava, Athens). The specific cost for these services could be lower compared to the regular water supply from long distances (Athens) or with lacking surface water (desalination in Costa Brava).

For the interpretation of the cost assessment, the uncertainties associated with the data must be taken into account: Partially low data quality, high sensitivity of data with regard to the depreciation period of infrastructure investments, high sensitivity of data with regard to certain cost items (primarily energy costs) due to market fluctuations.

The assessed scenarios are examples for new circular solutions in the water sector. The costs are valid in their geographical, regulatory and current market context. Such cost assessment can serve as an orientation for other contexts, to identify important cost types and related improvement options. A uniform methodology and presentation as in the NextGen technology factsheets increases the usefulness of such data. Interesting options can be further detailed in feasibility for other sites complemented with experimental data as necessary. The technologies and applications assessed are also not static. Their cost effectiveness will change as they are further developed and reach market maturity.

In general, it is necessary to use also other criteria than cost for decision making, in particular the environmental impact. Environmental technologies are usually driven by policy. System services such as water reuse, climate mitigation or reduction of pollution are not profitable, we decide to do them by respect for nature and for our own well-being. In a given policy framework a cost assessment can indicate the most cost-effective solution.

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Annex: Inventory data of energy and materials (A, adapted from KWB) and costs (B) of all demo case scenarios

A.1 Inventory data of the Braunschweig demo case

Inventory parameter and unit (annual values)	Mid-term scenarios (current sludge disposal)				Long-term scenarios (mono-incineration)			
	Baseline	Hydrolysis & N, P recovery	+ High temperature CHP	+ Max Struvite recovery	Baseline	Hydrolysis & N, P recovery	+ High temperature CHP	+ Max Struvite recovery
Electricity wastewater treatment [MWh]	8,696	8,609	8,609	8,608	8,797	8,639	8,639	8,638
Electricity sludge treatment [MWh]	2,333	2,771	2,771	2,684	2,595	3,027	3,026	2,889
Electricity effluent distribution [MWh]	4,666	4,663	4,663	4,663	4,654	4,655	4,655	4,655
Electricity credit CHP [MWh]	-9,036	-9,798	-10,795	-9,797	-9,073	-9,848	-10,850	-9,846
Electricity credit avoid. GW pumping [MWh]	-1,166	-1,166	-1,166	-1,166	-1,166	-1,166	-1,166	-1,166
Polyacrylamide [t]	85	131	131	131	133	164	164	164
$FeCl_3$ (14 %) [t]	745	783	783	773	751	799	799	786
$MgCl_2$ (30%) [t]	32	257	257	403	51	271	271	489
NaOH (50%) [t]	0	763	763	757	0	993	993	983
H_2SO_4 (96%) [t]	0	299	299	297	0	389	389	385
Natural gas [m^3]	13,868	2,159	15,438	2,069	14,186	5,306	15,791	5,165
Sludge production [t OS]	14,109	11,721	11,721	12,744	22,456	18,469	18,469	20,078
Struvite production [t]	0	-142	-142	-242	0	-143	-143	-294
ASL production [t]	0	-1,546	-1,546	-1,474	0	-1,983	-1,983	-1,875

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A.2 Inventory data of the Spernal demo case

Inventory parameter and unit (annual values)	Baseline	AnMBR/Degasser/IEX	AnMBR/Aerobic stage/IEX	AnMBR/Degasser/Irrigaiton
Wastewater influent (m³)	9,110,400	9,110,400	9,110,400	9,110,400
Electricity waterline + sludgeline (WWTP) (MWh)	4,271	1,002	1,002	1,002
Electricity IEX (MWh)		590	590	
Electricity AnMBR/Degasser/Aerobic stage (MWh)		4,977	3,683	4,977
Electricity avoided groundwater watering (MWh)			0	-911
Iron sulphate (t)	156			
Sodium hydroxide (t)		6	6	
Polymer (t)	12	9	9	9
Potassium chloride (t)		1,108	1,108	
Sulfuric acid (t)		1,155	1,155	
Water (t)		4,051	4,051	
Lime (t)		371	371	
Anionic IEX material (t)		12	12	
Cationic IEX material (t)		41	41	
Sludge production (m³)	6,040	3,533	3,533	3,533
Recovered N in ASL (t)		-323	-323	
Recovered P in Calcium phosphate (t)		-61	-61	

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A.3 Inventory data of the Athens demo case

Inventory parameter and unit (annual values)	NextGen
Wastewater influent (m^3/a)	62,250
Sewer mining unit	
Electricity for MBR (MWh)	156
Electricity for UV (MWh)	2.5
Electricity for storage tank (MWh)	0.7
Electricity for irrigation (MWh)	3.7
NaOCl (15%) (L)	2,490
Citric acid (50%) (L)	623
Rapid composting unit	
Electricity for rapid composting (MWh)	26
Heat for composting (MWh)	122
Recovered N in compost (t)	3.7
Recovered P in compost (t)	0.6
Heat exchanger	
Electricity for heat pump (MWh)	64
Heat extractable (MWh)	366
Surplus heat (MWh)	244

A.4 Inventory data of the La Trappe demo case

Inventory parameter and unit (annual values)	MNR/DAF/MF	MNR/DAF/MF/NF
Brewery effluent (m^3)	164,250	164,250
Total electricity (kWh)	534,360	582,540
N dosing (urea) (kg N)	6,090	6,090
P dosing (mineral P source) (kg P)	4,410	4,410
NaOH 50% (kg)	6,885	13,770
H_2SO_4 96% (kg)	10,050	10,050
$FeCl_3$ 40% (kg)	15,204	15,204
Polymer for DAF (active matter) (kg)	945	945
Polymer for belt filter (a.m.) (kg)	768	768
Polymer for external dewatering (a.m.) (kg)	1,452	1,452
NaOCl 10% (kg)		450
Citric acid 60% (kg)		231
NaOH 50% (kg)		144
Sludge production (kg)	366,205	366,205

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A.5 Inventory data of the Altenrhein demo case

Inventory parameter	Unit	Ozone and conventional GAC	Ozone and renewable GAC
Electricity ozone	MWh/a	240	720
Electricity raw water pump	MWh/a	96	96
Electricity other	MWh/a	264	264
GAC regeneration	t/a	50	119
Oxygen	t/a	76	228
Personnel	FTE	0.13	0.13

Inventory parameter	Unit	Ammonia stripping
Electricity	MWh/a	43
El. reduction reduced load	MWh/a	–55
Heat	MWh/a	502
NaOH 50%	t/a	486
H_2SO_4 88%	t/a	305
Citric acid 13.5%	t/a	4
Polymer 0.05%	t/a	111
Acid for off gas adsorber	t/a	33
Extra employees needed	FTE	0.25
Disposal return sludge	t/a	11,550
Ammonium sulphate 36% (7.7% N-NH_4)	t/a	836
N_2O reduction bonus	t CO_2eq/a	1,540

Inventory parameter	Unit	Fertiliser SS & MBMA Altenrhein	Fertiliser sludge greenfield EU
Electricity balance	MWh/a	–2,287	–940
Heat generated	MWh/a	–18,700	–14,025
Heat for drying	MWh/a	23,111	
Heat balance	MWh/a	4,411	
Fossil gas for start up	MWh/a	90	90
Dewatered sludge	t/a	40,000	
Dried sludge	t/a		8,333
MBM	t/a		5,498
KOH	t/a	1,575	3,817
$NaHCO_3$	t/a	218	158
Active carbon	t/a	8	8
NH_4OH	t/a	57	14
Extra employees needed	FTE	14	15
Disposal filter ash (German DK 2-3)	t/a	660	480
No disposal in mono-incineration needed	t/a	–40,000	

A.6 Inventory data of the Costa Brava demo case

Inventory parameter	Unit	Concentration (%)	UV tertiary	UF/NF tertiary	Denitrification +UF/NF tertiary
Electricity secondary & sludge	MWh/a		0.70	3.17	–65.00
Electricity tertiary	MWh/a		4.59	22.97	197.00
Polymer dewatering	t/a	95	0.01	0.01	–0.47
HCl	t/a	37	-	0.10	0.40
$AlCl_3$ tertiary	t/a	18	14.51	21.70	86.80
$Na_2S_2O_5$ Sodium metabisulfite tertiary	t/a	35	-	0.80	3.56
NaOCl tertiary	t/a	15	12.26	45.93	45.93
Antiscaling Flocon 260	t/a		-	0.65	2.91
Regenerated membranes	module/a		-	11.50	11.50
UF membranes	module/a		-	4.60	4.60
Extra employees needed	FTE		0.20	0.73	0.73
Drinking water	t/a		60,000	74,000	240,000

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B.1 Cost input data of the Braunschweig demo case

Cost item	Cost	Unit
Investment (referring to 350,000 PE)		
Investment process (NextGen additional)	6,664,399 (mid-term) 7,084,567 (long-term)	Euro
Investment building (NextGen additional)	5,615,522	Euro
Personnel (referring to 350,000 PE) (NextGen additional)	350,000	Euro/a
Specific costs		
Electricity	0.25	Euro/kWh
Polyacrylamide	3.37	Euro/kg
$FeCl_3$ (14 %)	0.05	Euro/kg
$MgCl_2$ (30%)	0.10	Euro/kg
NaOH (50%)	0.29	Euro/kg
H_2SO_4 (96%)	0.14	Euro/kg
Natural gas	1.3	Euro/m^3
Sludge disposal	60 (agriculture) 90 (co-incineration) 120 (mono-incineration)	Euro/t
Struvite	0.65	Euro/kg P
ASL (7.7% N)	0.08	Euro/kg

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B.2 Cost input data of the Spernal demo case

Cost item	Cost	Unit
Investment (referring to 100,000 PE)		
Investment process BNR + Iron dosing (Baseline)	15,900,000 (estimation based on OPEX) 7,403,519 (based on Huang et al. 2020)	Euro
Investment process AnMBR/Degasser/IEX (NextGen)	32,972,442 (based on equipment cost estimates) 12,852,810 (based on Huang et al. 2020)	Euro
Investment building BNR + Iron dosing (Baseline)	23,850,000 (based on OPEX, “CAPEX-OPEX-split”) 11,105,279 (based on Huang et al. 2020)	Euro
Investment building AnMBR/Degasser/IEX (NextGen)	10,990,814 (based on equipment cost estimates) 4,058,782 (based on Huang et al. 2020)	Euro
Personnel (referring to 100,000 PE) Baseline and NextGen	200,000	Euro/a
Specific costs		
Electricity	0.17	Euro/kWh
Iron sulphate	0.48	Euro/kg
Sodium hydroxide	0.55	Euro/kg
Polymer	3.00	Euro/kg
Potassium chloride	0.20	Euro/kg
Sulfuric acid	0.08	Euro/kg
Water	0.001	Euro/kg
Lime	0.71	Euro/kg
Anionic IEX material	12.11	Euro/kg
Cationic IEX material	1.47	Euro/kg
Sludge disposal	39 (agriculture)	Euro/t
ASL	0.07	Euro/kg
Calcium phosphate	0.35	Euro/kg

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B.3 Cost input data of the Athens demo case

Cost item	Cost	Unit
Investment (referring to 62,250 m^3/a water reuse)		
Investment process Sewer Mining Unit (SMU)	274,800	Euro
Investment process Rapid composting unit	205,500	Euro
Investment process Energy recovery unit	35,000	Euro
Personnel (referring to 62,250 m^3/a water reuse)		
Personnel Sewer Mining Unit (SMU)	3,600	Euro/a
Personnel Rapid composting unit	6,687	Euro/a
Specific costs		
Electricity	0.12	Euro/kWh
Heat	0.05	Euro/kWh
NaOCl (15%)	0.31	Euro/L
Citric acid (50%)	1.50	Euro/L
Membrane	1,875	Euro/a
Potable water (Baseline)	1.17	Euro/m^3
Pruning waste to disposal (Baseline)	9.5	Euro/t
ASL (7.7% N) (savings by compost production vs Baseline)	0.08	Euro/kg
P_2O_5 (savings by compost production vs Baseline)	0.47	Euro/kg

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B.4 Cost input data of the La Trappe demo case

Cost item	Cost	Unit
Investment (referring to 450 m^3/d brewery effluent treatment)		
Investment process MNR/DAF/MF	2,350,000	Euro
Investment process NF	200,000	Euro
Investment building MNR/DAF/MF	500,000	Euro
Personnel (referring to 450 m^3/d brewery effluent treatment)		
Personnel MNR/DAF/MF	30,000	Euro/a
Personnel NF	12,000	Euro/a
Specific costs		
Electricity	0.12	Euro/kWh
N dosing (urea)	0.54	Euro/kg
P dosing (mineral P source)	1.08	Euro/kg
NaOH (50%)	0.40	Euro/kg
H_2SO_4 (96%)	0.78	Euro/kg
$FeCl_3$ (40%)	0.29	Euro/kg
Polyelectrolyte (active matter)	1,300	Euro/m^3
NaOCl (10%)	0.45	Euro/kg
Citric acid (60%)	1.00	Euro/kg
Sludge disposal (agriculture)	60	Euro/t
Brewery effluent discharge fee (Baseline)	3.10	Euro/m^3

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B.5 Cost input data of the Altenrhein demo case

Cost item		Cost	Unit
Fertilizer sludge MBM Altenrhein	Investment costs technology	**30,751,000**	Euro
Fertilizer sludge MBM Altenrhein	Investment costs building	8,600,000	Euro
Fertilizer sludge greenfield EU	Investment costs technology	**20,524,000**	Euro
Fertilizer sludge greenfield EU	Investment costs building	5,224,000	Euro
Ammonia stripping	Investment costs technology	**2,435,000**	Euro
Ozone unit	Investment costs technology	6,660,645	Euro
Ozone unit	Investment costs building	**3,681,387**	Euro
GAC unit	Investment costs technology	4,939,355	Euro
GAC unit	Investment costs building	**4,018,613**	Euro

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Cost item	Cost	Unit
Employees	70,000	Euro/FTE a
Employees EU	50,000	Euro/FTE a
Electricity	140	Euro/MWh
Heat surplus	20	Euro/MWh
Heat	90	Euro/MWh
Active carbon	1,000	Euro/t
Active carbon EU	770	Euro/t
Citric acid 13.5%	2000	CHF/t
Dewatered sludge	0	Euro/t
Dried sludge	0	Euro/t
Fillters	20	CHF/n
H_2SO_4 88%	260	CHF/t
KOH	650	Euro/t
KOH EU	500	Euro/t
MBMA	0	Euro/t
$NaHCO_3$	600	Euro/t
$NaHCO_3$ EU	460	Euro/t
NaOH 50%	350	CHF/t
NH_4OH	350	Euro/t
NH_4OH EU	270	Euro/t
Polymer 0.05%	1.9	CHF/t
Disposal Monoincineration EU	105	Euro/t
Disposal filter ash (German DK 2-3)	120	Euro/t OS
Sludge transport to disposal	25	Euro/t
Treatment return sludge stripping	0.54	Euro/t OS
Ammonium sulphate 36% (7.7% N-NH_4)	105	Euro/t
K component fertililizer	190	Euro/t
N_2O reduction bonus	100	Euro/t
P component fertilizer	120	Euro/t

B.6 Cost input data of the Costa Brava demo case

Cost item	Concentration (%)	Cost	Unit
UV tertiary		32,468	Euro
UF/NF tertiary Investment costs technology		400,000	Euro
UF/NF tertiary Investment costs building		500,000	Euro
Employees		26,000	Euro/FTE a
Electricity		70	Euro/MWh
Polymer for dewatering	95	1,700	Euro/t
HCl	37	7,140	Euro/t
$AlCl_3$ tertiary	18	320	Euro/t
$Na_2S_2O_5$ Sodium metabisulfite tertiary	35	1,060	Euro/t
NaOCl tertiary	15	1,060	Euro/t
Antiscaling Flocon 260		6,670	Euro/t
Regenerated membranes		19	Euro/module
UF membranes		450	Euro/module
Drinking water		0.29	Euro/t

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