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D3.5: Evaluation of the different techniques

Task 3.5: Life cycle cost, cost-benefit analysis and anthropogenic noise pollution evaluation

WP3: Removal and remediation of chemical pollutants via innovative technologies

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ABSTRACT	The assessment reports the life cycle costing and cost benefit analysis from the application of the iMERMAID wastewater treatment technologies. The assessment considers industrial scale applications, based on technical performance from the Use Case demonstration, and indicates the techno-economic viability of the technologies.

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Document Revision Log

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Executive Summary

This report presents the Life Cycle Costing assessment of the iMERMAID wastewater treatment technologies developed and demonstrated in the project. The analysis was carried out to quantify and compare the costs associated with the baseline treatment configurations and the corresponding iMERMAID scenarios. In Use Cases 1-3, innovative technologies are integrated as additional treatment steps, whereas in Use Case 5, the innovative technology is replaced with the state-of-the-art tertiary treatment, reverse osmosis membrane filtration (RO). The assessment was developed over a 20-year horizon and includes acquisition, operation, maintenance, replacement, waste treatment, and end-of-life costs, where relevant. In line with the project scope, the results are interpreted as cost-of-function results rather than as indicators of profitability, since no revenue streams, tariff adjustments, or avoided compliance costs were included.

In addition to direct life cycle costs, the assessment considers, where possible, selected monetized environmental externalities. This remains a partial view, since current methods do not allow all environmental benefits, particularly the reduction of pollutant-related impacts, to be consistently expressed in monetary terms. Direct costs are therefore presented as the core economic result and complemented, where feasible, by monetized environmental externalities and qualitative interpretation of the additional environmental benefits.

For Use Case 1, the iMERMAID scenario shows a higher cost profile than the baseline scenario due to the integration of the IRIS Pulsed Discharge Plasma system as an additional tertiary treatment step. The increase is mainly associated with the additional equipment and the operational requirements of the PDP system. The broader interpretation of the case therefore reflects the additional cost of introducing an enhanced treatment configuration under the current project boundary.

For Use Case 2, the iMERMAID scenario also leads to a higher life cycle cost than the baseline activated sludge process, mainly due to the acquisition and renewal of the ENIG and EDEN systems, together with the additional operating and maintenance requirements of the integrated treatment train. The monetized environmental externalities likewise indicate a higher external cost for the iMERMAID scenario within the subset of impact categories for which environmental price factors were available.

For Use Case 3, the iMERMAID scenario involved an additional tertiary treatment step for the removal of heavy metals after a conventional two-stage wastewater treatment process for treating municipal and industrial wastewater. The WeeeFiner 4D scavenger treatment increased treatment costs by approximately 80% compared with the baseline, while the cost of environmental externalities increased only 25% compared with the baseline. The main part of the direct cost increase was derived from operational costs, of which the highest share arose from wastewater disposal and the replacement of the filter media. Environmental benefits were not monetarised because of the limited subset of monetised environmental impact categories available.

For Use Case 5, the iMERMAID scenario considered the replacement of reverse osmosis (RO) with EDEN technology. The replacement increased costs; however, the uncertainty of the cost estimate is relatively high. Approximately 97% of the total cost was attributed to investment and equipment retrofit. The iMERMAID scenario showed a clear benefit in terms of environmental pricing, mainly due to the negligible consumption of chemicals and electricity by EDEN technology compared with RO. The sensitivity analysis further indicated that the cost level of RO could potentially be approached if the technology lifetime were extended from three to five years or if the investment cost were reduced by 25%.

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Acronyms

BPA	Bisphenol A
BTZ	Bentazone
CBA	Cost-benefit analysis
CoEC	Contaminants for emerging concerns
LCA	Life cycle analysis
LCC	Life cycle costing
MSW	Municipal solid waste
NPC	Net present cost
PCR	Propamocarb
RO	Reverse osmosis
WWTP	Waste water treatment plant

1.0 Introduction

The overall aim of the iMERMAID project is to safeguard the Mediterranean Sea basin from contaminants for emerging concerns (CoEC) by integrating, coordinating, and synergizing innovative preventive, monitoring, and remediation solutions. One target of the project is to develop next generation sensor and remediation solutions within iMERMAID to monitor and remove prioritized chemicals from its source while reducing upstream pollution.

Work package 3 in the project concentrates on optimising, demonstrating, and deploying several technologies for the effective remediation of organic CoEC in demonstration sites upstream with extrapolation to Mediterranean Sea and work package 4 concentrates on the planning and realization of the use case demonstration of the remediation technologies at sites. The technologies considered include AKVO microfluidic based system, plasma enabled system (PDP), 4D scavenger system and reclaimed RO membrane conversion to NF and UF pre filtration membranes

This task 3.5 in WP3 evaluates the performance of the technologies which were demonstrated for removal of contaminants in the Use Cases 1, 2, 3 and 5. The evaluated Use Cases are listed in Table 1. The evaluation includes Life cycle costing (LCC), cost benefit analysis and anthropogenic noise pollution evaluation. Monitoring equipment is excluded from the evaluation. This deliverable contains the results of task 3.5.

Table 1: The evaluated Use Cases.

Use Case number	Company/ location	Target contaminants/ treatment plant	Technology	Technology owner
1	Aqlara/ San Sebastian de Litera, Spain	Agricultural WW/ WWTP on agriculturally based town	PDP (Plasma)	IRIS (Italy)
2a	OP/Kalaat al Andalouss, Tunisia	Pharmaceutical contaminants/ Pharmaceutical company	AKVO Microfluidic system	EDEN (France)
2b	OP/Kalaat al Andalouss, Tunisia		Reclaimed EoL Membranes based Prefiltration system	ENIG (Tunisia)
3	SMAT/Turin, Italy	Heavy metals/ WWTP in Turin area (domestic + industrial	4D Scavenger	Weeefiner (Finland)
5	Esdak/Crete, Greece	Organic contaminants from landfill leachates/ Landfill leachate treatment plant	AKVO Microfluidic system	EDEN (France)

The iMERMAID project develops and demonstrates advanced technologies for the monitoring and remediation of contaminants of emerging concern in wastewater treatment systems across the Mediterranean region. These technologies are intended to improve the removal of pollutants that are not effectively addressed by conventional treatment processes, including pharmaceutical residues, pesticides, heavy metals, and other substances of environmental concern. In parallel to the environmental assessment of these solutions, it is also relevant to examine the costs associated with their implementation and operation.

In this context, Life Cycle Costing is applied to provide a structured economic assessment of the iMERMAID technologies across relevant life cycle stages. The method enables the identification and quantification of costs associated with the acquisition, operation, maintenance, replacement, and end-of-life management of the assessed systems, where applicable. Its application within the project supports a more comprehensive understanding of the implications of integrating advanced treatment technologies into existing wastewater treatment configurations.

The economic assessment follows the same comparative logic adopted in the environmental analysis. For each use case, a baseline scenario representing the existing treatment configuration is assessed alongside an iMERMAID scenario in which the innovative technology is integrated as an additional treatment step. The assessment therefore focuses on the economic implications of enhancing an existing treatment system, rather than on the development of a completely new wastewater treatment plant configuration.

Given the nature of the demonstrated systems, the purpose of the LCC is not to assess financial return in a conventional business sense, but to quantify the costs associated with the additional treatment function delivered by the iMERMAID technologies. Within the scope of the project, no robust and consistent revenue streams, tariff adjustments, or other direct monetary inflows can be attributed to the implementation of the technologies. The economic assessment is therefore developed as a comparative life cycle cost analysis of the baseline and iMERMAID scenarios, with the objective of identifying cost profiles, cost drivers, and cost differences between treatment configurations.

This approach is particularly relevant in the context of wastewater treatment, where technological choices are often guided not only by direct financial considerations, but also by environmental performance, treatment effectiveness, regulatory developments, and long-term system requirements. In this sense, the LCC results are intended to complement the environmental findings by clarifying the economic burden associated with the implementation of the iMERMAID solutions under the specific conditions of the assessed pilot sites.

The findings are intended to inform about the costs associated with the deployment of the iMERMAID technologies and their integration into existing wastewater treatment plants. From a systemic perspective, the knowledge generated aims to support decision-making related to the implementation of advanced remediation technologies for the mitigation of chemical pollution in the Mediterranean region.

The report is structured as follows. First, the Life Cycle Costing framework applied in the study is introduced. Subsequently, the goal and scope of the economic assessment are defined, including the functional unit, system boundaries, and scenario configuration. The methodological approach is then presented, including the treatment of cost categories, analysis period, discounting approach, and main assumptions. The following sections describe the life cycle cost inventory and the calculation procedure, present the results for the assessed use cases, and discuss the main cost drivers, uncertainties, and limitations of the analysis.

2.0 Methodology for Life cycle costing (LCC) and cost-benefit analysis (CBA)

This chapter presents the methodological framework applied for the economic assessment of the iMERMAID wastewater treatment technologies. The analysis is based on Life Cycle Costing and is developed to complement the environmental assessment by quantifying the costs associated with the implementation and operation of the demonstrated technologies across relevant life cycle stages. In line with the comparative structure adopted in the project, the assessment considers the baseline treatment configurations and the corresponding iMERMAID scenarios in which the innovative technologies are integrated as additional treatment steps.

The chapter introduces the Life Cycle Costing approach adopted in the study, defines the goal and scope of the economic assessment, and describes the methodological choices related to the cost inventory, calculation procedure, and discounting approach. In addition, it clarifies the role of environmental externalities in the broader economic interpretation of the project results, particularly in relation to the cost-benefit discussion developed for the assessed technologies.

2.1 *Introduction and approach*

Life Cycle Costing is a method used to quantify the costs associated with a product, process, or system over the life cycle stages considered in the assessment. In contrast to approaches focused only on initial investment costs, LCC includes the costs arising during implementation, operation, maintenance, replacement, and end-of-life management, where relevant. Its application supports a more comprehensive understanding of the economic implications of alternative system configurations and is particularly relevant in the assessment of environmental technologies, whose cost profile is often distributed across multiple life cycle stages.

In the context of wastewater treatment plants, LCC enables the identification of the main economic burdens associated with the provision of a treatment function and supports the comparison of conventional and enhanced treatment configurations on a consistent basis. This is particularly relevant when innovative technologies are introduced as additional treatment steps within an already operating system, since the economic implications are not limited to acquisition costs, but also include operation-related expenditures, component replacement, and other costs occurring over time. In this sense, LCC provides a structured basis for evaluating the economic implications of introducing advanced remediation technologies in existing treatment configurations.

LCC can be applied with different scopes and purposes depending on the objective of the study. In some cases, it is used to identify and compare the cost profile of alternative technical options over their life cycle. In others, it is combined with discounting in order to express future cost streams on a present value basis, or extended to support broader economic appraisals in combination with monetized externalities. In the present study, LCC is applied as a comparative and discounted cost assessment of baseline and iMERMAID treatment configurations, with a focus on the incremental cost associated with the additional treatment function delivered by the demonstrated technologies.

Within the iMERMAID project, LCC is applied to assess the economic implications of integrating advanced remediation technologies into existing wastewater treatment plants. The analysis follows the same comparative logic adopted in the environmental assessment and considers, for each use case, a baseline scenario and an iMERMAID scenario in which the innovative technology is added to the existing treatment train. The purpose of the assessment is therefore not to evaluate the financial return of a stand-alone commercial investment, but to quantify and compare the costs associated with the integration and operation of the additional treatment step.

Given the nature of the demonstrated systems and the scope of the project, the economic assessment is not developed as a profitability analysis. No robust and consistent revenue streams, tariff adjustments, or other direct monetary inflows can be attributed to the implementation of the new innovative iMERMAID technologies. The LCC is therefore applied as a comparative cost assessment, with the objective of identifying cost profiles, major cost drivers, and cost differences between baseline and iMERMAID scenarios. Where relevant, future cost streams are discounted in order to express costs occurring at different points in time on a consistent present value basis. This allows a coherent comparison of treatment configurations whose cost elements occur at different stages of the life cycle.

The outcomes of the LCC provide information on the total life cycle cost associated with the assessed treatment configurations and on the contribution of individual cost categories and life cycle stages to the overall economic profile. In addition to total and discounted costs, the assessment supports the identification of economic hotspots and, where possible, the derivation of normalized indicators related to the treatment function delivered. In this way, the method contributes to a more comprehensive understanding of the implications of deploying advanced remediation technologies under the technical and operational conditions represented by the iMERMAID pilot sites.

2.2 Goal and scope

The objective of the economic assessment is to quantify the costs associated with the implementation of the iMERMAID wastewater treatment technologies and to compare them with the costs of the corresponding baseline treatment configurations. The assessment evaluates the relevant cost items associated with the integration and operation of the demonstrated technologies and is intended to identify the main cost drivers across the life cycle of the assessed systems. The results are expected to support the understanding of the economic implications of introducing advanced remediation technologies into existing wastewater treatment plants and to complement the environmental assessment developed within the project.

The scope of the assessment is defined by the compared scenarios, the system boundaries, and the selected functional unit. The analysis follows a comparative approach and considers, for each use case, a baseline scenario representing the existing treatment configuration and an iMERMAID scenario in which the innovative technology is integrated as an additional treatment step. The assessment therefore focuses on the incremental cost associated with the enhanced treatment configuration, rather than on the cost of a completely new treatment plant.

The system boundaries include the relevant cost elements associated with the assessed treatment configurations across the life cycle stages considered in the study. These include acquisition, operation, maintenance, replacement of shorter-lived components, and end-of-life management. The baseline scenario includes the costs associated with the existing wastewater treatment configuration, while the iMERMAID scenario includes the costs associated with the additional treatment step and its integration into the existing system. The analysis is developed in alignment with the technical and operational configurations of the pilot sites and includes all cost elements considered relevant for the economic assessment of the compared scenarios.

The functional unit is defined as 1 cubic meter of treated wastewater. This provides a consistent reference for the quantification and comparison of costs across scenarios and use cases, in line with the functional logic adopted in the environmental assessment. All relevant costs are therefore scaled to the treatment of 1 m3 of wastewater, allowing a normalized comparison of the economic burden associated with the baseline and iMERMAID configurations.

Given the nature of the demonstrated systems and the scope of the project, no co-products or direct revenue streams are considered in the core LCC. The economic assessment is therefore not intended to determine profitability, investment recovery, or commercial viability in a conventional business sense. Instead, it is developed as a comparative life cycle cost analysis of the treatment configurations under assessment, with the purpose of identifying total cost, cost distribution across life cycle stages, and the main economic hotspots of the systems.

2.3 Methodological Approach

The economic assessment is developed through a comparative Life Cycle Costing procedure that quantifies and compares the costs associated with the baseline and iMERMAID treatment configurations. The methodological approach is structured to capture the relevant costs occurring across the life cycle of the assessed systems and to express them on a consistent basis for comparison across scenarios and use cases.

The calculation is based on the identification and structuring of all relevant cost categories associated with each treatment configuration. For both the baseline and iMERMAID scenarios, cost items are classified according to their occurrence in the life cycle and their functional role within the system. These include acquisition costs, operational expenditures, maintenance activities, replacement of components with shorter service life, and end-of-life management. Acquisition costs are treated as one-time expenditures associated with the implementation of the treatment configuration. Operational expenditures are treated as recurring costs and include the resource and service inputs required for the functioning of the system, such as electricity consumption, chemical use, water use, waste handling, and other directly related operating items. Maintenance costs are considered as recurring or periodic expenditures associated with inspection, servicing, cleaning, and other activities required to ensure continued system performance. Replacement costs are assigned to components whose service life is shorter than the selected analysis period, so that their renewal is represented explicitly in the cost profile of the system. End-of-life costs are included where relevant in order to reflect the management of equipment and materials at the end of their useful life.

The assessment is carried out over a defined analysis period that is selected to reflect the expected service life of the assessed treatment configurations and to ensure that the main cost items occurring over time are captured in the calculation. The analysis period therefore provides the temporal framework within which one-time, recurring, and replacement-related costs are aggregated. For components whose lifetime is shorter than the analysis period, the number and timing of replacements are estimated based on their expected service life and incorporated into the cost calculation accordingly. In this way, the methodological approach accounts not only for the initial implementation cost of the systems, but also for the time-dependent costs associated with continued operation and component renewal over the assessment horizon. This is particularly relevant for the iMERMAID technologies, whose economic profile may be influenced not only by initial equipment cost, but also by operating requirements and the replacement frequency of specific parts or consumable elements.

Future cost streams are discounted in order to express costs occurring at different points in time on a consistent present value basis. This allows the aggregation and comparison of one-time and recurring costs within a single economic framework and supports a coherent comparison between treatment configurations whose cost profiles differ in timing and structure. The discounting approach is therefore applied to improve the comparability of life cycle costs over the assessment horizon.

All relevant costs are normalized to the functional unit of 1 m3 of treated wastewater. This ensures consistency with the environmental assessment and allows the cost results to be expressed in relation to the treatment function delivered. The comparative logic of the assessment is based on the evaluation of baseline and iMERMAID scenarios for each use case, with the objective of identifying the incremental cost associated with the integration of the additional treatment step and of comparing the cost profile of the alternative configurations on a consistent basis.

2.4 Environmental Externalities and Link to Cost-Benefit Analysis

In addition to the direct costs captured through the Life Cycle Costing, the broader economic interpretation of the iMERMAID technologies considers environmental externalities. These externalities represent environmental damages that are not directly reflected in the financial costs borne by the plant operator or technology provider, but that may nevertheless be relevant from a societal perspective. In the context of wastewater treatment technologies, such effects may be associated with emissions, resource use, and other environmental interventions occurring along the life cycle of the assessed systems.

To account for these broader effects, the environmental impacts quantified in the LCA are monetized using environmental prices provided by the CE Delft Environmental Prices Handbook. This handbook provides monetary values for a wide range of pollutants and environmental themes and is intended for applications in which environmental impacts need to be expressed in economic terms, including life cycle analyses, social business cases, and social cost-benefit analyses. The monetization approach is based on the translation of environmental impacts into welfare-related damage costs, thereby enabling the expression of environmental burdens in monetary units. (CE Delft, 2024)

Within the present study, the monetization of environmental externalities is based on the EF 3.1 results obtained in the environmental assessment. The characterized results for the selected impact categories are combined with the corresponding environmental price factors from the CE Delft methodology in order to estimate the external environmental cost associated with each treatment configuration. In practical terms, this means that the quantified environmental impacts of the baseline and iMERMAID scenarios are multiplied by the relevant monetization factors provided in the handbook, allowing the environmental performance of the systems to be expressed in monetary terms alongside the direct life cycle costs. The use of CE Delft environmental prices is methodologically suitable in this context because the handbook provides valuation factors compatible with PEF midpoint categories and explicitly supports their use in LCA-based weighting and valuation exercises.

The resulting monetized environmental impacts are not included in the core LCC results. Instead, they are treated as a complementary analytical layer and used to support the broader cost-benefit discussion of the assessed technologies. This distinction is important because the LCC focuses on direct internal costs associated with implementation and operation, whereas the monetized environmental externalities reflect societal costs linked to environmental damage. Their separate treatment preserves the methodological clarity of the LCC while allowing a broader interpretation of the implications of the iMERMAID technologies.

This approach is particularly relevant for the iMERMAID project, where the demonstrated technologies are introduced as additional treatment steps and are not expected to generate direct monetary inflows within the pilot context because remediation is not required by regulation. Under these conditions, the direct cost assessment alone does not capture the full societal relevance of the technologies. The monetization of environmental externalities therefore provides an additional perspective by allowing the environmental implications of the baseline and iMERMAID scenarios to be expressed in economic terms and compared with the direct cost burden of implementation.

The results obtained through this procedure are intended to support the cost-benefit discussion by indicating whether the additional treatment function is associated with higher or lower external environmental costs relative to the baseline configuration. In this way, the analysis expands the interpretation of the project results beyond direct financial expenditures and supports a more comprehensive assessment of the broader economic implications of advanced remediation technologies for wastewater treatment systems.

2.5 Implementation of Life cycle costing (LCC) in iMERMAID

The Life Cycle Cost Inventory phase consists of the systematic identification, collection, and structuring of the cost data required for the economic assessment of the baseline and iMERMAID treatment configurations. It provides the economic data foundation for the calculation of life cycle costs and supports the comparative assessment of the treatment systems under the technical and operational conditions represented by the pilot sites.

The inventory includes the cost elements associated with the relevant life cycle stages of the assessed treatment configurations. These comprise costs related to equipment acquisition, electricity consumption, chemical inputs, water use, maintenance activities, component replacement, waste handling, and end-of-life management, where relevant, at the capacity of the WWTP at the Use Case site. The specific inventory structure is defined in accordance with the technical characteristics of each use case and the configuration of the demonstrated technologies.

Cost data are compiled from project partners, technology developers, plant operators, and engineering-based estimates. Where direct cost information is not available, complementary assumptions and proxy values are applied in order to ensure completeness and consistency of the inventory. The selection of cost data follows the technical and operational characteristics of the pilot sites and aims to reflect as closely as possible the conditions under which the systems are demonstrated within the project.

The inventory is organized by scenario, cost category, and temporal occurrence of the cost item. In this way, one-time costs related to acquisition are distinguished from recurring operational and maintenance costs, while replacement and end-of-life costs are assigned according to the expected timing of their occurrence. This structure allows the cost data to be incorporated consistently into the subsequent life cycle cost calculation.

All inventory data are prepared in a manner consistent with the functional unit and the comparative logic of the study. This supports the calculation of total and discounted life cycle costs, the normalization of results to 1 m^3 of treated wastewater, and the comparison of baseline and iMERMAID scenarios for each use case.

2.6 Equations and common financial parameters used in the Life cycle costing

Net present cost (NPC) is calculated in the following way

$$NPC = \sum_{i=0}^{n} \frac{CF_i}{(1+r)^i}$$

where

CF_i = cash flow in the year I, EUR

r = discount rate, %

n = total years of the considered time period (selected period for LCC), a

Life cycle cost of the functional unit (EUR/m^3) may be calculated as a performance indicator of a specified year or as a performance indicator over the analysed period according to the equation below

$$cost_{functional\ unit}(EUR/m3) = \frac{Net\ present\ cost\ (EUR)}{annual\ volume\ of\ wastewater\ input(m3/a) \cdot analysed\ period\ (a)}$$

Financial parameters used for all analysis are summarized in Table 2.

Table 2: Financial parameters for LCC calculation.

		Baseline	Min	Max	Reference
Period selected for the LCC analysis	a	20			Ianes et al 2025
Discount rate	%	5 %	4 %	6 %	European Commission 2025
Annual escalation of costs index	%	2 %			European Commission 2025

3.0 Results of the Economic Assessment

This chapter presents the results of the economic assessment of the iMERMAID wastewater treatment technologies. In line with the methodological framework described in the previous chapter, the results are structured around the comparison of baseline treatment configurations and the corresponding iMERMAID scenarios in which the innovative technologies are integrated as additional treatment steps.

The chapter first presents the direct cost results obtained through the Life Cycle Costing analysis, followed by the monetized environmental externalities and the broader cost-benefit interpretation. The final section provides a synthesis of the main findings, with particular attention to the incremental cost of enhanced treatment, the main economic hotspots, and the relation between direct costs and environmental externalities across the assessed use cases.

3.1 Use Case 1 – LCC results of Application of PDP technology at Socamex

This use case concerns the treatment of wastewater at the San Esteban de Litera wastewater treatment plant in Spain, where the iMERMAID scenario includes the integration of the Pulsed Discharge Plasma system developed by IRIS as an additional tertiary treatment step. The baseline scenario represents the existing treatment configuration of the plant, based on conventional biological treatment without an advanced polishing stage. The iMERMAID scenario builds on this configuration through the addition of the PDP unit downstream of the biological treatment. The economic assessment therefore addresses the life cycle cost associated with the existing treatment configuration and the additional cost elements associated with the implementation and operation of the PDP system.

The baseline scenario reflects the costs associated with the existing treatment system under the operating conditions of the Socamex[1] plant. Its life cycle cost structure includes recurring costs related to plant operation, particularly electricity consumption, labour, maintenance activities, and the management of treatment residuals. As the baseline configuration does not include an advanced tertiary treatment step, no additional equipment acquisition, operation, replacement, or end-of-life costs associated with contaminant-specific polishing are incurred in this scenario. The baseline configuration therefore provides the economic reference for the assessment of the enhanced treatment system.

In the iMERMAID scenario, the life cycle cost structure includes the baseline treatment costs together with the additional costs associated with the PDP system. These comprise the acquisition of the reactor, operation of the unit during the use phase, maintenance requirements, replacement of shorter-lived components where relevant, and end-of-life management of the installed equipment. The PDP system is designed to operate without the continuous use of treatment reagents, which limits the contribution of consumable chemical inputs to the cost structure. Labour costs are also considered in the assessment and, for this use case, no change is assumed between the baseline and iMERMAID scenarios. The comparative

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[1] The partner originally referred to in the project documentation and Grant Agreement as Socamex is now named AQLARA Infraestructuras. For consistency with earlier project materials, figures, and use case references, the name Socamex has been retained in this report. All mentions of Socamex should therefore be understood as referring to AQLARA Infraestructuras.

results and the contribution of the individual cost categories to the overall economic profile are presented in the following sections.

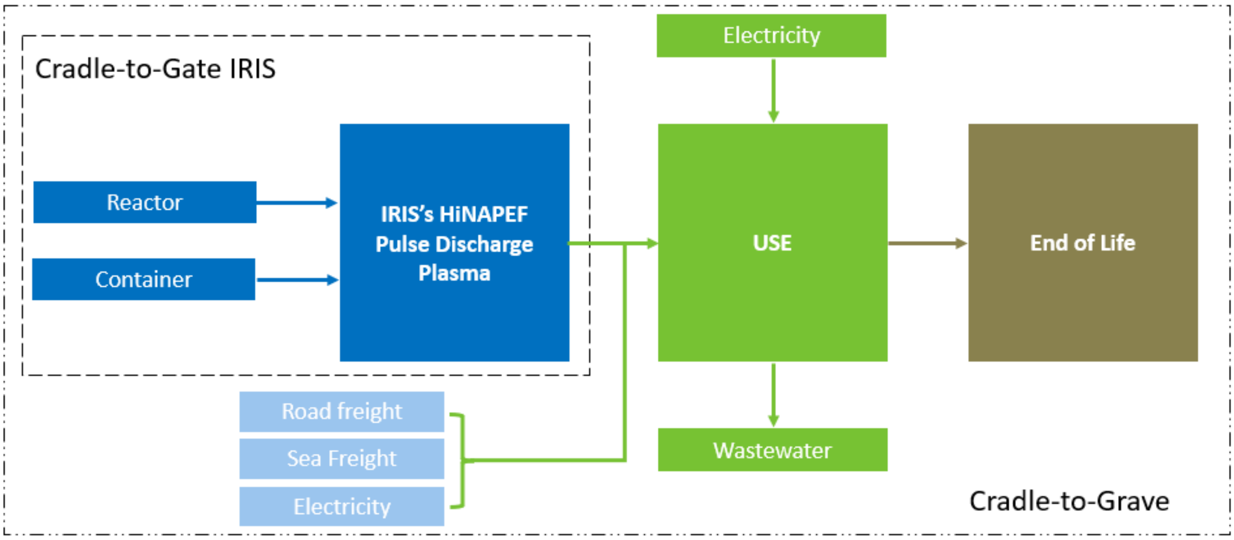

Figure 1: System boundaries for Use Case 1 considered in the economic assessment

3.1.1 Use Case 1 – Baseline LCC Result

For the baseline scenario, the direct cost structure includes operational expenditure, labour cost, and waste treatment cost. In this use case, the operational expenditure corresponds to the Socamex operating cost reported for the use phase. Based on the annual treatment capacity of 54,750 m3/year and the cost assumptions adopted in the assessment, the direct annual cost in Year 1 amounts to 208,156.78 EUR/year, corresponding to 3.80 EUR/m3 of treated wastewater. Operational expenditure, corresponding exclusively to electricity consumption during the operation of the WWTP, represents the dominant cost component, amounting to 201,906.78 EUR/year, or 3.69 EUR/m3, corresponding to 97.0% of the total direct annual cost. Labour contributes 6,250.00 EUR/year, or 0.11 EUR/m3, representing the remaining 3.0%. No waste treatment cost was included in the baseline scenario. According to information provided by Socamex, the sludge generated in the treatment process is transferred to farmers without cost to the WWTP. These results indicate that the baseline economic profile of the Socamex treatment system is driven almost entirely by operational expenditure, while labour represents a comparatively limited contribution.

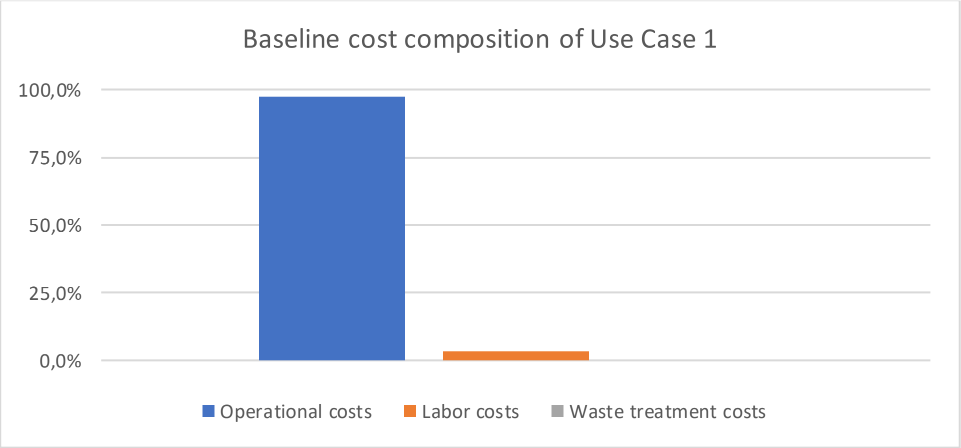

Figure 2: Contribution of operational costs, labour costs, and waste treatment costs to the total direct annual cost of the baseline scenario for Use Case 1 in Year 1, expressed as percentage shares

Over time, the undiscounted annual direct cost increases gradually as a result of inflation, from 208,156.78 EUR/year in Year 1 to 303,245.12 EUR/year in Year 20. On the same basis, the undiscounted direct cost per functional unit increases from 3.80 EUR/m3 to 5.54 EUR/m3 over the assessment horizon. This reflects the effect of cost escalation on the recurring expenditures associated with system operation. Across the full 20-year analysis period, the cumulative undiscounted direct cost amounts to 5,057,662.17 EUR.

When discounting is applied at the central rate of 5%, the annual cost profile decreases in present value terms. Accordingly, the discounted annual cost decreases from 208,156.78 EUR/year in Year 1 to 120,004.39 EUR/year in Year 20, while the corresponding discounted cost per functional unit decreases from 3.80 EUR/m3 to 2.19 EUR/m3. Under the sensitivity cases, the discounted annual cost in Year 20 amounts to 143,933.00 EUR/year, or 2.63 EUR/m3, at a 4% discount rate, and 100,226.46 EUR/year, or 1.83 EUR/m3, at a 6% discount rate. As expected, a lower discount rate results in a higher present value of future annual costs, while a higher discount rate reduces them.

Over the full 20-year analysis horizon, the discounted cumulative direct cost amounts to 3,205,337.90 EUR at the central discount rate of 5%, which is 36.6% lower than the cumulative undiscounted cost. Under the sensitivity analysis, the discounted cumulative direct cost amounts to 3,483,569.49 EUR at a 4% discount rate, corresponding to a reduction of 31.1%, and 2,960,379.93 EUR at a 6% discount rate, corresponding to a reduction of 41.5%, relative to the undiscounted total. These results show that the total present value of the baseline scenario is moderately sensitive to the discount rate assumption over the 20-year period considered.

Overall, the baseline LCC result shows that the direct economic profile of the Socamex treatment system is dominated by operational expenditure, with labour representing a secondary contribution and no direct waste treatment cost being assigned to the WWTP under the current sludge management practice. The discounted analysis confirms that, over the 20-year horizon considered in the study, the cost profile remains strongly influenced by recurring operational requirements, while the total present value of the system is moderately sensitive to the discount rate assumption. This baseline result provides the economic reference against which the iMERMAID configuration is assessed in the following subsection.

3.1.2 Use Case 1 – iMERMAID LCC Result

The iMERMAID LCC result for Use Case 1 reflects the direct costs associated with the enhanced treatment configuration at the Socamex facility, consisting of the baseline wastewater treatment operation complemented by the IRIS plasma technology.

The iMERMAID configuration combines the existing Socamex treatment system with an additional IRIS treatment module of lower nominal capacity. The annual wastewater volume treated at the Socamex plant is 54,750 m3/year, whereas the nominal treatment capacity of one IRIS module is 8,760 m3/year. As the IRIS unit alone is not sufficient to cover the full Socamex treatment demand, the modular system was scaled up linearly in the assessment in order to represent treatment of the full annual flow. Accordingly, no staged utilisation profile was applied, and the iMERMAID configuration was assumed to operate at 100% utilisation throughout the 20-year analysis period. This assumption affects the cost profile of the scenario, as the additional IRIS related costs are incorporated from Year 1 onwards at full scale.

The direct cost structure of the iMERMAID scenario includes the initial acquisition of the IRIS system, operational expenditures related exclusively to electricity consumption during the operation of Socamex and IRIS, maintenance costs for IRIS, labour costs, waste treatment costs, end of life costs, and retrofit or replacement costs over the analysis horizon. The lifetime assumption adopted for IRIS is 5 years. This lifetime is directly relevant for the LCC, as it determines the timing of technology renewal and therefore the occurrence of discrete cost peaks over the 20-year period.

Based on the assumptions adopted in the assessment, the direct annual cost in Year 1 amounts to 458,189.35 EUR/year, corresponding to 6.54 EUR/m3 of treated wastewater. In contrast to the baseline scenario, the Year 1 economic profile is no longer driven only by the operation of the existing WWTP, but by the combined effect of baseline operation, additional IRIS operation and maintenance, and the initial acquisition of the scaled IRIS system. Socamex operational cost remains the largest individual component, amounting to 201,906.78 EUR/year and corresponding to 44.1% of the total direct annual cost. The initial IRIS acquisition cost amounts to 125,000.00 EUR, representing 27.3% of the total, while IRIS operational cost contributes 78,495.08 EUR/year, corresponding to 17.1%, and IRIS maintenance contributes 46,537.50 EUR/year, corresponding to 10.2%. Labour cost amounts to 6,250.00 EUR/year, representing the remaining 1.4%. No waste treatment cost was included in the scenario, as according to information provided by Socamex, the sludge generated in the treatment process is transferred to farmers without cost to the WWTP. These results indicate that the economic profile of the iMERMAID configuration in Year 1 is driven primarily by recurring operational expenditure, while the acquisition of IRIS also represents a significant upfront contribution.

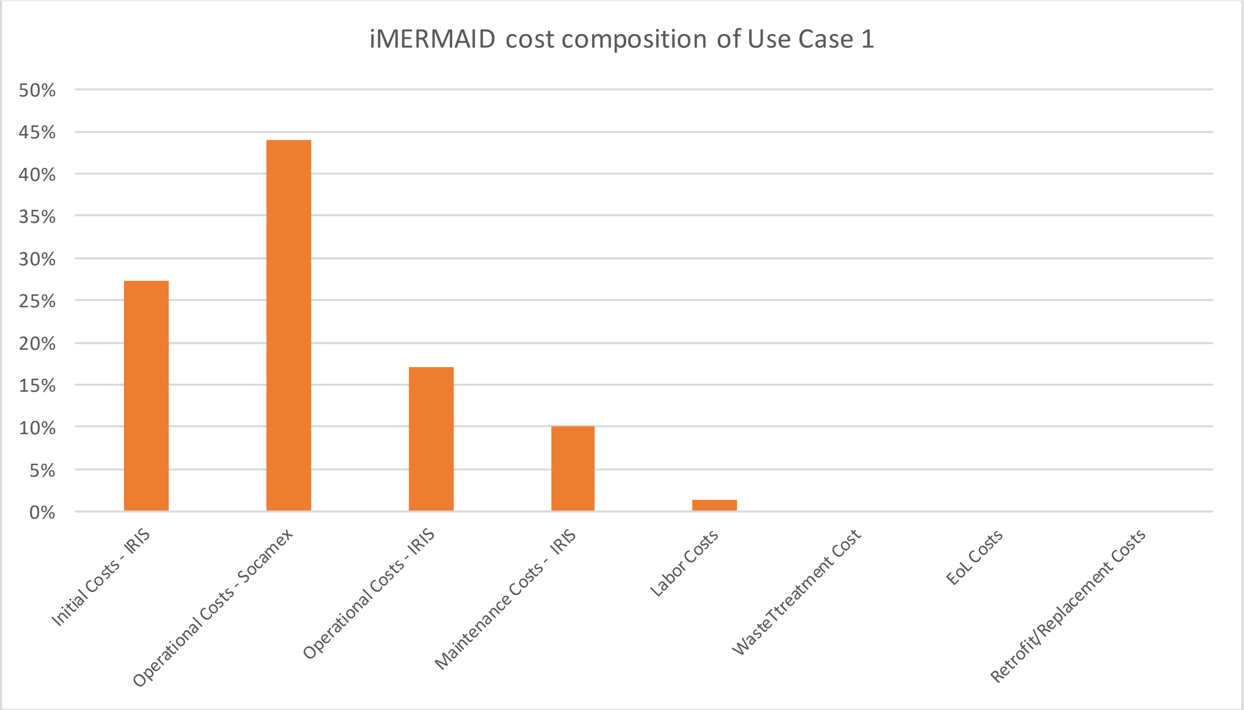

Figure 3: Contribution of initial acquisition costs, operational costs, maintenance costs, labour costs, and waste treatment costs to the total direct annual cost of the iMERMAID scenario for Use Case 1 in Year 1, expressed as percentage shares.

From Year 2 onwards, the direct annual cost decreases because the initial acquisition cost is not repeated, and the annual cost profile is then shaped mainly by recurring operation, maintenance, labour, inflation, and the replacement cycle of the IRIS system. Under undiscounted conditions, the annual direct cost decreases from 458,189.35 EUR/year in Year 1 to 339,853.14 EUR/year in Year 2, corresponding to a reduction from 6.54 EUR/m3 to 6.21 EUR/m3. Thereafter, the annual cost increases gradually as inflation affects the recurring cost elements, reaching 353,583.21 EUR/year, or 6.46 EUR/m3, in Year 4 and 485,393.97 EUR/year, or 8.87 EUR/m3, in Year 20.

In addition to this general trend, marked cost peaks occur in years where replacement events are required according to the lifetime assumption of IRIS. A first relevant increase appears in Year 5, when the total annual cost reaches 495,962.28 EUR/year, or 7.08 EUR/m3, reflecting the first IRIS replacement cycle. A second increase is observed in Year 10, where the annual cost rises to 547,582.43 EUR/year, or 7.82 EUR/m3, and a third in Year 15, where the annual cost reaches 604,575.25 EUR/year, or 8.63 EUR/m3. These peaks are driven primarily by retrofit or replacement costs, amounting to 135,304.02 EUR in Year 5, 149,386.57 EUR in Year 10, and 164,934.85 EUR in Year 15. End of life costs are also included in the same years, but remain negligible in magnitude. In contrast, no full IRIS replacement is charged in Year 20. This methodological choice is made because the 20-year horizon represents the end of the assessed service period, and including a full IRIS renewal at that point would assign the entire replacement cost to the analysis without capturing the service that the renewed system would provide beyond the assessment boundary. From an LCC perspective, this treatment is considered more appropriate, as it avoids overestimating the cost burden of the iMERMAID configuration at the end of the analysis horizon. Overall, the temporal cost profile of the iMERMAID scenario is therefore characterized by a comparatively high entry year, consistently elevated recurring annual costs, and discrete replacement peaks associated with the 5-year lifetime of IRIS. Across the full 20-year analysis period, the cumulative undiscounted direct cost amounts to 8,670,261.59 EUR.

When discounting is applied at the central rate of 5%, the annual cost profile decreases in present value terms relative to the undiscounted stream, while preserving the same overall structure. Accordingly, the discounted annual direct cost decreases from 458,189.35 EUR/year in Year 1 to 323,669.66 EUR/year in Year 2, corresponding to a decline from 6.54 EUR/m3 to 5.91 EUR/m3. During the recurring operating phase, the discounted annual cost remains lower than the undiscounted values, amounting to 408,029.40 EUR/year, or 5.83 EUR/m3, in Year 5 and 192,086.88 EUR/year, or 3.51 EUR/m3, in Year 20. Replacement related peaks remain clearly visible under discounting, although at lower present value levels, including 408,029.40 EUR/year, or 5.83 EUR/m3, in Year 5, 352,976.52 EUR/year, or 5.04 EUR/m3, in Year 10, and 305,351.59 EUR/year, or 4.36 EUR/m3, in Year 15. Compared with the corresponding undiscounted values, discounting at 5% reduces the annual direct cost by 4.8% in Year 2, 17.7% in Year 5, 35.5% in Year 10, 49.5% in Year 15, and 60.4% in Year 20. Under the sensitivity cases, the discounted annual cost in Year 20 amounts to 230,388.57 EUR/year, or 4.21 EUR/m3, at a 4% discount rate, corresponding to a reduction of 52.5% relative to the undiscounted annual cost of the same year, and 160,429.02 EUR/year, or 2.93 EUR/m3, at a 6% discount rate, corresponding to a reduction of 66.9%. As expected, a lower discount rate results in a higher present value of future annual costs, while a higher discount rate reduces them.

Over the full 20-year horizon, the cumulative discounted direct cost amounts to 5,546,594.97 EUR at the central discount rate of 5%, corresponding to a reduction of 36.0% relative to the cumulative undiscounted cost. Under the sensitivity analysis, the cumulative discounted direct cost amounts to 6,016,898.33 EUR at a 4% discount rate, corresponding to a reduction of 30.6%, and 5,132,130.46 EUR at a 6% discount rate, corresponding to a reduction of 40.8%.

Table 3: Direct cost per functional unit of the iMERMAID scenario for Use Case 1 over the 20-year analysis period, expressed in EUR/m3 of treated wastewater under undiscounted conditions and under discount rates of 5%, 4%, and 6%.

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Undiscounted cost (EUR/m3)	6.54	6.21	6.33	6.46	7.08	6.72	6.85	6.99	7.13	7.82	7.42	7.57	7.72	7.87	8.63	8.19	8.35	8.52	8.69	8.87
Discounted cost at 5% (EUR/m3)	6.54	5.91	5.74	5.58	5.83	5.26	5.11	4.97	4.83	5.04	4.55	4.42	4.30	4.17	4.36	3.94	3.83	3.72	3.61	3.51
Discounted cost at 4% (EUR/m3)	6.54	5.97	5.85	5.74	6.05	5.52	5.42	5.31	5.21	5.49	5.01	4.92	4.82	4.73	4.98	4.55	4.46	4.37	4.29	4.21
Discounted cost at 6% (EUR/m3)	6.54	5.86	5.64	5.42	5.61	5.02	4.83	4.65	4.47	4.63	4.14	3.99	3.84	3.69	3.82	3.42	3.29	3.16	3.05	2.93

Overall, the iMERMAID LCC result shows that the economic profile of the enhanced treatment configuration is driven primarily by recurring operational expenditure associated with the combined Socamex and IRIS system, while the modular deployment and periodic replacement of IRIS introduce additional capital related cost peaks over time. The discounted analysis confirms that, over the 20-year horizon considered in the study, the temporal cost profile remains characterized by high recurring annual costs and discrete renewal events, while the total present value of the system is moderately sensitive to the discount rate assumption. This result provides the economic basis for comparing the additional cost burden associated with the iMERMAID configuration against the baseline scenario.

A note on updated electricity consumption data for the IRIS PDP system, shared after completion of the main analyses, is provided in Technical Note I.

3.1.3 Use Case 1 – CBA results

In addition to the direct costs assessed through the Life Cycle Costing, the broader economic interpretation of Use Case 1 considers the monetized environmental costs associated with the baseline and iMERMAID scenarios. These external costs were estimated by combining the environmental impact results obtained in the LCA with environmental price factors derived from the CE Delft Environmental Prices Handbook. In this way, selected environmental burdens of the two treatment configurations are translated into monetary terms and can be interpreted as external costs from a broader societal perspective.

For Use Case 1, the monetization was carried out for the impact categories for which environmental price factors were available in the adopted methodology. As a result, the monetized external cost does not represent the full environmental profile of the baseline and iMERMAID scenarios, but the subset of impact categories that could be expressed in monetary terms on a consistent basis. The categories included in the present assessment are climate change, ozone depletion, ionising radiation, oxidant formation affecting human health, particulate matter formation, acidification, freshwater eutrophication, marine eutrophication, and terrestrial eutrophication. The environmental prices provided by the CE Delft methodology are expressed in EUR2021 and were updated here to EUR2026 in order to ensure consistency with the economic assumptions adopted in the present study.

Based on this approach, the total monetized environmental cost of the baseline scenario amounts to 1.38 EUR/m3, while the corresponding value for the iMERMAID scenario amounts to 1.44 EUR/m3. In both cases, climate change is the dominant contributor, amounting to 1.09 EUR/m3 in the baseline and 1.14 EUR/m3 in the iMERMAID scenario. Marine eutrophication also represents a relevant contribution in both scenarios, amounting to 0.12 EUR/m3. In the baseline scenario, acidification contributes 0.10 EUR/m3, oxidant formation 0.04 EUR/m3, terrestrial eutrophication 0.03 EUR/m3, and freshwater eutrophication 0.01 EUR/m3, while ozone depletion, ionising radiation, and particulate matter formation are negligible. In the iMERMAID scenario, acidification contributes 0.09 EUR/m3, oxidant formation 0.04 EUR/m3, terrestrial eutrophication 0.03 EUR/m3, freshwater eutrophication 0.01 EUR/m3, and ionising radiation 0.01 EUR/m3, whereas the remaining priced categories remain negligible. Overall, the difference between the two scenarios in terms of monetized environmental burden is limited, with the iMERMAID configuration increasing the total external cost by only 0.06 EUR/m3 relative to the baseline.

Table 4: Environmental price factors and resulting monetized environmental costs for Use Case 1, expressed in EUR2026 per unit of impact and in EUR/m3 of treated wastewater for the baseline and iMERMAID scenarios

Impact category	Unit	Environmental prices per unit, EU27	Extenalities	
		EUR (2026)	Baseline	iMERMAID
Climate change	kg CO2-eq.	0.16	1.09	1.14
Ozone depletion	kg CFC-11-eq.	35.58	0.00	0.00
Ionising radiation	kBq U235-eq.	0.001	0.00	0.01
Oxidant formation, human health	kg NMVOC-eq.	1.59	0.04	0.04
Particulate matter formation	Disease incidence	934.99	0.00	0.00
Acidification	mol H+-eq.	2.49	0.10	0.09
Freshwater eutrophication	kg P-eq.	4.57	0.01	0.01
Marine eutrophication	kg N-eq.	17.42	0.12	0.12

Terrestrial eutrophication	mol N-eq.	0.40	0.03	0.03
TOTAL costs			**1.38**	**1.44**

When the monetized environmental externalities are added to the direct annual costs, their influence on the overall economic profile becomes evident in both scenarios. In the baseline scenario, externalities increase the annual cost from 208,156.78 EUR/year to 283,824.46 EUR/year in Year 1, corresponding to an increase of about 36.4%, or from 3.80 EUR/m3 to 5.18 EUR/m3. By Year 20, the annual cost rises from 303,245.12 EUR/year to 413,478.65 EUR/year, corresponding to a similar increase of about 36.4%, or from 5.54 EUR/m3 to 7.55 EUR/m3. This indicates that, in the baseline configuration, externalities constitute a consistently significant addition to the direct cost profile across the full analysis horizon.

In the iMERMAID scenario, the relative contribution of externalities is lower than in the baseline case because the direct economic profile is already substantially increased by the additional IRIS related costs. In Year 1, externalities increase the annual cost from 458,189.35 EUR/year to 536,836.55 EUR/year, corresponding to an increase of about 17.2%, or from 6.54 EUR/m3 to 7.98 EUR/m3. In Year 2, when the initial acquisition cost is no longer present and the profile is dominated by recurring operation and maintenance, the annual cost rises from 339,853.14 EUR/year to 420,073.28 EUR/year, corresponding to an increase of about 23.6%, or from 6.21 EUR/m3 to 7.67 EUR/m3. In years where replacement events occur, the relative contribution of externalities becomes smaller again because the annual cost is increased by retrofit and replacement costs. In Year 5, the annual cost rises from 495,962.28 EUR/year to 581,092.53 EUR/year, corresponding to an increase of about 17.2%, or from 7.08 EUR/m3 to 8.64 EUR/m3. A similar pattern is observed in Year 10, where the cost increases from 547,582.43 EUR/year to 641,573.11 EUR/year, corresponding to about 17.2%, or from 7.82 EUR/m3 to 9.54 EUR/m3, and in Year 15, where the annual cost rises from 604,575.25 EUR/year to 708,348.56 EUR/year, again corresponding to about 17.2%, or from 8.63 EUR/m3 to 10.53 EUR/m3. By Year 20, when the scenario returns to a recurring cost profile without a new replacement event, the annual cost increases from 485,393.97 EUR/year to 599,968.08 EUR/year, corresponding to about 23.6%, or from 8.87 EUR/m3 to 10.96 EUR/m3. These results show that, in the iMERMAID configuration, the additional burden associated with externalities is moderate in years dominated by technology acquisition or replacement, and more pronounced in years dominated by recurring operation.

Table 5: Contribution of monetized environmental costs to the baseline and iMERMAID scenarios of Use Case 1, expressed in EUR/m3 and as percentage increase relative to direct costs.

Scenario	Year	Direct cost without externalities (EUR/m3)	Cost with externalities (EUR/m3)	Additional cost due to externalities (EUR/m3)	Increase due to externalities (%)
Baseline	1	3.8	5.18	1.38	36.4
Baseline	20	5.54	7.55	2.01	36.4
iMERMAID	1	6.54	7.98	1.44	17.2
iMERMAID	2	6.21	7.67	1.46	23.6
iMERMAID	5	7.08	8.64	1.56	17.2
iMERMAID	10	7.82	9.54	1.72	17.2
iMERMAID	15	8.63	10.53	1.9	17.2
iMERMAID	20	8.87	10.96	2.09	23.6

At the same time, the interpretation of these monetized environmental costs requires caution. The increase from 1.38 EUR/m3 in the baseline to 1.44 EUR/m3 in the iMERMAID scenario does not capture the beneficial remediation effect of the treatment configuration on the selected contaminants of concern discharged in the effluent. This is because the monetization is based only on the subset of LCA impact categories for which environmental price factors were available and therefore does not include the avoided freshwater ecotoxicity associated with the removal of isoproturon, terbutryn, and bisphenol A from the treated wastewater.

This limitation is particularly relevant in Use Case 1, where the broader environmental interpretation should not rely on the monetized externalities alone and must be complemented by the handprint assessment. The monetized external cost values reflect only the priced upstream burdens associated with system operation and technology deployment, whereas they do not capture the potential environmental benefit linked to the degradation of the selected substances of concern in the treated effluent.

In the present case, the quantified handprint remains comparatively small in absolute terms. This result should be interpreted in light of the low concentrations of the selected substances of concern in the assessed effluent. Under such conditions, the quantified reduction in freshwater ecotoxicity per functional unit is also limited. Therefore, the relatively small handprint obtained for Use Case 1 should not be interpreted as evidence of low treatment capability, but rather as a result that is strongly conditioned by the concentration levels observed in the assessed stream.

At the same time, the experimental results indicate that the IRIS technology achieved complete degradation of the three selected compounds under the tested conditions. This confirms the treatment potential of the technology for these substances within the experimental scope considered. While the present assessment does not provide a basis for quantifying how the handprint would change under different concentration conditions or in other application contexts, the results suggest that the environmental relevance of this treatment effect could become more pronounced in situations where the selected substances are present at higher levels.

From a broader economic and environmental perspective, the monetized external cost result should therefore be interpreted together with the handprint assessment and with the limitations of the available evidence. The monetized values indicate that the iMERMAID scenario introduces a slightly higher environmental burden within the priced impact categories, whereas the handprint assessment provides complementary evidence on the remediation function demonstrated under the tested conditions. Taken together, these results show that the iMERMAID configuration entails a higher monetized environmental burden within the priced categories, while also delivering a treatment effect that is not reflected in the monetized values presented here.

3.1.4 Use Case 1 – Comparative analysis of the economic results of the baseline and iMERMAID

The comparison of the baseline and iMERMAID scenarios for Use Case 1 shows two distinct cost profiles. The baseline configuration is characterized by a comparatively stable annual cost structure dominated by operational expenditure, which in this case refers exclusively to electricity consumption for WWTP operation. In contrast, the iMERMAID configuration combines the same baseline treatment costs with the additional costs associated with the IRIS technology, including acquisition, operation, maintenance, and replacement. The comparison therefore reflects both higher recurring annual costs and the effect of periodic technology renewal.

From the perspective of direct life cycle costs, the baseline scenario remains lower than the iMERMAID scenario throughout the assessment horizon. In Year 1, the direct cost amounts to 3.80 EUR/m3 in the baseline and 6.54 EUR/m3 in the iMERMAID scenario. In Year 5, the corresponding values are 4.12 EUR/m3 and 7.08 EUR/m3, while in Year 20 they reach 5.54 EUR/m3 and 8.87 EUR/m3, respectively. The iMERMAID scenario also shows cost peaks in Years 5, 10, and 15, consistent with the assumed 5-year lifetime of IRIS. Across the 20-year horizon, the cumulative undiscounted direct cost amounts to 5,057,662.17 EUR for the baseline and 8,670,261.59 EUR for the iMERMAID scenario. When discounting is applied at 5%, these values decrease to 3,205,337.90 EUR and 5,546,594.97 EUR, respectively. This confirms that the iMERMAID configuration remains associated with a higher time adjusted cost burden than the baseline. The summarised comparison of the baseline scenario and iMERMAID scenario is presented in Figure 4.

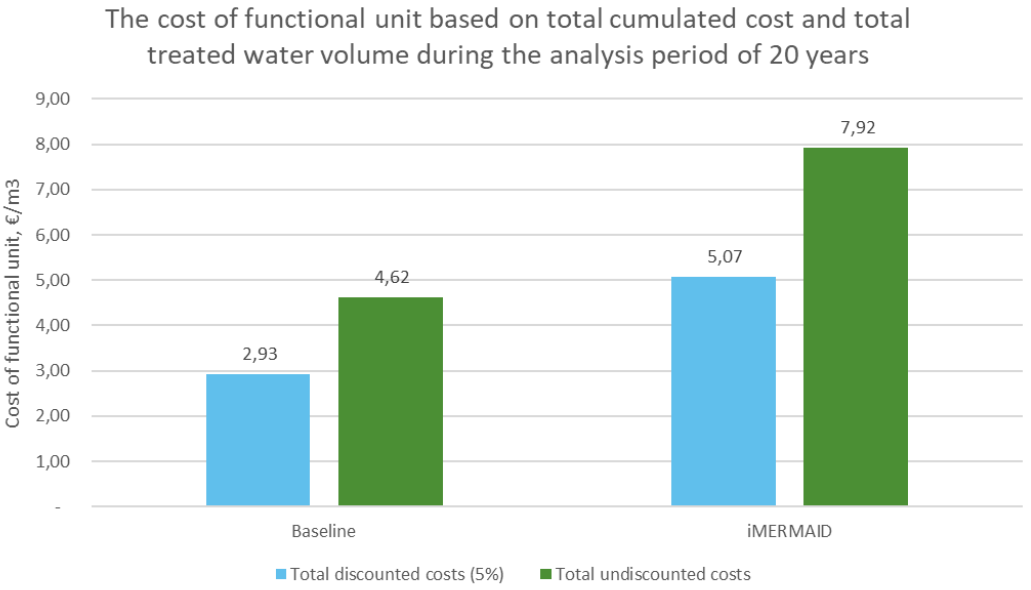

Figure 4: Comparison of summarised LCC results between *Use Case 1* baseline scenario and iMERMAID scenario *over the 20-year analysis period, under an inflation assumption of 2%.*

The comparison of monetized environmental costs shows the same overall direction, although the difference between scenarios is much smaller. Based on the subset of impact categories for which environmental prices were available, the monetized environmental cost amounts to 1.38 EUR/m3 for the baseline scenario and 1.44 EUR/m3 for the iMERMAID scenario. This indicates a limited increase in the priced upstream environmental burden of the iMERMAID configuration relative to the baseline.

When direct costs and monetized environmental costs are considered together, the same pattern remains. In the baseline scenario, monetized environmental costs increase the annual cost from 3.80 EUR/m3 to 5.18 EUR/m3 in Year 1 and from 5.54 EUR/m3 to 7.55 EUR/m3 in Year 20, corresponding in both cases to an increase of about 36.4%. In the iMERMAID scenario, the annual cost increases from 6.54 EUR/m3 to 7.98 EUR/m3 in Year 1, from 6.21 EUR/m3 to 7.67 EUR/m3 in Year 2, and from 8.87 EUR/m3 to 10.96 EUR/m3 in Year 20. Relative to the direct cost profile, this corresponds to increases ranging from about 17.2% to 23.6%, depending on the year considered.

At the same time, this comparison has an important methodological limitation. The monetized environmental costs do not capture the remediation benefit associated with the degradation of the selected substances of concern in the treated effluent. This point is relevant for Use Case 1, because the handprint assessment provides complementary evidence that is not reflected in the monetized values. In the present case, the quantified handprint is comparatively small in absolute terms, amounting to 0.44 CTUe/m³ for the combined removal of isoproturon, terbutryn, and bisphenol A. This should be interpreted in relation to the concentration and ecotoxicity weighted profile of the selected substances in the assessed Socamex effluent, rather than as a limitation of the treatment performance itself. At the same time, the experimental results indicate that the IRIS technology achieved complete degradation of the three selected substances under the tested conditions, removing the freshwater ecotoxicity potential associated with these contaminants from the final effluent. While the present assessment does not provide a basis for quantifying how the handprint would change under other concentration conditions, the results suggest that the environmental relevance of this treatment effect may become more pronounced where the selected substances are present at higher levels or where they represent a larger share of the freshwater ecotoxicity profile of the treated effluent. This point should, however, be interpreted cautiously and not as a quantified outcome of the present study.

Overall, the comparison shows that the iMERMAID configuration entails a higher economic burden than the baseline over the 20-year analysis horizon, both in direct life cycle costs and in monetized environmental costs within the priced impact categories. At the same time, it provides an additional remediation function that is not captured in the monetized external cost values. For UC1, the handprint results show that this remediation function is technically effective for the selected contaminants under the assessed conditions, but that its quantified freshwater ecotoxicity benefit is not sufficient to offset the additional freshwater ecotoxicity burden associated with PDP operation in the present case. The comparison should therefore be interpreted as the assessment of a lower cost conventional treatment configuration against a higher cost enhanced treatment configuration that provides an additional treatment function, the environmental relevance of which is only partially captured within the present economic boundary and is expected to depend on the contaminant load, ecotoxicity weighted relevance, treatment demand, and operating conditions of the specific application context.

3.2 Use Case 2 – Application of Microfluidic System and reclaimed RO membranes at Opalia

This use case concerns the treatment of pharmaceutical wastewater at the Opalia facility in Kalaat Al Andalouss, Tunisia, where the baseline scenario is represented by an on-site wastewater treatment plant based on a conventional activated sludge process. The iMERMAID scenario builds on this configuration through the integration of two additional treatment steps: ENIG's pre-filtration system based on reclaimed reverse osmosis membranes and EDEN's microfluidic remediation technology. The economic assessment therefore addresses the life cycle cost associated with the existing treatment configuration and the additional cost elements associated with the implementation and operation of the integrated iMERMAID treatment system.

The baseline scenario reflects the costs associated with the operation of the existing activated sludge process under the conditions of the Opalia plant. Its life cycle cost structure includes recurring costs related to electricity consumption, labour, maintenance activities, sludge handling, and other operating requirements associated with the treatment process. As the baseline configuration does not include an advanced tertiary polishing step specifically designed for the removal of pharmaceutical contaminants, no additional equipment acquisition, replacement, or end-of-life costs associated with the ENIG and EDEN systems are incurred in this scenario. The baseline configuration therefore provides the economic reference for the assessment of the enhanced treatment system.

In the iMERMAID scenario, the life cycle cost structure includes the baseline treatment costs together with the additional costs associated with ENIG and EDEN technologies. These comprise the acquisition of the additional equipment, operation of the systems during the use phase, maintenance requirements, replacement of shorter-lived components where relevant, and end-of-life management of the installed units.

The comparative results and the contribution of the individual cost categories to the overall economic profile are presented in the following sections.

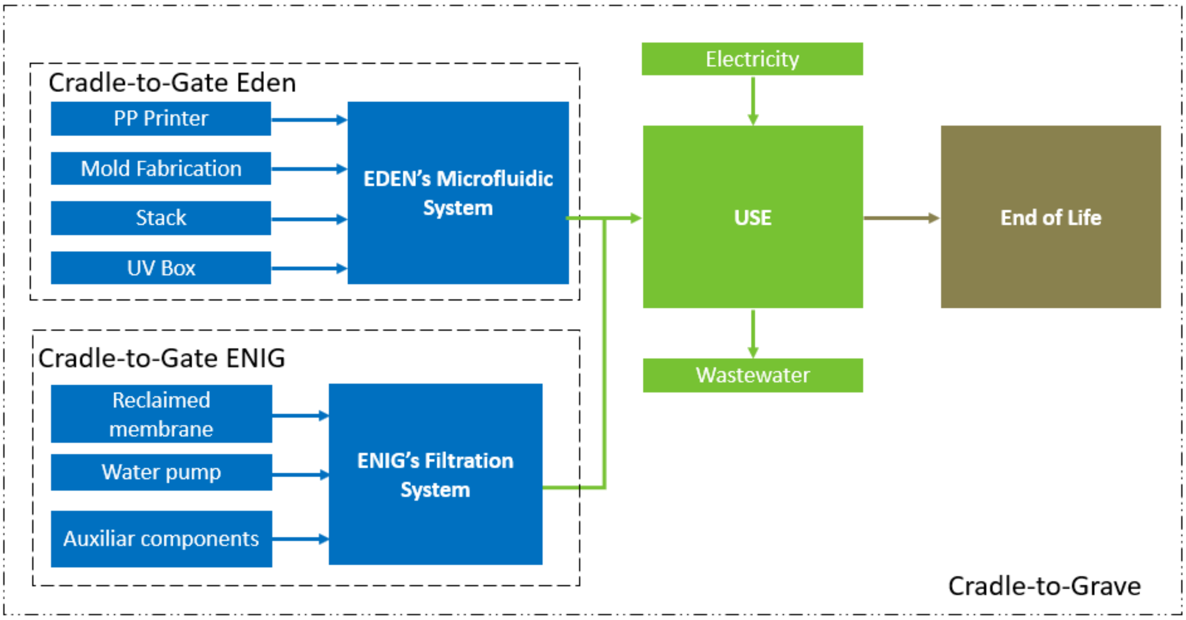

Figure 5: System boundaries for Use Case 2 considered in the economic assessment

3.2.1 Use Case 2 – Baseline LCC Result

For the baseline scenario, the direct cost structure includes operational expenditure, labour cost, and waste treatment cost. In this use case, the operational expenditure refers exclusively to electricity consumption during the use phase. Based on the annual treatment capacity of 5,218 m3/year and the cost assumptions adopted in the assessment, the direct annual cost in Year 1 amounts to 8,727.55 EUR/year, corresponding to 1.67 EUR/m3 of treated wastewater. Labour represents the dominant cost component, amounting to 7,350.00 EUR/year, or 1.41 EUR/m3, corresponding to 84.2% of the total direct annual cost. Electricity consumption accounts for 939.24 EUR/year, or 0.18 EUR/m3, corresponding to 10.8%, while waste treatment contributes 438.31 EUR/year, or 0.08 EUR/m3, representing 5.0% of the total. These results indicate that the baseline economic profile of the Opalia treatment system is driven primarily by labour requirements, while electricity and waste treatment remain comparatively limited contributors.

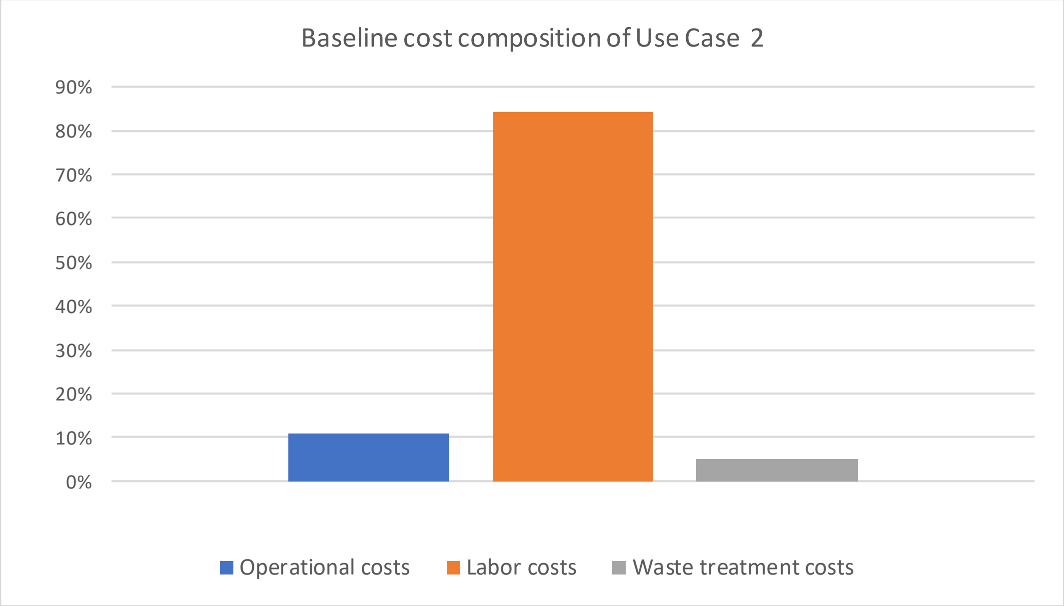

Figure 6: Contribution of operational costs, labour costs, and waste treatment costs to the total direct annual cost of the baseline scenario for Use Case 2 in Year 1, expressed as percentage shares

Over time, the undiscounted annual direct cost increases gradually as a result of inflation, from 8,727.55 EUR/year in Year 1 to 12,714.40 EUR/year in Year 20. On the same basis, the undiscounted direct cost per functional unit increases from 1.67 EUR/m3 to 2.44 EUR/m3 over the assessment horizon. This reflects the effect of cost escalation on the recurring expenditures associated with system operation. Across the full 20-year analysis period, the cumulative undiscounted direct cost amounts to 212,056.56 EUR.

When discounting is applied at the central rate of 5%, the annual cost profile decreases in present value terms, indicating that the discount effect outweighs the annual cost escalation. Accordingly, the discounted annual cost decreases from 8,727.55 EUR/year in Year 1 to 5,031.52 EUR/year in Year 20, while the corresponding discounted cost per functional unit decreases from 1.67 EUR/m3 to 0.96 EUR/m3. Under the sensitivity cases, the discounted annual cost in Year 20 amounts to 6,034.79 EUR/year, or 1.16 EUR/m3, at a 4% discount rate, and 4,202.27 EUR/year, or 0.81 EUR/m3, at a 6% discount rate. As expected, a lower discount rate results in a higher present value of future annual costs, while a higher discount rate reduces them.

Over the full 20-year analysis horizon, the discounted cumulative direct cost amounts to 134,392.71 EUR at the central discount rate of 5%, which is 36.6% lower than the cumulative undiscounted cost. Under the sensitivity analysis, the discounted cumulative direct cost amounts to 146,058.34 EUR at a 4% discount rate, corresponding to a reduction of 31.1%, and 124,122.17 EUR at a 6% discount rate, corresponding to a reduction of 41.5%, relative to the undiscounted total. These results show that the total present value of the baseline scenario is moderately sensitive to the discount rate assumption over the 20-year period considered.

Overall, the baseline LCC result shows that the direct economic profile of the Opalia treatment system is dominated by labour cost, with electricity and waste treatment representing secondary contributions. The discounted analysis confirms that, over the 20-year horizon considered in the study, the cost profile remains strongly influenced by recurring labour requirements, while the total present value of the system is moderately sensitive to the discount rate assumption. This baseline result provides the economic reference against which the iMERMAID configuration is assessed in the following subsection.

3.2.2 Use Case 2 – iMERMAID LCC Result

The iMERMAID LCC result for Use Case 2 reflects the direct costs associated with the enhanced treatment configuration at the Opalia facility, consisting of the baseline activated sludge process complemented by ENIG's pre-filtration system and EDEN's microfluidic remediation technology. The assessment is developed using the same assumptions applied to the baseline scenario, namely a 20-year analysis period, 2% inflation, and a central discount rate of 5%, with sensitivity analysis performed at 4% and 6%.

The iMERMAID configuration combines the existing Opalia treatment system with two additional treatment units of different nominal capacities. The annual wastewater volume treated at the Opalia plant is 5,218 m3/year. ENIG is designed for a nominal treatment capacity of 17,520 m3/year, whereas EDEN is designed for 5,218 m3/year. The staged utilisation profile adopted during the first years of operation applies only to EDEN. ENIG is not constrained by the same assumption, as its nominal capacity is substantially higher than the treated flow considered in the assessment. Accordingly, EDEN utilisation is assumed at 85% in Year 1, 90% in Year 2, 95% in Year 3, 98% in Year 4, and 100% from Year 5 onwards. This assumption affects the recurring annual cost profile of the iMERMAID scenario during the first years of operation.

The direct cost structure of the iMERMAID scenario includes the initial acquisition of ENIG and EDEN, operational expenditures related exclusively to electricity consumption, maintenance costs for both units, labour costs, waste treatment costs, end-of-life costs, and retrofit or replacement costs over the analysis horizon. The lifetime assumptions adopted for the two technologies are 7 years for ENIG and 10 years for EDEN. These lifetimes are directly relevant for the LCC, as they determine the timing of technology renewal and therefore the occurrence of discrete cost peaks over the 20-year period.

Based on the assumptions adopted in the assessment, the direct annual cost in Year 1 amounts to 109,426.34 EUR/year, corresponding to 3.83 EUR/m3 of treated wastewater. This cost profile is dominated by the initial acquisition of the EDEN unit, which amounts to 85,000.00 EUR, or 77.7% of the total direct annual cost. The initial cost of ENIG amounts to 13,530.00 EUR, corresponding to a further 12.4%. Labour cost contributes 7,350.00 EUR/year, representing 6.7% of the total. The remaining cost items are comparatively limited, including ENIG operational cost at 1,543.17 EUR/year, or 1.4% of the total, Opalia operational cost at 939.24 EUR/year, or 0.9%, waste treatment cost at 438.31 EUR/year, or 0.4%, EDEN maintenance cost at 332.65 EUR/year, or 0.3%, EDEN operational cost at 216.27 EUR/year, or 0.2%, and ENIG maintenance cost at 76.70 EUR/year, or 0.1%. These results show that the economic profile of the iMERMAID configuration in the first year is still strongly influenced by the upfront acquisition of the additional treatment technologies, and particularly by EDEN, although much less strongly than in the previous configuration.

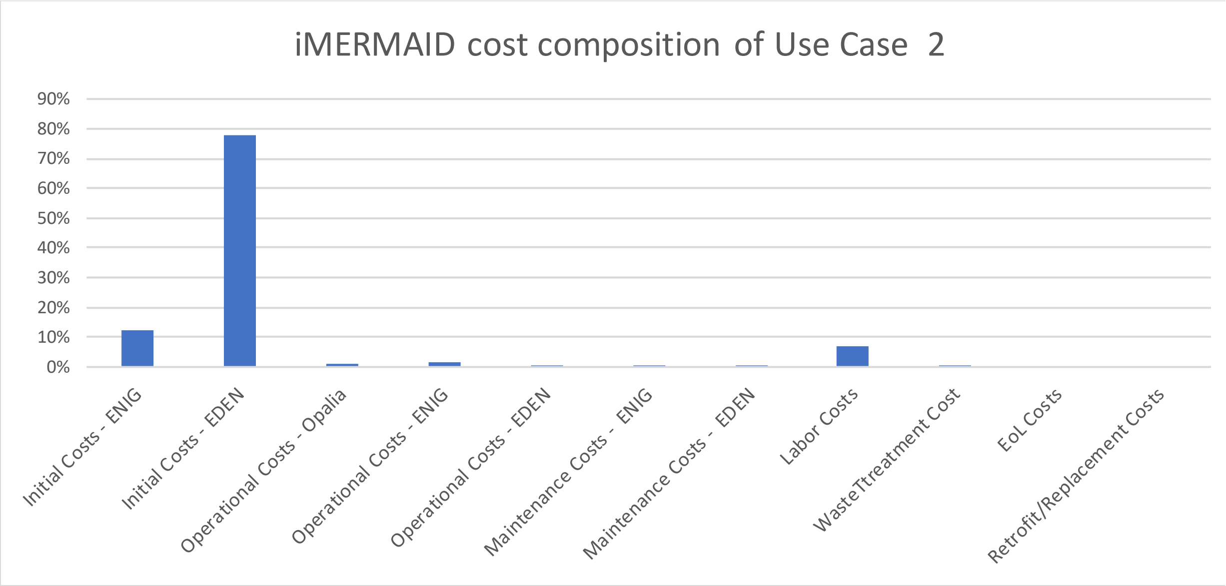

Figure 7: Contribution of initial acquisition costs, operational costs, maintenance costs, labour costs, and waste treatment costs to the total direct annual cost of the iMERMAID scenario for Use Case 2 in Year 1, expressed as percentage shares.

From Year 2 onwards, the direct annual cost decreases because the initial acquisition costs are not repeated, and the annual cost profile is then shaped mainly by recurring operation, labour, maintenance, waste treatment, inflation, and the progressive increase in utilisation. Under undiscounted conditions, the annual direct cost decreases from 109,426.34 EUR/year in Year 1 to 11,147.20 EUR/year in Year 2, corresponding to a reduction from 3.83 EUR/m3 to 2.14 EUR/m3. Thereafter, the annual cost evolves over time as the system reaches full utilisation and inflation affects the recurring cost elements, reaching 11,899.40 EUR/year, or 2.28 EUR/m3, in Year 5 and 16,015.11 EUR/year, or 3.15 EUR/m3, in Year 20.

In addition to this general trend, marked cost peaks occur in years where replacement events are required according to the lifetime assumptions of the technologies. A first relevant increase appears in Year 7, when the total annual cost reaches 27,617.18 EUR/year, or 2.50 EUR/m3, reflecting the renewal cycle associated with ENIG. A second and larger peak appears in Year 10, where the annual cost rises to 114,720.84 EUR/year, or 4.54 EUR/m3, driven by the replacement of EDEN. A further increase is observed in Year 14, where the annual cost reaches 31,723.45 EUR/year, or 3.12 EUR/m3, reflecting the second renewal cycle associated with ENIG. In contrast, no full EDEN replacement is charged in Year 20. This methodological choice is made because the 20-year horizon represents the end of the assessed service period, and including a full EDEN renewal at that point would assign the entire replacement cost to the analysis without capturing the service that the renewed unit would provide beyond the assessment boundary. From an LCC perspective, this treatment is considered more appropriate, as it avoids overestimating the cost burden of the iMERMAID configuration at the end of the analysis horizon. Overall, the temporal cost profile of the iMERMAID scenario is therefore characterized by a high capital entry year, a lower recurring operating phase, and discrete renewal peaks associated with the finite lifetime of ENIG and EDEN. Across the full 20-year analysis period, the cumulative undiscounted direct cost amounts to 499,748.62 EUR.

When discounting is applied at the central rate of 5%, the annual cost profile decreases in present value terms relative to the undiscounted stream, while preserving the same overall structure. Accordingly, the discounted annual direct cost decreases from 109,426.34 EUR/year in Year 1 to 10,616.38 EUR/year in

Year 2, corresponding to a decline from 3.83 EUR/m3 to 2.03 EUR/m3. During the recurring operating phase, the discounted annual cost remains lower than the undiscounted values, amounting to 9,789.67 EUR/year, or 1.88 EUR/m3, in Year 5 and 6,337.72 EUR/year, or 1.25 EUR/m3, in Year 20. Replacement related peaks remain clearly visible under discounting, although at lower present value levels, including 20,608.36 EUR/year, or 1.86 EUR/m3, in Year 7, 73,950.08 EUR/year, or 2.93 EUR/m3, in Year 10, and 16,823.62 EUR/year, or 1.66 EUR/m3, in Year 14. Compared with the corresponding undiscounted values, discounting at 5% reduces the annual direct cost by 4.8% in Year 2, 17.7% in Year 5, 25.4% in Year 7, 35.5% in Year 10, 47.0% in Year 14, and 60.4% in Year 20. Under the sensitivity cases, the discounted annual cost in Year 20 amounts to 7,601.45 EUR/year, or 1.50 EUR/m3, at a 4% discount rate, corresponding to a reduction of 52.5% relative to the undiscounted annual cost of the same year, and 5,293.20 EUR/year, or 1.04 EUR/m3, at a 6% discount rate, corresponding to a reduction of 66.9%. As expected, a lower discount rate results in a higher present value of future annual costs, while a higher discount rate reduces them.

Over the full 20-year horizon, the cumulative discounted direct cost amounts to 353,742.29 EUR at the central discount rate of 5%, corresponding to a reduction of 29.2% relative to the cumulative undiscounted cost. Under the sensitivity analysis, the cumulative discounted direct cost amounts to 376,225.87 EUR at a 4% discount rate, corresponding to a reduction of 24.7%, and 333,747.84 EUR at a 6% discount rate, corresponding to a reduction of 33.2%.

Overall, the iMERMAID LCC result shows that the economic profile of the enhanced treatment configuration remains influenced by the acquisition and replacement of the additional treatment technologies, particularly EDEN, while the recurring annual costs become more visible in the overall profile than in the previous configuration. The discounted analysis confirms that, over the 20-year horizon considered in the study, the temporal cost profile remains characterized by an upfront capital contribution, lower recurring annual costs, and discrete renewal peaks, while the total present value of the system is moderately sensitive to the discount rate assumption. This result provides the economic basis for comparing the additional cost burden associated with the iMERMAID configuration against the baseline scenario.

Table 6: Direct cost per functional unit of the iMERMAID scenario for Use Case 2 over the 20-year analysis period, expressed in EUR/m3 of treated wastewater under undiscounted conditions and under discount rates of 5%, 4%, and 6%.

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Undiscounted cost	3.83	2.14	2.19	2.23	2.28	2.33	2.50	2.42	2.47	4.54	2.57	2.62	2.67	3.12	2.78	2.84	2.89	2.95	3.01	3.15
Discounted cost at 5%	3.83	2.03	1.98	1.93	1.88	1.82	1.86	1.72	1.67	2.93	1.58	1.53	1.49	1.66	1.40	1.36	1.32	1.29	1.25	1.25
Discounted cost at 4%	3.83	2.05	2.02	1.99	1.95	1.91	1.97	1.84	1.80	3.19	1.73	1.70	1.67	1.88	1.61	1.57	1.54	1.51	1.49	1.50
Discounted cost at 6%	3.83	2.02	1.95	1.87	1.81	1.74	1.76	1.61	1.55	2.69	1.43	1.38	1.33	1.46	1.23	1.18	1.14	1.10	1.05	1.04

3.2.3 Use Case 2 – CBA results

In addition to the direct costs assessed through the Life Cycle Costing, the broader economic interpretation of Use Case 2 considers the monetized environmental costs associated with the baseline and iMERMAID scenarios. These external costs were estimated by combining the environmental impact results obtained in the LCA with environmental price factors derived from the CE Delft Environmental Prices Handbook. In this way, selected environmental burdens of the two treatment configurations are translated into monetary terms and can be interpreted as external costs from a broader societal perspective.

For Use Case 2, the monetization was carried out for the impact categories for which environmental price factors were available in the adopted methodology. As a result, the monetized external cost does not represent the full environmental profile of the baseline and iMERMAID scenarios, but the subset of impact categories that could be expressed in monetary terms on a consistent basis. The categories included in the present assessment are climate change, ozone depletion, ionising radiation, oxidant formation affecting human health, particulate matter formation, acidification, freshwater eutrophication, marine eutrophication, and terrestrial eutrophication. The environmental prices provided by the CE Delft methodology are expressed in EUR2021 and were updated here to EUR 2026 in order to ensure consistency with the economic assumptions adopted in the present study.

Based on this approach, the total monetized environmental cost of the baseline scenario amounts to 1.20 EUR/m3, while the corresponding value for the iMERMAID scenario amounts to 1.91 EUR/m3. In both cases, climate change is the dominant contributor, amounting to 1.13 EUR/m3 in the baseline and 1.74 EUR/m3 in the iMERMAID scenario. The remaining monetized impact categories contribute only marginally to the total. In the baseline scenario, marine eutrophication contributes 0.03 EUR/m3, oxidant formation and acidification each contribute 0.02 EUR/m3, and terrestrial eutrophication contributes 0.01 EUR/m3, while the other priced categories are negligible. In the iMERMAID scenario, marine eutrophication contributes 0.07 EUR/m3, acidification 0.05 EUR/m3, oxidant formation 0.04 EUR/m3, terrestrial eutrophication 0.02 EUR/m3, and freshwater eutrophication 0.01 EUR/m3, whereas the remaining categories remain negligible.

Table 7: Environmental price factors and resulting monetized environmental costs for Use Case 2, expressed in EUR2026 per unit of impact and in EUR/m3 of treated wastewater for the baseline and iMERMAID scenarios

Impact category	Unit	Environmental prices per unit, EU27	Extenalities	
		EUR (2026)	Baseline	iMERMAID
Climate change	kg CO2-eq.	0.159	1.13	1.74
Ozone depletion	kg CFC-11-eq.	35.58348	0.00	0.00
Ionising radiation	kBq U235-eq.	0.000868188	0.00	0.00
Oxidant formation, human health	kg NMVOC-eq.	1.59	0.02	0.04
Particulate matter formation	Disease incidence	934.986	0.00	0.00
Acidification	mol H+-eq.	2.494512	0.02	0.05
Freshwater eutrophication	kg P-eq.	4.573272	0.00	0.01
Marine eutrophication	kg N-eq.	17.4249	0.03	0.07
Terrestrial eutrophication	mol N-eq.	0.4047468	0.01	0.02
TOTAL costs			1.20	1.91

When the monetized environmental externalities are added to the direct annual costs, their influence on the overall economic profile becomes evident in both scenarios. In the baseline scenario, externalities increase the annual cost from 8,727.55 EUR/year to 14,997.04 EUR/year in Year 1, corresponding to an increase of about 71.9%, or from 1.67 EUR/m3 to 2.87 EUR/m3. By Year 20, the annual cost rises from 12,714.40 EUR/year to 21,847.86 EUR/year, which represents a similar increase of about 71.7%, or from 2.44 EUR/m3 to 4.19 EUR/m3. This indicates that, in the baseline configuration, externalities constitute a consistently significant addition to the direct cost profile across the full analysis horizon.

In the iMERMAID scenario, the relative contribution of externalities remains dependent on the annual cost structure, but the updated LCC results show a different balance from the previous configuration. In Year 1, externalities increase the annual cost from 109,426.34 EUR/year to 119,404.72 EUR/year, corresponding to an increase of about 49.9%, or from 3.83 EUR/m3 to 5.74 EUR/m3. This first year profile is still influenced by the initial acquisition of ENIG and EDEN, but the relative importance of externalities is now more visible than in the previous setup because the direct capital burden is lower. A similar pattern is observed in Year 10, where the replacement of EDEN increases the direct annual cost to 114,720.84 EUR/year, while the inclusion of externalities raises the combined annual cost to 126,645.93 EUR/year, corresponding to an increase of about 50.2%, or from 4.54 EUR/m3 to 6.82 EUR/m3.

In years dominated more strongly by recurring operation, the relative contribution of externalities becomes even more pronounced. In Year 2, externalities increase the annual cost from 11,147.20 EUR/year to 21,325.15 EUR/year, corresponding to an increase of about 91.1%, or from 2.14 EUR/m3 to 4.09 EUR/m3. In Year 7, the annual cost rises from 27,617.18 EUR/year to 38,854.45 EUR/year, corresponding to an increase of about 86.0%, or from 2.50 EUR/m3 to 4.65 EUR/m3. In Year 14, the increase is from 31,723.45 EUR/year to 44,631.54 EUR/year, corresponding to about 71.8%, or from 3.12 EUR/m3 to 5.36 EUR/m3. By Year 20, the annual cost rises from 16,015.11 EUR/year to 30,551.72 EUR/year, corresponding to about 85.4%, or from 3.15 EUR/m3 to 5.84 EUR/m3. These results show that, in the updated iMERMAID configuration, monetized environmental costs remain a substantial addition to the annual cost profile not only in the recurring operating years, but also in the years affected by technology acquisition and replacement.

Table 8: Contribution of monetized environmental costs to the baseline and iMERMAID scenarios of Use Case 2, expressed in EUR/m3 and as percentage increase relative to direct costs.

Scenario	Year	Direct cost without externalities (EUR/m3)	Cost with externalities (EUR/m3)	Additional cost due to externalities (EUR/m3)	Increase due to externalities (%)
Baseline	1	1.67	2.87	1.2	71.9
Baseline	20	2.44	4.19	1.75	71.7
iMERMAID	1	3.83	5.74	1.91	49.9
iMERMAID	2	2.14	4.09	1.95	91.1
iMERMAID	7	2.5	4.65	2.15	86
iMERMAID	10	4.54	6.82	2.28	50.2
iMERMAID	14	3.12	5.36	2.24	71.8
iMERMAID	20	3.15	5.84	2.69	85.4

At the same time, the interpretation of these monetized environmental costs requires caution. The increase from 1.20 EUR/m3 in the baseline to 1.91 EUR/m3 in the iMERMAID scenario does not capture the beneficial remediation effect of the treatment train on the pharmaceutical substances of concern discharged in the effluent. This is because the monetization is based only on the subset of LCA impact categories for which price factors are available and therefore does not include the avoided freshwater ecotoxicity associated with the removal of diclofenac, ketoprofen, and ibuprofen from the treated wastewater.

This omission is particularly relevant in Use Case 2, where the handprint assessment shows substantial reductions in the potential freshwater ecotoxicity of the discharged stream. In all three cases, the ecotoxicity burden associated with operation of the treatment train remains minor in comparison with the reduction achieved in the discharged stream. These results indicate that the ENIG and EDEN configuration delivers a substantial remediation benefit, even though this benefit is not reflected in the monetized environmental cost values presented here.

From a broader economic and environmental perspective, the monetized external cost result should therefore be interpreted together with the handprint assessment. The monetized values indicate that the updated iMERMAID scenario introduces additional upstream environmental burdens related to technology deployment and operation, whereas the handprint demonstrates that the same configuration provides a strong reduction in the freshwater ecotoxicity potential of the final effluent. Taken together, these results show that the iMERMAID treatment train entails a higher monetized environmental burden within the priced impact categories, while at the same time delivering a significant positive environmental effect through the removal of pharmaceutical substances of concern. This combined perspective is essential for the subsequent comparison of the baseline and iMERMAID scenarios in the broader economic assessment.

3.2.4 Use Case 2 – Comparative analysis of the economic results of the baseline and iMERMAID scenarios

The comparison of the baseline and iMERMAID scenarios for Use Case 2 shows two different economic profiles. The baseline configuration is characterized by a comparatively stable annual cost structure dominated by recurring labour, electricity, and waste treatment costs. In contrast, the iMERMAID configuration combines the same baseline treatment costs with the additional economic burden associated with the ENIG and EDEN technologies, including initial acquisition, operation, maintenance, and scheduled replacement events. As a result, the comparison is not limited to a simple difference in recurring annual expenditure, but reflects the cost implications of introducing a new treatment train with finite component lifetimes into an already operating wastewater treatment system.

From the perspective of direct life cycle costs, the baseline scenario remains substantially lower than the iMERMAID scenario throughout the assessment horizon. In Year 1, the direct annual cost of the baseline amounts to 8,727.55 EUR/year, or 1.67 EUR/m3, whereas the iMERMAID configuration reaches 109,426.34 EUR/year, or 3.83 EUR/m3. This difference is explained mainly by the initial acquisition of ENIG and EDEN, with EDEN remaining the dominant capital contributor. The first-year incremental direct cost of the iMERMAID configuration therefore amounts to 100,698.79 EUR/year, corresponding to an additional 2.16 EUR/m3 relative to the baseline.

Once the initial acquisition costs are excluded, the comparison becomes more representative of the recurring economic burden associated with operation of the enhanced treatment system. In Year 2, the baseline direct cost amounts to 8,902.10 EUR/year, or 1.71 EUR/m3, whereas the iMERMAID scenario reaches 11,147.20 EUR/year, or 2.14 EUR/m3. This corresponds to an additional direct cost of 2,245.10 EUR/year, or 0.43 EUR/m3, equal to an increase of about 25.2% relative to the baseline. A similar pattern is observed once full utilisation is reached. In Year 5, the baseline direct cost is 1.81 EUR/m3, while the iMERMAID scenario reaches 2.28 EUR/m3, corresponding to an additional 0.47 EUR/m3, or about 26.0%. By Year 20, the direct cost rises from 2.44 EUR/m3 in the baseline to 3.15 EUR/m3 in the iMERMAID configuration, corresponding to an additional 0.71 EUR/m3, or about 26.0%. This gradual increase over time reflects not only the additional recurring burden associated with the ENIG and EDEN train, but also the effect of the inflation assumption applied to all recurring cost items across the analysis horizon.

These values indicate that, apart from the initial investment year and the years involving major technology renewal, the recurring direct cost burden of the iMERMAID scenario is higher than the baseline, but remains within a comparatively moderate range. At the same time, the temporal profile of the iMERMAID scenario is shaped by replacement events that have no equivalent in the baseline configuration. This produces marked cost peaks associated with the lifetime assumptions of the two treatment technologies, namely 7 years for ENIG and 10 years for EDEN. In Year 7, the direct cost rises to 27,617.18 EUR/year, or 2.50 EUR/m3, reflecting the first ENIG replacement. In Year 10, the annual cost reaches 114,720.84 EUR/year, or 4.54 EUR/m3, due to the replacement of EDEN. In Year 14, the annual cost increases again to 31,723.45 EUR/year, or 3.12 EUR/m3, corresponding to the second ENIG renewal. The comparison therefore shows that the economic burden of the iMERMAID scenario is driven by two distinct mechanisms: a moderate increase in recurring annual costs during normal operation, and pronounced peaks associated with technology renewal. From an LCC perspective, this means that the enhanced treatment configuration cannot be interpreted solely through its annual operating cost, since a significant part of its economic profile is determined by the lifetime and replacement schedule of the installed technologies.

The discounted analysis adds an important layer to this interpretation. In a conventional financial appraisal, discounting is used to express future cash flows in present value terms, allowing expenditures occurring at different times to be compared on a consistent basis. In the present study, however, discounting is not used to calculate a profitability-type Net Present Value based on revenues and costs. Rather, it is used to derive the present value of cost streams over the 20-year horizon and thereby support a consistent comparison between the baseline and iMERMAID scenarios. In this context, the discounted outcome should be interpreted as a measure of the time-adjusted economic burden of each scenario, not as an indicator of financial return or investment attractiveness.

This distinction is particularly relevant for Use Case 2, where no direct revenue stream, tariff adjustment, or monetized operational saving is attributed to the implementation of the additional treatment train. Under the current project boundary, the iMERMAID configuration represents an incremental treatment function added to an existing system, and its economic effect is therefore expressed as additional cost rather than as recoverable income. The discounted analysis is useful because it shows how the burden of future recurring costs and replacement events changes when viewed from a present-value perspective. At the same time, the sensitivity analysis is used to evaluate the extent to which the discounted life cycle cost results are influenced by the choice of discount rate. In practical terms, it shows how changes in the discounting assumption affect the present value assigned to future recurring costs and replacement events over the 20-year horizon. A lower discount rate increases the present weight of these future costs, whereas a higher discount rate reduces their contribution to the discounted result. This supports the interpretation of the discounted LCC by clarifying how strongly the result depends on the discounting assumption. The summarised comparison of the baseline scenario and iMERMAID scenario is presented in Figure 8.

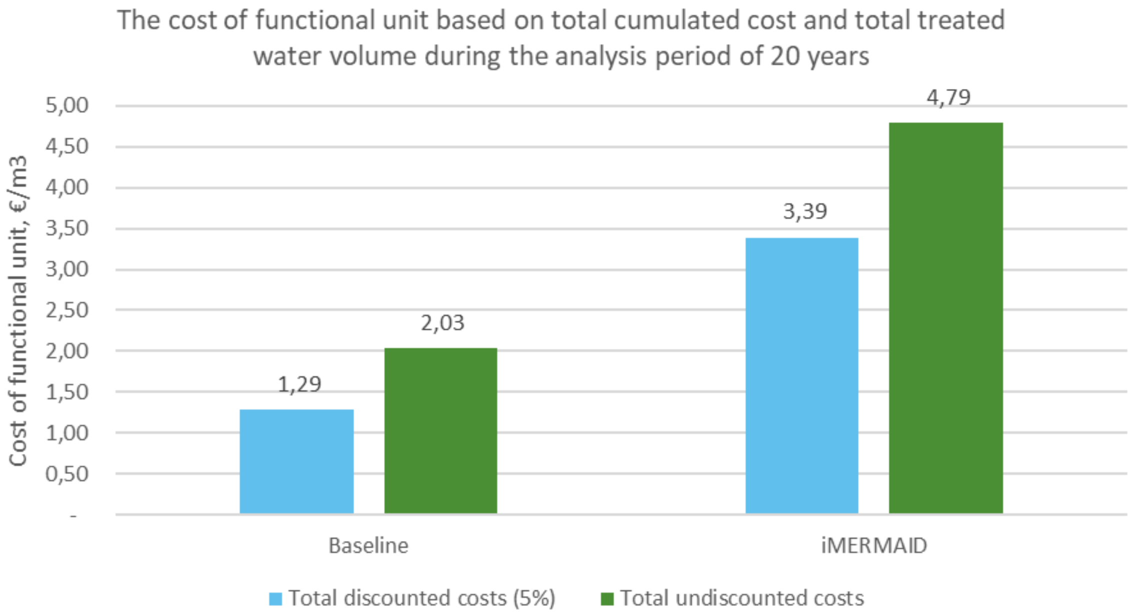

Figure 8: Comparison of summarised LCC results between *Use Case 2* baseline scenario and iMERMAID scenario *over the 20-year analysis period, under an inflation assumption of 2%.*

The monetized environmental cost comparison follows a similar direction. Based on the subset of impact categories for which environmental prices were available, the total monetized environmental cost amounts to 1.20 EUR/m3 for the baseline scenario and 1.91 EUR/m3 for the iMERMAID scenario. This corresponds to an increase of 0.71 EUR/m3, or about 59.2%, in the iMERMAID configuration. In both scenarios, climate change is the dominant contributor, but the iMERMAID configuration shows higher monetized burdens due to the additional manufacturing requirements of ENIG and EDEN and the additional electricity use associated with their operation. The monetized environmental cost analysis therefore confirms that, within the priced impact categories, the iMERMAID scenario imposes a higher external environmental burden than the baseline.

When direct costs and monetized environmental costs are considered together, the analysis focuses on quantifying the additional burden introduced by the monetized environmental costs and on assessing their relative importance within the overall economic profile of each scenario. In the baseline scenario, monetized environmental costs increase the annual cost from 8,727.55 EUR/year to 14,997.04 EUR/year in Year 1, corresponding to an increase of about 71.9%, or from 1.67 EUR/m3 to 2.87 EUR/m3. By Year 20, the annual cost rises from 12,714.40 EUR/year to 21,847.86 EUR/year, which again corresponds to an increase of about 71.7%, or from 2.44 EUR/m3 to 4.19 EUR/m3. This indicates that, in the baseline configuration, monetized environmental costs constitute a consistently significant addition to the direct economic profile across the full horizon.

In the iMERMAID scenario, the relative significance of monetized environmental costs depends strongly on the cost structure of each year. In years dominated by technology acquisition or replacement, the contribution of monetized environmental costs is smaller in relative terms, but still substantial, because the direct annual economic profile is no longer as strongly dominated by capital expenditure as in the previous configuration. In contrast, in years more representative of routine operation, the contribution of monetized environmental costs becomes more significant. In Year 2, the annual cost increases from 11,147.20 EUR/year to 21,325.15 EUR/year, corresponding to an increase of about 91.1%, or from 2.14

EUR/m3 to 4.09 EUR/m3. In Year 7, the annual cost increases from 27,617.18 EUR/year to 38,854.45 EUR/year, corresponding to about 86.0%, or from 2.50 EUR/m3 to 4.65 EUR/m3. In Year 10, the annual cost rises from 114,720.84 EUR/year to 126,645.93 EUR/year, corresponding to about 50.2%, or from 4.54 EUR/m3 to 6.82 EUR/m3. In Year 14, the annual cost increases from 31,723.45 EUR/year to 44,631.54 EUR/year, corresponding to about 71.8%, or from 3.12 EUR/m3 to 5.36 EUR/m3. By Year 20, the annual cost rises from 16,015.11 EUR/year to 30,551.72 EUR/year, corresponding to about 85.4%, or from 3.15 EUR/m3 to 5.84 EUR/m3. These results show that, in the updated iMERMAID configuration, the additional burden associated with monetized environmental costs remains substantial across the full cost profile, becoming particularly pronounced in the years dominated by recurring operation and still remaining relevant in the years affected by acquisition or replacement.

However, the economic comparison also has an important methodological limitation that must be made explicit. The monetized environmental costs do not capture the remediation benefit associated with the removal of the pharmaceutical substances of concern from the discharged effluent. This is a critical point for Use Case 2, because the handprint assessment shows that the ENIG and EDEN treatment train achieves substantial reductions in the potential freshwater ecotoxicity of the discharged stream. The overall reduction reaches about 88% for diclofenac, 75% for ketoprofen, and 96% for ibuprofen, while the freshwater ecotoxicity burden associated with operation of the treatment train remains comparatively minor. In other words, the monetized environmental costs capture the additional burdens associated with manufacturing and operating the new technologies, but they do not monetize the positive environmental effect of reducing the ecotoxicity potential of the treated wastewater.

For this reason, the comparison between scenarios should be interpreted at two levels. From a strict cost perspective, the baseline scenario is economically preferable, since it shows lower direct annual costs, lower discounted cost burden, and lower monetized environmental costs across the assessment horizon. From a broader environmental remediation perspective, however, the iMERMAID scenario provides an additional treatment function that the baseline does not deliver and that is associated with a substantial reduction in freshwater ecotoxicity potential. The economic comparison therefore indicates that the improved treatment performance is achieved at an additional cost, both in direct financial terms and in monetized upstream environmental burdens. At the same time, the handprint results show that this additional cost is linked to a clear and substantial remediation benefit that is not reflected in the monetized environmental values used in the present assessment.

This point is especially important in the current regulatory and economic context. Within the scope of the present study, no direct income is associated with the improved removal of diclofenac, ketoprofen, and ibuprofen, and no revenue stream is assigned to the introduction of the ENIG and EDEN treatment train. The analysis therefore reflects the current project boundary as a cost-of-function assessment rather than a revenue-generating investment appraisal. In this context, a broader policy and market environment may evolve, including the possible development of extended producer responsibility schemes for pharmaceuticals and cosmetics. If future regulatory frameworks, producer-responsibility mechanisms, or service-payment arrangements were to attribute economic value to the improved removal of such substances, the additional treatment step could, in principle, become associated with a recoverable income stream or avoided compliance costs. Under the current study assumptions, however, no such inflow is considered, and the enhanced treatment train remains an additional cost borne in exchange for improved treatment performance.

Overall, the comparison of the baseline and iMERMAID scenarios for Use Case 2 shows that the enhanced treatment configuration imposes a higher economic burden over the 20-year analysis horizon, driven by the acquisition and renewal of ENIG and EDEN, additional electricity demand, and higher monetized environmental costs within the priced impact categories. At the same time, the same configuration delivers a substantial reduction in the freshwater ecotoxicity potential of the discharged effluent, which constitutes the main environmental added value of the treatment train. The economic interpretation of Use Case 2 should therefore not be reduced to a simple cost minimization exercise. Rather, it should be understood as the comparison of a lower-cost conventional treatment configuration with a higher-cost enhanced treatment configuration that provides an additional and environmentally relevant remediation function, the value of which is only partially captured within the present economic boundary.

3.3 Use Case 3

The baseline scenario of Use Case 3 was set at the municipal wastewater treatment plant (WWTP) Brandizzo, located in the Metropolitan Area of Turin (approximately 20 km north-east of Turin). It serves a population of 9.000 equivalent inhabitants and treats both domestic and industrial wastewater. Specifically, industrial wastewater is derived from metal treatment, coating industry and car accessories factory. Brandizzo WWTP is owned and operated by Societa Metropolitana Acque Torino (SMAT).

The contaminants for emerging concerns (CoEC) in Use Case 3 were heavy metals in wastewater. Thus, Use Case 3 focused on the removal of selected three heavy metals from wastewater (Cu, Zn and Al) using the 4D Scavenger technology.

The iMERMAID scenario added 4D Scavenger technology, which is aimed to remove metails from remove metals from industrial and municipal wastewater, after the baseline system. 4D Scavenger technology is based on 3D-printed, porous, thick filters, which selectively attach dissolved metals from wastewater to the filter surface. The 4D Scavenger system has three operation modes. The first operation mode is the removal of the target metals from the wastewater by attaching them to the filter surface. Before all vacant spots on the filter surfaces are fulfilled, the operation mode is changed to evaluation mode. In the evaluation mode, the attached metals are detached from filter surface by eluent solution (sulphuric acid). Eluent solution removes metals from the filter surface. Regeneration mode follows the evaluation mode. In the regeneration mode, the filter material is regenerated by rinsing it with regeneration solution (sodium hydroxide). Between the different operation modes the reactor is rinsed with water.

The removal efficiency of heavy metals was to be demonstrated in the iMERMAID project. As the demonstration faced several challenges which affected the performance of the scavenger, Weeefiner simulated the performance of the scavenger based on another application in Finland and the results were applied to iMERMAID Use Case 3.

The baseline scenario shows the costs associated with the operation of the existing Brandizzo wastewater treatment plant. In the iMERMAID scenario, the life cycle cost structure includes the baseline operation costs together with the additional costs caused by 4D Scavenger technology. The additional costs of 4D Scavenger technology consists of the purchase of equipment, operation during the use phase, maintenance, replacement of shorter-lived components, and costs related to end-of-life phase.

The comparative results of the assessment are presented in the following sections. The technical and economic parameters and mass balances used the life cycle costing are presented in Annex 1. The selected functional unit was 1 m^3 of water at the inlet of new technology.

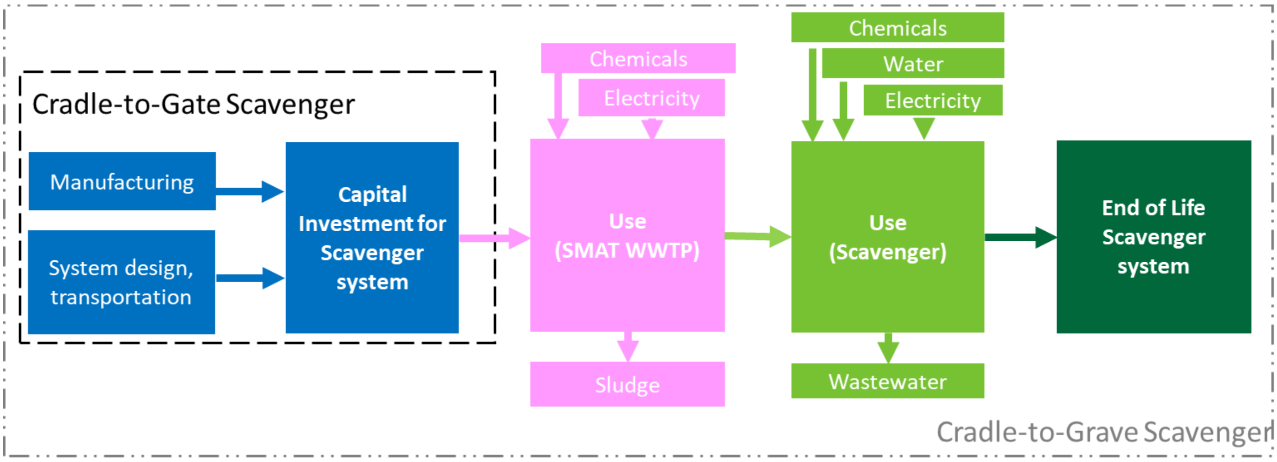

Figure 9: System boundaries for Use Case 3.

3.3.1 Use Case 3 - Baseline LCC results

Use Case 3 baseline scenario included operating costs of the Brandizzo wastewater treatment plant based on activated sludge processing. The operating cost of the baseline scenario includes both the direct costs to treatment (reagents, energy costs, personnel, disposal of products generated by the process, etc.) and costs related to ancillary activities (e.g., fees payable to third parties, activities carried out for the maintenance of the facilities present in the plant).

The approach was selected because the main interest was in the iMERMAID scenario. However, also the long operational lifetime of the wastewater treatment plant causes the original investment cost to become insignificant in the long run. Similarly, instead of end-of-life phase defined at some point in the future, the continuous improvement and maintenance keep the plant in operation. Thus begin-of-life and end-of-life were excluded from the analysis because their impact was considered negligible.

Capacity of the WWTP plant is 86 m^3/h, resulting in annual flow rate of 750 000 m^3/a. The estimated operating cost was 0.59 EUR/m^3 treated water, resulting in annual cost of 441 000 EUR in Year 1. At the end of the analysed period, Year 20, the annual cost has increased due to assumed annual 2% inflation to 642 000 EUR, corresponding to functional unit cost of 0.85 EUR/m^3 treated water.

Across the full 20-year analysis period, the cumulative undiscounted cost amounts to 10.7 MEUR. Considering the volume of treated water during the analysis period (15 million m^3), the average cost per functional unit during the analysis period is 0.71 EUR/m^3. When using the recommended discount rate 5%, the corresponding discounted cumulative cost over the analysis period was 6.8 MEUR and the average cost per functional unit 0.45 EUR/m^3. A sensitivity analysis was performed for the discount rate from 4% to 6%, resulting in cumulated cost from 7.4 to 6.3 MEUR and in cost per functional unit from 0.49 to 0.42 EUR/m^3, respectively. The results are summarised in Table 9.

Table 9: LCC results for the Use Case 3 baseline scenario over the 20-year analysis period, under an inflation assumption of 2%.

For the selected analysis period of 20 a		Discount rate %	Cumulative cost MEUR	Cost per functional unit EUR/m^3 water
Total undiscounted costs		0 %	10.7	0.71
Total discounted costs (Net present costs, NPC)	Sensitivity low	4 %	7.4	0.49
	Baseline	**5 %**	6.8	0.45
	Sensitivity high	6 %	6.3	0.42

Both undiscounted and discounted cumulative cost curves over the analysed period are presented in Figure 10 to illustrate the effect of discounting.

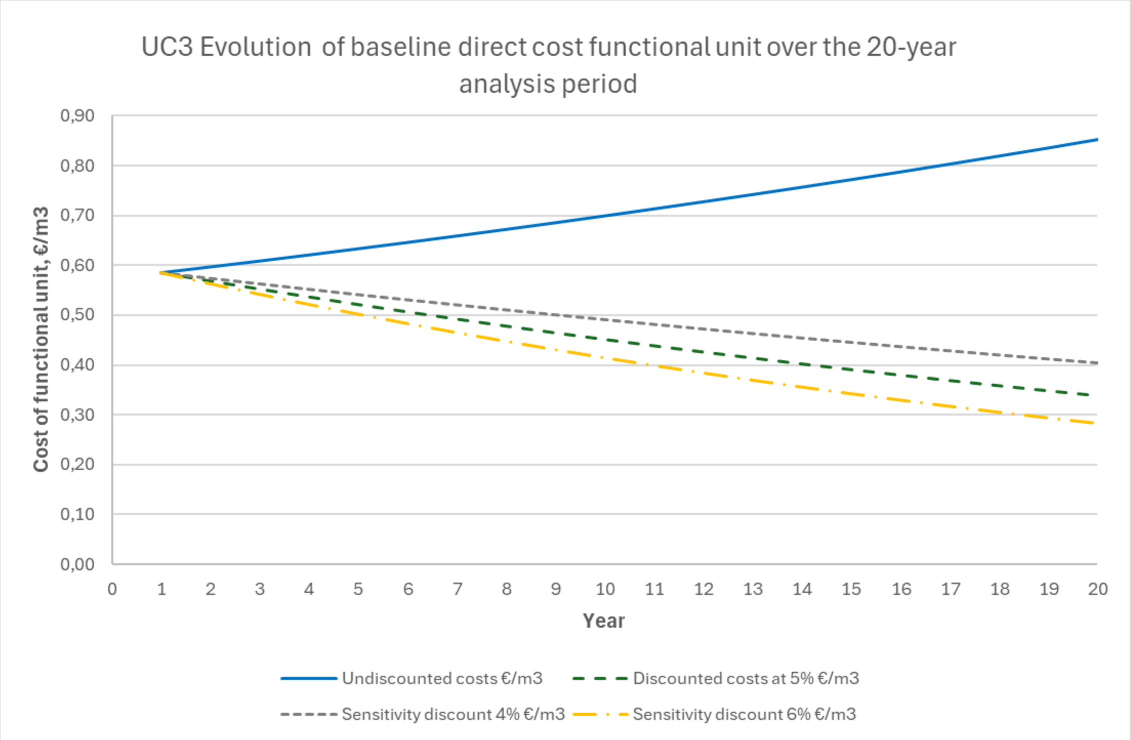

Figure 10: Evolution of the direct cost per functional unit of the baseline scenario for Use Case 3 over the 20-year analysis period, expressed in EUR/m³ of treated wastewater. The figure compares the undiscounted annual cost profile with the discounted annual cost profiles obtained using discount rates of 4%, 5%, and 6%, under an inflation assumption of 2%.

3.3.2 Use Case 3 - iMERMAID LCC results

The iMERMAID scenario of Use Case 3 combines the operation costs of the baseline operation, Brandizzo wastewater treatment plant based on activated sludge processing, with the life cycle costs of the additional heavy metal removal by the new 4D Scavenger technology by Weeefiner Oy. The analysis was performed utilising the same assumptions which were used in the analysis for the baseline scenario: 20-year analysis period, 2% inflation and discount rate of 5% with sensitivity range from 4 to 6%.

The 4D Scavenger was designed to process the volume of treated water from the Brandizzo wastewater treatment plant, 86 m^3/h. However, at the first year the 4D Scavenger system was to be installed, taking 6 months, and after the installation the annual operational availability of the system during the first 3.5 years was estimated to be 98%. The lifetime of the 4D Scavenger system was assumed to be 12 years, after which the system was replaced with a new one. The filters inside the 4D Scavenger were assumed to be changed every second year, and old filters were disposed as waste (incineration of non-hazardous waste). Filter changing process was assumed to be conducted in such a way that no downtime of the 4D Scavenger was required.

The cost structure of the 4DScavenger technology include during the analysed period initial investment cost of the system at the begin-of-life, operational costs at the use phase and at the end-of-life both the dismantling cost of the existing equipment and purchase cost of the retrofit. The investment cost was assumed to be turnkey price and additional cost were considered negligible. Use phase costs included all operation costs related to 4D scavenger: chemicals (sulphuric acid and sodium hydroxide), changing of the filters, electricity, waste (acid water solution with increased heavy metal content, used filters) and other maintenance cost. Additional labour cost to the baseline personnel was not considered necessary due to automation. Cost of changing filters included also their installation. End-of-life cost included estimation of labour required for dismantling and disposing or recycling the materials. Steel and WEEE residues were considered for recycling process with a revenue, whereas PVC materials were assumed to incineration of non-hazardous waste. Annual inflation was added to all costs.

The annual costs and cumulative costs were calculated for the selected analysis period, 20 years. All costs were treated with the inflation factor. Both undiscounted costs and discounted costs were calculated and summed up to the results of the iMERMAID scenario. For the total treated water volume of 14.6 million m^3, the cost of the functional unit over the analysed period was 1.32 EUR/m^3 based on total undiscounted cumulated costs of 19.4 MEUR and 0.85 EUR/m^3 based on total discounted cumulated costs of 12.5 MEUR. The summarised results are presented in Table 10 with sensitivities to discount rate.

Table 10: LCC results for the Use Case 3 iMERMAID scenario over the 20-year analysis period, under an inflation assumption of 2%.

For the analysis period of 20 a		Discount rate %	Cumulative cost MEUR	Cost per functional unit EUR/m^3
Total undiscounted costs		0 %	19.4	1.32
Total discounted costs (Net present costs, NPC)	Sensitivity low	4 %	13.5	0.92
	Baseline	5 %	12.5	0.85
	Sensitivity high	6 %	11.6	0.79

A detailed look to the yearly costs per functional unit is presented in Table 11. The annual cost per functional unit in Table 11 show a high cost peak at the year 1 (4.35 EUR/m^3) due to the initial investment for the 4D scavenger system (1.03 MEUR) and significantly shorter annual operation time, 49% or 4292 h of the year. In the second year the annual cost per functional unit decreases to 0.97 EUR/m^3 based on undiscounted cost or 0.92 EUR/m^3 based on discounted cost. Another cost peak per functional unit during the analysed period, 2.96 EUR/m^3 based on undiscounted costs or 1.65 EUR/m^3 based on discounted costs, is shown in year 13. During year 13 a retrofit occurs, and both end-of-life costs of the old system and the beginning of life costs of a new system are realised.

Table 11: Direct cost per functional unit of the iMERMAID scenario for Use Case 3 over the 20-year analysis period, expressed in EUR/m^3 of treated wastewater under undiscounted conditions and under discount rates of 5%, 4%, and 6%.

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Undiscounted cost	4.35	0.97	0.99	1.01	1.01	1.03	1.06	1.08	1.10	1.12	1.14	1.16	2.96	1.21	1.24	1.26	1.29	1.31	1.34	1.36
Discounted cost at 5%	4.35	0.92	0.90	0.87	0.83	0.81	0.79	0.76	0.74	0.72	0.70	0.68	1.65	0.64	0.62	0.61	0.59	0.57	0.56	0.54
Discounted cost at 4%	4.35	0.93	0.91	0.89	0.87	0.85	0.83	0.82	0.80	0.79	0.77	0.76	1.85	0.73	0.71	0.70	0.69	0.67	0.66	0.65
Discounted cost at 6%	4.35	0.91	0.88	0.84	0.80	0.77	0.74	0.72	0.69	0.66	0.64	0.61	1.47	0.57	0.55	0.53	0.51	0.49	0.47	0.45

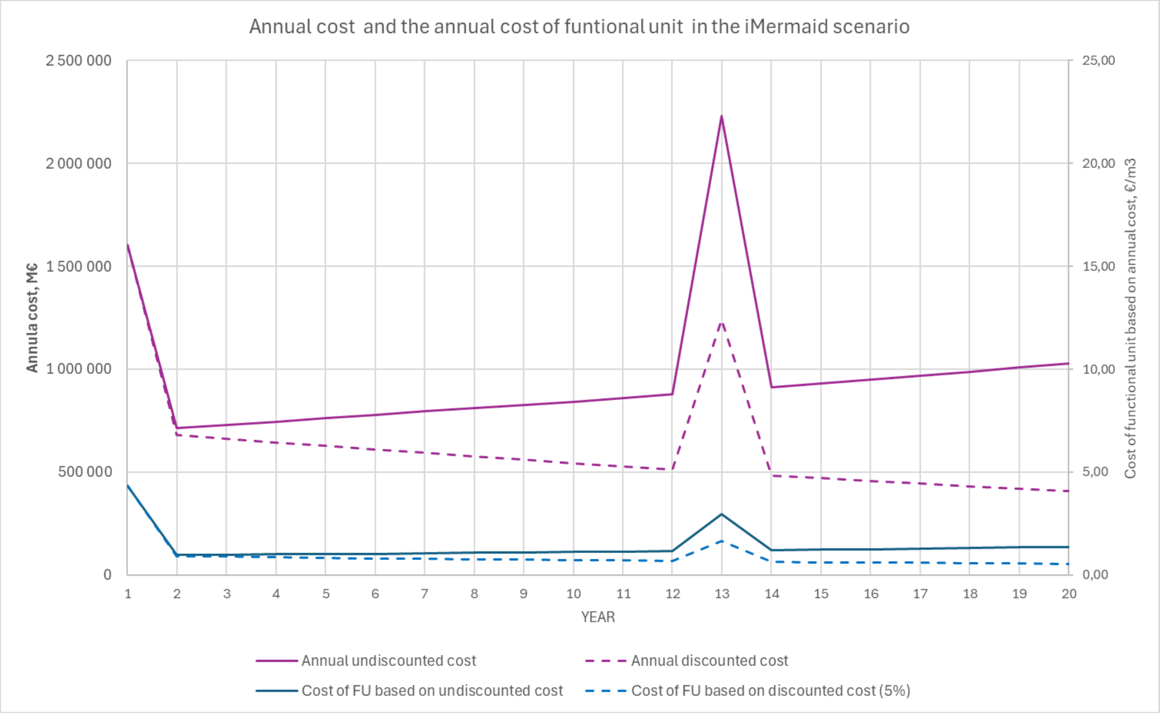

Figure 11: Annual undiscounted (direct) cost, annual discounted cost (at 5% discount rate), annual cost of functional unit based on a) undiscounted cost and b) discounted cost during the 20-year analysis period for Use Case 3 iMERMAID scenario.

Cost distribution is presented in Figure 12 for the selected years, taking into consideration annual inflation but not discounting. Year 1 represents the start-up year of iMERMAID scenario, Year 13 shows the retrofit year of the 4D scavenger technology, and Year 14 represents a basic year. The figure illustrates the cost escalation by inflation during the years. It also shows the cost distribution during a basic year, Year 14 as an example, in which 62% of total cost consists of the baseline WWTP costs, 18% of disposal cost for acid wastewater rich in heavy metals, and 13% of costs allocated to annual filter material changing. Other costs categories in Year 14 are below 2% of total cost, most significant of them chemical costs, electricity cost and maintenance cost.

Figure 12: Annual direct cost distribution for selected years in the 20-year analysis period for Use Case 3 iMERMAID scenario (considering annual 2% inflation).

A sensitivity analysis was performed for the iMERMAID scenario in Use Case 3. Parameters selected to the sensitivity analysis were all related to the 4d scavenger technology and included those which were considered having highest uncertainties: investment cost, filter material changing cost, sulphuric acid cost, sodium hydroxide cost, wastewater disposal cost and required additional personnel due to 4D scavenger. The effect of each parameter was analysed separately.

The results of the sensitivity analysis to the cost of the functional unit over the 20 years analysis period are presented in Figure 13. The results showed that sensitivity to the wastewater cost had highest effect to the results. Other parameters had significantly lower sensitivity to the cost of the functional unit.

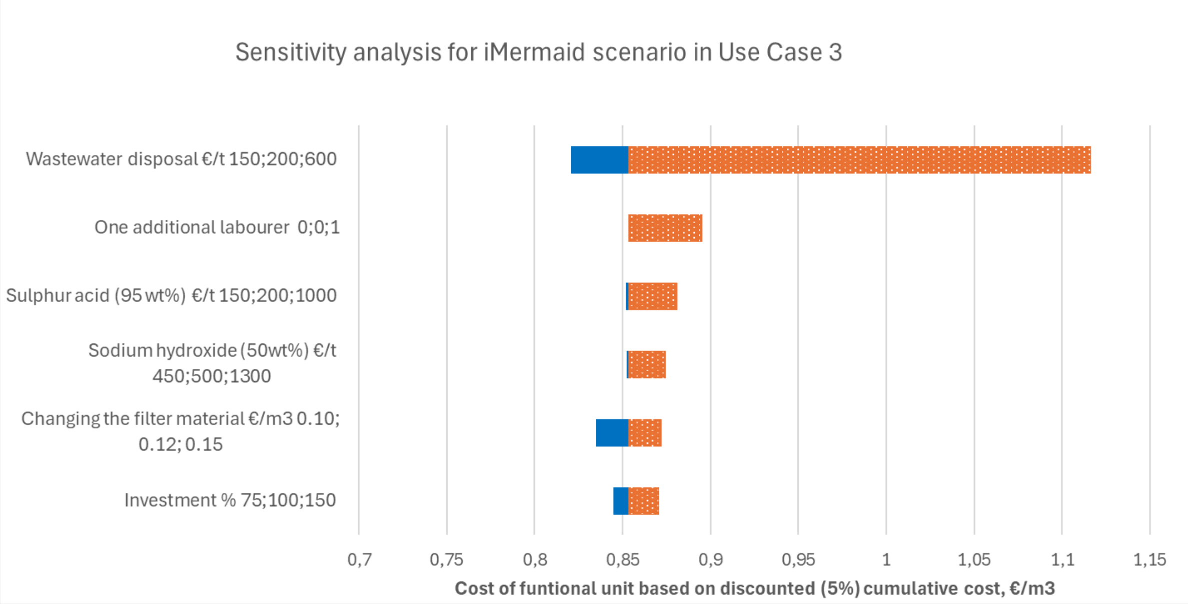

Figure 13: Sensitivity analysis of functional unit cost based on total discounted (5% discount rate) cumulative cost (NPC) and total treated water volume during the analysis period of 20 years for Use Case 3 iMERMAID scenario.

The baseline wastewater cost was based on Italian cost of landfilling hazardous waste from year 2021. However, the exact cost may depend on the volumes and composition, and thus the cost has high uncertainty. For that reason, the selected maximum value of the wastewater cost in the sensitivity analysis was set to 600 EUR/t. It was based on the realised wastewater cost at after the demonstration, 675 EUR/t, with assumption that somewhat lower cost may be negotiable. In case the wastewater cost will be at the higher end of the sensitivity range, considering additional treatment or concentration at the site prior disposal is recommended. The cost of the functional unit increased 31% when adding an additional operator cost.

In the LCC calculation, it was assumed that the operation of 4D scavenger does not require no additional personnel at the site due to automation. The impact of an addition of one operator cost per year was analysed in the sensitivity analysis. The cost of the functional unit increased 5% when adding an additional operator cost.

The cost of 5% sulphuric acid was 120 EUR/t and 5% sodium hydroxide was 180 EUR/t for demonstration. The chemical costs are assumed to drop significantly economically the most feasible acid/base concentration is selected, if needed dilution takes place at site and if the contract of annual volumes is negotiated. In addition, economically the most feasible should be analysed. Thus, the 95wt % sulphuric acid cost was set to 200 EUR/t in the assessment and 50 wt% sodium hydroxide cost 500 EUR/t, which are somewhat higher than very high volume market prices. However, in sensitivity analysis the impact of higher chemical prices was evaluated, cost range for 95% sulphuric acid from 150 to 1000 EUR/t and for 50% sodium hydroxide from 450 to 1300 EUR/t. The cost of the functional unit increased 3% higher sulphuric acid cost and 2% with higher sodium hydroxide cost.

Investment cost for emerging technologies is often more an estimate. Thus, the sensitivity analysis included the investment cost range from 75% to 150% of the original estimate, resulting the cost of the functional unit ranges from -1% to +2%. Similarly, as for investment estimate, estimated filter changing cost was varied. The range was set from -20% to +20%, resulting the cost of the functional unit ranges from -2% to +2%.

3.3.3 Use Case 3 - Cost-benefit analysis

The contaminants for emerging concerns (CoEC) to be removed using the 4D Scavenger technology in Use Case 3 were heavy metals in wastewater. Specifically, the measured metals were Cu, Zn and Al. Copper and zinc are essential nutrients to cells at low concentration but toxic to aquatic/marine organisms at higher concentrations. Aluminium is known to be toxic at higher concentration but not to have biological function. The contents of these metals in the treated water exiting the Brandizzo wastewater treatment plant is in compliance with current regulations. However, the aim of iMERMAID was to assess the benefit of more intense purification. For this reason, there is environmental benefit but no clear monetary benefit for the additional removal far as the current regulation remains and thus the analysis included only the additional costs related to the enhanced purification.

In addition to the economic cost calculation, the analysis was broadened to include monetarised externalities or in other words environmental pricing, based on the CE Delft's Environmental Prices Handbook 2024: EU27 version. Although environmental quality has no explicit market price, environmental pricing aims to make environmental externalities such as impacts on human health, ecosystems, buildings, and well-being comparable with financial costs and benefits. In other words, it represents the loss of social welfare resulting from the environmental impact into the environment. Environmental prices are calculated values, derived from scientific cause–effect models linking emissions to impacts, and economic valuation methods that convert those impacts into monetary welfare losses. In practise, environmental pricing allocates a monetary value to environmental impact, expressed as a cost per unit of emission. The environmental prices in CE Delft publication are in euros of year 2021 and thus they were updated to year 2026 euros.

Monetarisation of externalities was limited in Use Case 3 to impact categories for which environmental price factors were available in the adopted methodology. Consequently, the reported monetised external costs represent only a partial environmental profile of the baseline and iMERMAID scenarios. It covers only impact categories that can be consistently translated into monetary values. These categories are climate change, ozone depletion, ionising radiation, oxidant formation affecting human health, particulate matter formation, acidification, freshwater eutrophication, marine eutrophication, and terrestrial eutrophication.

The resulted monetised environmental cost is presented in Table 12 and in Figure 14 for both the baseline scenario and the iMERMAID scenario. The cost of monetised externalities per functional unit is 0.13 EUR/m^3 for the baseline scenario and 0.17 for the iMERMAID scenario. The highest contributor is climate change for both the baseline scenario (95%) and the iMERMAID scenario (91%). The other significant contributors are marine eutrophication (the baseline scenario 2.6% and the iMERMAID scenario 3.8%), acidification (the baseline scenario 1.3% and the iMERMAID scenario 2.9%), oxidant formation (human health) (the baseline scenario 0.7% and the iMERMAID scenario 1.1%) and terrestrial eutrophication (the baseline scenario 0.4% and the iMERMAID scenario 0.6%). Other categories have negligible effect to the total cost.

Table 12: Environmental price factors and resulting monetized environmental costs for Use Case 3, expressed in EUR2026 per unit of impact and in EUR/m³ of treated wastewater for the baseline and iMERMAID scenarios

Impact category	Unit	Environmental prices per unit, EU27	Externalities	
		EUR (2026)	Baseline	iMERMAID
Climate change	kg CO2-eq.	0.159	0,13	0,15
Ozone depletion	kg CFC-11-eq.	35.58348	0,00	0,00
Ionising radiation	kBq U235-eq.	0.000868188	0,00	0,00
Oxidant formation, human health	kg NMVOC-eq.	1.59	0,00	0,00
Particulate matter formation	Disease incidence	934.986	0,00	0,00
Acidification	mol H+-eq.	2.494512	0,00	0,00
Freshwater eutrophication	kg P-eq.	4.573272	0,00	0,00
Marine eutrophication	kg N-eq.	17.4249	0,00	0,01
Terrestrial eutrophication	mol N-eq.	0.4047468	0,00	0,00
TOTAL costs			0,13	0,17

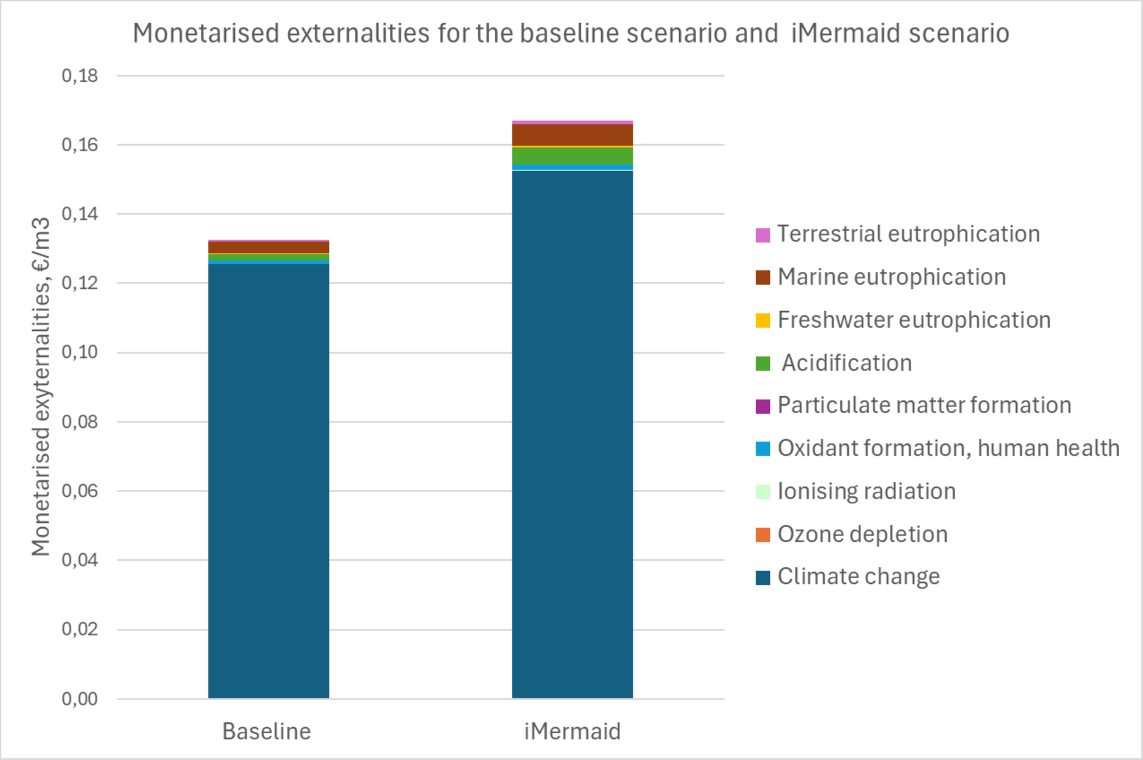

Figure 14: Distribution of monetized environmental costs for Use Case 3, expressed in EUR2026 per unit of impact and in EUR/m³ of treated wastewater for the baseline and iMERMAID scenarios.

To evaluate the results of monetarised externalities, they were added to the conventional LCC results. The combined results are presented in Table 13 for selected years during the analysed period. In the baseline scenario, the annual cost increased from 0.44 MEUR to 0.54 MEUR when adding externalities at the Year

1 and from 0.64 MEUR to 0.79 MEUR at Year 20. Similarly, the cost of the functional unit increased when adding externalities 23%, from 0.59 EUR/m^3 to 0.72 EUR/m^3 in Year 1. At the Year 20, the cost of the functional unit increased when adding externalities from 0.85 EUR/m^3 to 0.72 EUR/m^3.

In the iMERMAID scenario the yearly variance is higher due to the investment and retrofit costs at the Year 1 and again at the Year 13. The annual cost increased from 1.60 MEUR to 1.72 MEUR when adding externalities at the Year 1 and from 2.23 MEUR to 2.39MEUR at Year 13. The cost of the functional unit increased when adding externalities 7.0%, from 4.35 EUR/m^3 to 4.65 EUR/m^3 at the Year 1 and 7.2%, from 2.96 EUR/m^3 to 3.17 EUR/m^3 at the Year 13. The significantly higher cost of the functional unit at the year 1 in comparison to the cost at the year 13 derived from the significantly shorter annual operation (49% of the year versus 100%) due to the initial installation of the system.

The increase of monetarised externalities is higher during those years in which no additional investment is required, 18%. The annual cost increased from 0.71 MEUR to 0.84 MEUR when adding externalities at the Year 2 and from 1.03 MEUR to 1.21 MEUR at Year 20. The cost of the functional unit increased when adding externalities 7.0%, from 4.35 EUR/m^3 to 4.65 EUR/m^3 at the Year 2 and 7.2%, from 2.96 EUR/m^3 to 3.17 EUR/m^3 at the Year 20.

Table 13: Contribution of monetized environmental costs to the baseline and iMERMAID scenarios of Use Case 3, expressed in EUR/m^3 and as percentage increase relative to direct costs.

Scenario	Year	Direct cost without externalities (EUR/m^3)	Cost with externalities (EUR/m^3)	Additional cost due to externalities (EUR/m^3)	Increase due to externalities (%)
Baseline	1	0.59	0.72	0.13	23 %
Baseline	20	0.85	1.05	0.19	23 %
iMERMAID	1	4.35	4.65	0.31	7.0 %
iMERMAID	2	0.97	1.14	0.17	18 %
iMERMAID	7	1.06	1.24	0.19	18 %
iMERMAID	10	1.12	1.32	0.20	18 %
iMERMAID	13	2.96	3.17	0.21	7.2 %
iMERMAID	20	1.36	1.61	0.24	18 %

A summarised comparison of the conventional LCC results and the LCC results with addition of monetarised externalities are presented in Table 14. Adding the monetarised externalities to the baseline scenario increased it 23%, to the total undiscounted cost of 13.1 MEUR and to the cost per functional unit of 0.87 EUR/m^3. In case of the iMERMAID scenario, the addition of monetarised externalities caused 16% increase in cost, to the total undiscounted cost of 22.4 MEUR and to the cost per functional unit of 1.53 EUR/m^3.

Table 14: Undiscounted (direct) costs with and without externalities for the Use Case 3 baseline scenario over the 20-year analysis period, under an inflation assumption of 2%.

For the analysis period of 20 years	Cumulative cost	Cost per functional unit
	MEUR	EUR/m^3
Baseline		
Total undiscounted costs	10.7	0.71
Total undiscounted costs incl. externalities	13.1	0.87
iMERMAID scenario		
Total undiscounted costs	19.4	1.32
Total undiscounted costs incl. externalities	22.4	1.53

There are however limitations which should be taken into consideration when viewing these results which contain monetised externalities. The selected method used here does not include all LCA impact categories. For example, freshwater ecotoxicity is not included in the monetised impact categories for the adopted methodology. In the sustainability impact assessment of the iMERMAID scenario with 4D scavenger (Deliverable 1.4), potential for beneficial environmental impact was indicated in freshwater ecotoxicity due to the decrease in the concentration of Cu, Al and Zn. A total remediation performance based on the metal inlet and outlet concentrations (Al, Zn, Cu) was 1.87 CTUe/m^3. Considering the total handprint assessment, or in other words combining the beneficial impact of the remediation performance and the ecotoxicity footprint of the of the SMAT plant operation and of the Scavenger (production, supporting components, transportation and installation, use and end-of-life), the potential of the 4D Scavenger (iMERMAID scenario) lead to an overall reduction of the ecotoxicity footprint by 37%. This beneficial potential was not monetised here, because freshwater ecotoxicity was not included in the limited impact categories for which environmental price factors are available. Thus, these results suggest that 4D Scavenger may provide substantial remediation benefit although this effect is not shown in the monetized environmental cost indicator presented here and that that the monetized external cost result should therefore be interpreted together with the handprint assessment.

3.3.4 Use Case 3 – Comparative analysis of the economic results of the baseline and iMERMAID scenarios

The assessment evaluated life cycle costs (LCC) of adding an advanced heavy-metal removal technology, 4D Scavenger by Weeefiner, to the existing Brandizzo wastewater treatment plant in Italy. The baseline scenario considered only operating costs of the Brandizzo plant, since the plant's original investment cost and end-of-life phases were deemed negligible due to long operational lifetime. In the iMERMAID scenario 4D scavenger was added at treated water outlet stream of the wastewater treatment plant for enhanced removal of heavy metals, and a combined the life cycle cost of baseline WWTP operation with the 4D Scavenger system were analysed for the analysed period of 20 years. This cost includes initial investment, operational costs (chemicals, electricity, filter changes, waste disposal, maintenance), and system replacement after a 12-year lifetime.

For the baseline scenario the cost of the functional unit was 0.59 EUR/m^3, and total undiscounted cost 0.44 MEUR in Year 1 with a treatment capacity of 86 m^3/h (750,000 m^3/a). The total undiscounted cost for the iMERMAID scenario was 1.60 MEUR and the cost of the functional unit 4.35 EUR/m^3. The higher total undiscounted cost in comparison to the baseline scenario is explained by the initial investment cost of the

4D scavenger system, and the very high cost of the functional unit due to investment and lower utilisation rate (operation hours 4292 h/a) due to the installation period.

In case of the baseline scenario, the cost of the functional unit increasing to 0.60 EUR/m³ at year 2 due to a 2% inflation assumption and continues raising steadily to 0.85 EUR/m³ by Year 20. Over the 20-year period, annual undiscounted cost increases to 0.64 MEUR, while at 5% discount rate discounted cost decreases to 0.25 MEUR. In comparison, for the iMERMAID scenario the cost of the functional unit decreased to 0.97 EUR/m³ and the annual undiscounted cost to 0.71MEUR at year 2, and after that they increased steadily until another peak cost (2.96 EUR/m³, 2.29 MEUR) occurred at year 13, when the 4D scavenger system is replaced. The cumulative cost comparison of the baseline scenario and the iMERMAID scenario is illustrated in *Figure 15*.

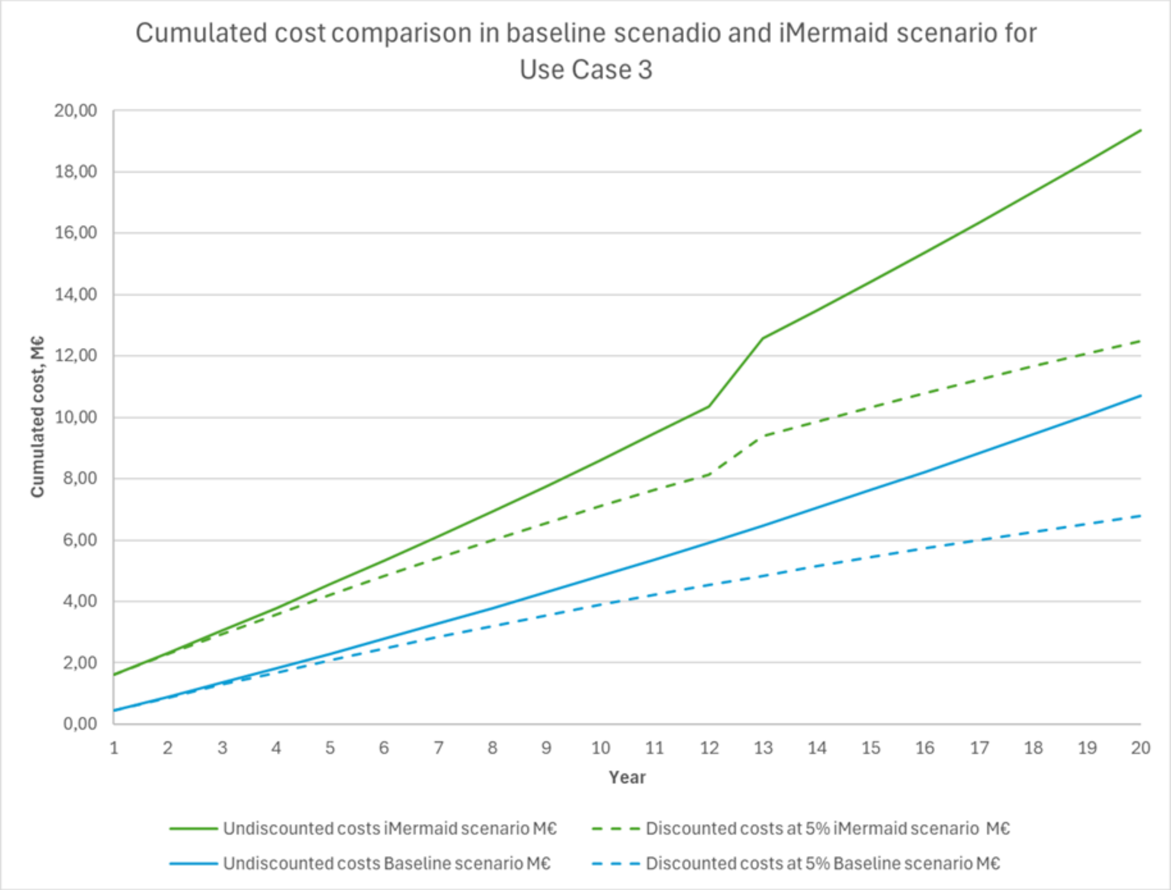

Figure 15: Comparison of undiscounted (direct) and discounted cumulative costs of Baseline scenario and iMERMAID scenario for Use Case 3.

Over 20 years, the total cumulative undiscounted costs reach 10.7 MEUR for baseline scenario and 19.4 MEUR for iMERMAID scenario, while discounted costs amount to 6.8 MEUR and 12.5 MEUR, respectively. The cost of the functional unit based on total undiscounted cumulative cost versus total treated water volume was for the baseline scenario 0.71 EUR/m³ and for the iMERMAID scenario 1.32 EUR/m³. Similarly, the cost of the functional unit based on total at 5% discount rate discounted cumulative cost versus total treated water volume was for the baseline scenario 0.45 EUR/m³ and for the iMERMAID scenario 0.85 EUR/m³.

Cumulative cost distribution over on the 20-year analysis period, calculated per functional unit, is presented in Figure 16. Figure 16 shows that the most significant cost factors are disposal of the wastewater rich in heavy metals, changing the filter material in Scavenger and the investment cost of the scavenger.

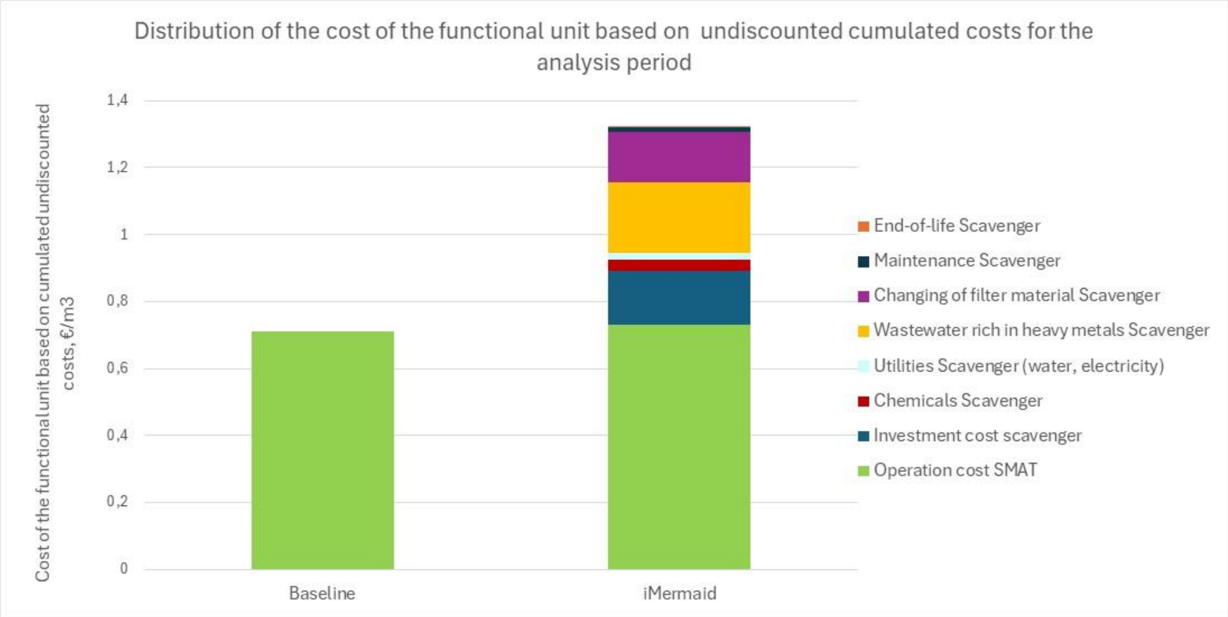

Figure 16: Cumulative cost distribution of Use Case 3 over the 20-year analysis period, calculated per functional unit.

Enhanced heavy-metal remediation is not required under current regulation. The metal concentration in the wastewater is too low economically feasible for metal recovery. Thus, no direct monetary benefit in terms of fees avoided or resources recovered is obtained by the enhanced metal removal. The benefits of the iMERMAID scenario are primarily environmental via improved quality of treated water and enhanced remediation to Mediterranean Sea. To monetarise externalities, a monetised environmental cost comparison was conducted using CE Delft environmental price factors. The assessment was based on the limited subset of environmental impact categories, which were available for the utilised LCA methodology. For the baseline scenario the monetised environmental cost amounted 0.13 EUR/m³ and for the iMERMAID scenario 26% higher, 0.17 EUR/m³. Climate change was clearly dominating in both the baseline scenario (95%) and in the iMERMAID scenario (91%), however the iMERMAID scenario increased notably the share of acidification and marine eutrophication. When the externalities were added to the total undiscounted cost, the cost increased for the baseline scenario to 13.1 MEUR (0.87 EUR/m³) and for the iMERMAID scenario to 22.4 MEUR (1.53 EUR/m³). The summarised comparison of the baseline scenario and iMERMAID scenario is presented in Figure 17 and in Table 15.

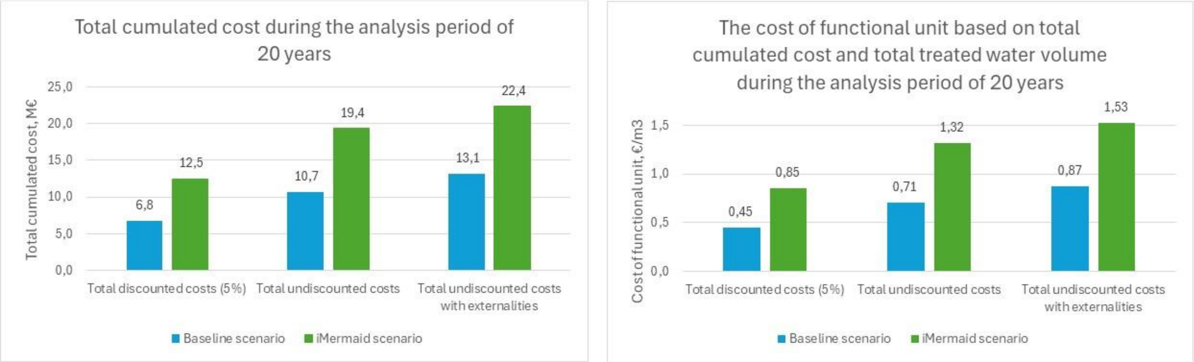

Figure 17: Comparison of summarised LCC results between *Use Case 3* baseline scenario and iMERMAID scenario *over the 20-year analysis period, under an inflation assumption of 2%.*

Table 15: Comparison of summarised LCC results between Use Case 3 baseline scenario and iMERMAID scenario over the 20-year analysis period, under an inflation assumption of 2%.

For analysed period of 20 years	Unit	Baseline scenario	iMERMAID scenario
Total undiscounted costs	MEUR	10.7	19.4
- Cost per functional unit	EUR/m^3	0.71	1.32
Total discounted costs (5% discount rate)	MEUR	6.8	12.5
- Cost per functional unit	EUR/m^3	0.45	0.85
Monetarised externalities	EUR/m^3	0.13	0.17
Total undiscounted costs with externalities	MEUR	13.1	22.4
- Cost per functional unit	EUR/m^3	0.87	1.53

However, the reduced heavy metal emission, which is an important benefit of the iMERMAID scenario, is not shown in the monetised externalities because freshwater ecotoxicity was not included in the available monetised impact categories. This is significant for Use Case 3, as the 4D Scavenger is expected to achieve reduction in Cu, Zn, and Al concentrations, which corresponds to an estimated 1.78 CTUe/m^3 reduction in ecotoxicity potential. The handprint assessment (Deliverable 1.4) showed an overall 37% reduction in freshwater ecotoxicity, representing a significant environmental benefit that is excluded from the monetised externality results. In other words, the societal environmental benefits of the iMERMAID scenario are underestimated by the financial metrics. These non-monetized benefits should be considered together with the LCC results.

As conclusion, the analysis shows that the iMERMAID configuration leads to higher life cycle costs due to additional treatment infrastructure and operation, while delivering a clear environmental remediation benefit that remains largely unvalued in monetary terms under current methodological and regulatory boundaries. The monetised LCC results should therefore be interpreted together with the handprint assessment rather than as a standalone indicator of sustainability.

3.4 Use Case 5

Use Case 5 was located at a leachate treatment plant in Pera Galini, Crete (Greece). It receives leachate produced by the municipal sanitary landfill of Pera Galini, which is located 40 km west of Heraklion city in an area of 45 acres. The most recent annual data for 2025 indicate that the landfill receives 165 600 tonnes of municipal solid waste (MSW) and sludge from wastewater treatment plant (Deliverable 4.3). The leachate treatment plant along with the whole facility of the Pera Galini Landfill is operated by Thalis SA, under ESDAK supervision through a public contract. The average untreated leachate flow rate entering the plant is 210 m^3/day and is divided into two parallel treatment lines:

a) 100 m^3/d is directed to two-stage physicochemical treatment consisting of coagulation and flocculation in the first stage and biochemical (MBR) treatment at second stage, followed by reverse osmosis (RO) unit
b) the rest is directed to a new RO unit with a capacity of 110 100 m^3/d

Effluents from both RO systems are directed to degasification and chlorination and are then either directed to landfill cells or used for irrigation of restored landfill areas.

The selected contaminants for emerging concern (CoEC) in Use Case 5 were bisphenol A (BPA), bentazone (BTZ) and propamocarb (PCR).

EDEN Tech has developed a microfluidic water treatment system. It is intended to be used as an advanced tertiary solution for the remediation of water contaminated with organic pollutants. The reactor is made of transparent polymer, and it contains photocatalyst (TiO2) which catalyses the degradation of organic pollutants with light energy provided by LEDs. The reactor system consists of microfluidic CDs engraved with the microfluidic networks, which can operate at a high flow rate. The microfluidic channels enhance the efficiency of the degradation by operation at micro level, leading to improved mass transfer and thus faster reactions. The specific benefit of the EDEN Tech is higher flow rates than those typically achieved in microfluidic systems.

The operating pressure of the EDEN microfluidic reactor is 1-2 bar, and the pressure drop across the reactor is 100 mbar. The system is physically compact and has low electricity demand. The system requires a prefiltration (microfiltration) system to remove suspended solids. In Use Case 5, atlas cartridge filters were used (hollow fibre filtrates). However, the demonstration showed that the filters used were not sufficient.

The state-of-the-art commercial technology for tertiary purification system is reverse osmosis membrane filtration (RO). However, RO has limitations. RO removes nearly all compounds and ions from water but requires high pressure and results in addition to the purified water stream (permeate) also a wastewater stream (retentate) which contains all the removed contaminants in higher concentrations. The retentate stream may be relatively large. Chemicals are required for cleaning the RO membranes and high pressure is required for press permeate through the membrane. In comparison, EDEN microfluidic technology operates at low pressure, its targeted energy consumption is lower than that of RO and it decomposes organic matter, resulting in a smaller wastewater stream than RO.

Use Case 5 compares the baseline scenario consisting of the existing 3 stages leachate treating system with the iMERMAID scenario, in which RO is replaced by pre-filtering and EDEN's microfluidic system. In addition, a separate comparison was conducted between RO and EDEN's microfluidic system, in which only variable operating costs and investment cost of RO and EDEN's microfluidic system are considered.

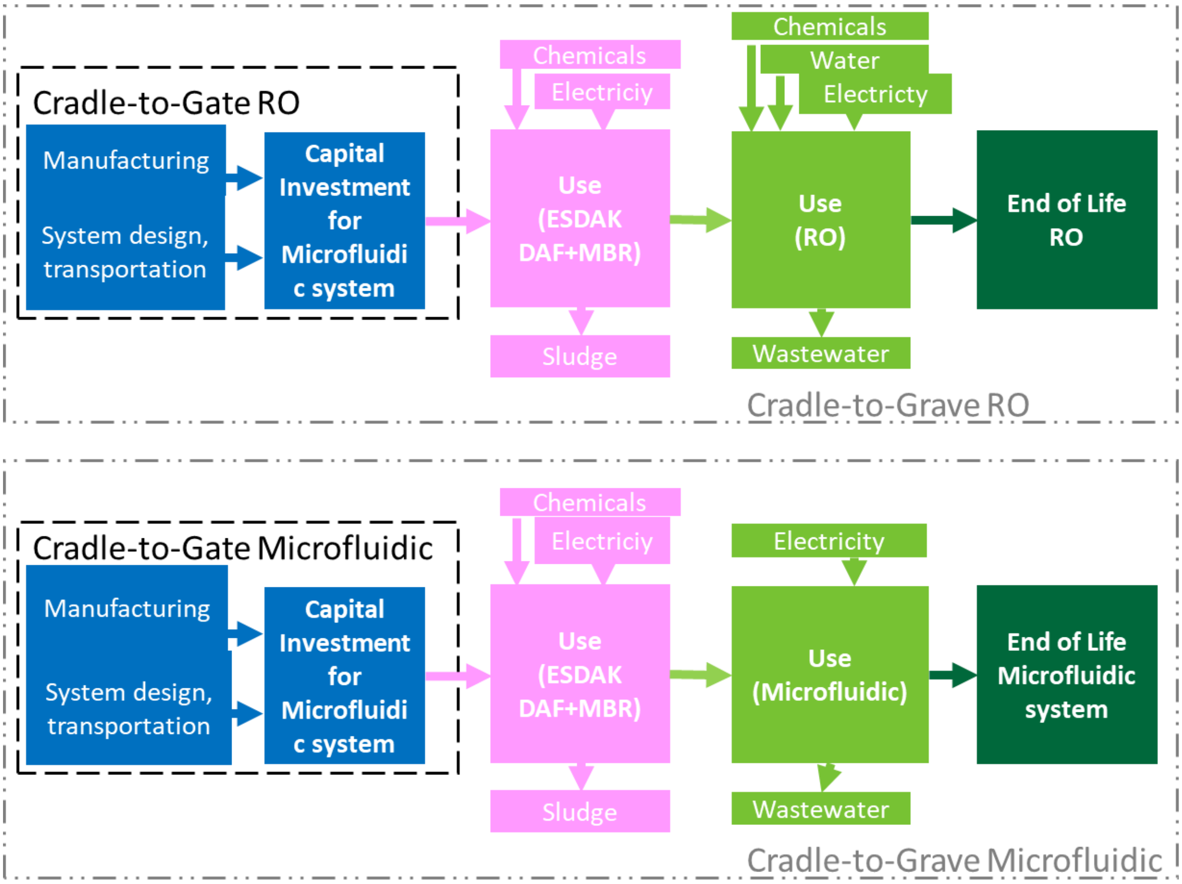

Figure 18: System boundaries for the comparison of the baseline scenario and the iMERMAID scenario in Use Case 5.

The comparative results of the assessment are presented in the following sections. The technical and economic parameters and mass balances used the life cycle costing are presented in Annex 2. The selected functional unit was 1 m^3 of water at the inlet of new technology.

3.4.1 Use Case 5 - Baseline LCC results

The baseline scenario represents the reference treatment used for the economic comparison in Use Case 5. It consists of a two-stage treatment system, starting with physicochemical treatment consisting of coagulation and flocculation in the first stage, followed by biochemical (MBR) treatment in the second stage, after which a reverse osmosis (RO) unit (the tertiary stage) and chlorination are applied.

This Use Case compares two alternative tertiary treatment approaches, contrary to the other Use Cases, in which an additional tertiary treatment stage was added to the existing process line. To maintain comparability in the life cycle cost assessment, an investment cost for the reverse osmosis system was assumed from the first year of the analysis period, even though the unit is already in operation. This assumption ensures that the baseline case reflects the full cost of the treatment configuration over the selected 20-year assessment period. The lifetime of the RO membranes was assumed to be 5 years.

The flow rate of the three-stage process line was 1.3 m^3/h in March 2026 resulting in an estimated annual flow rate of 11 500 m^3. The estimated operating cost was 13 EUR/m^3 of input water, resulting in an annual operating cost of 145 000 EUR in Year 1. With the addition of the RO investment cost, the total annual cost in Year 1 was 495 000EUR. At the end of the analysis period, in Year 20, the annual cost had increased due to the assumed annual inflation rate of 2% to 211 000 EUR, corresponding to a functional unit cost of 19 EUR/m3 of treated water. Every fifth year RO membrane replacement cost was applied. Both undiscounted and discounted cumulative cost curves over the analysis period are presented in Figure 19 to illustrate the effect of discounting.

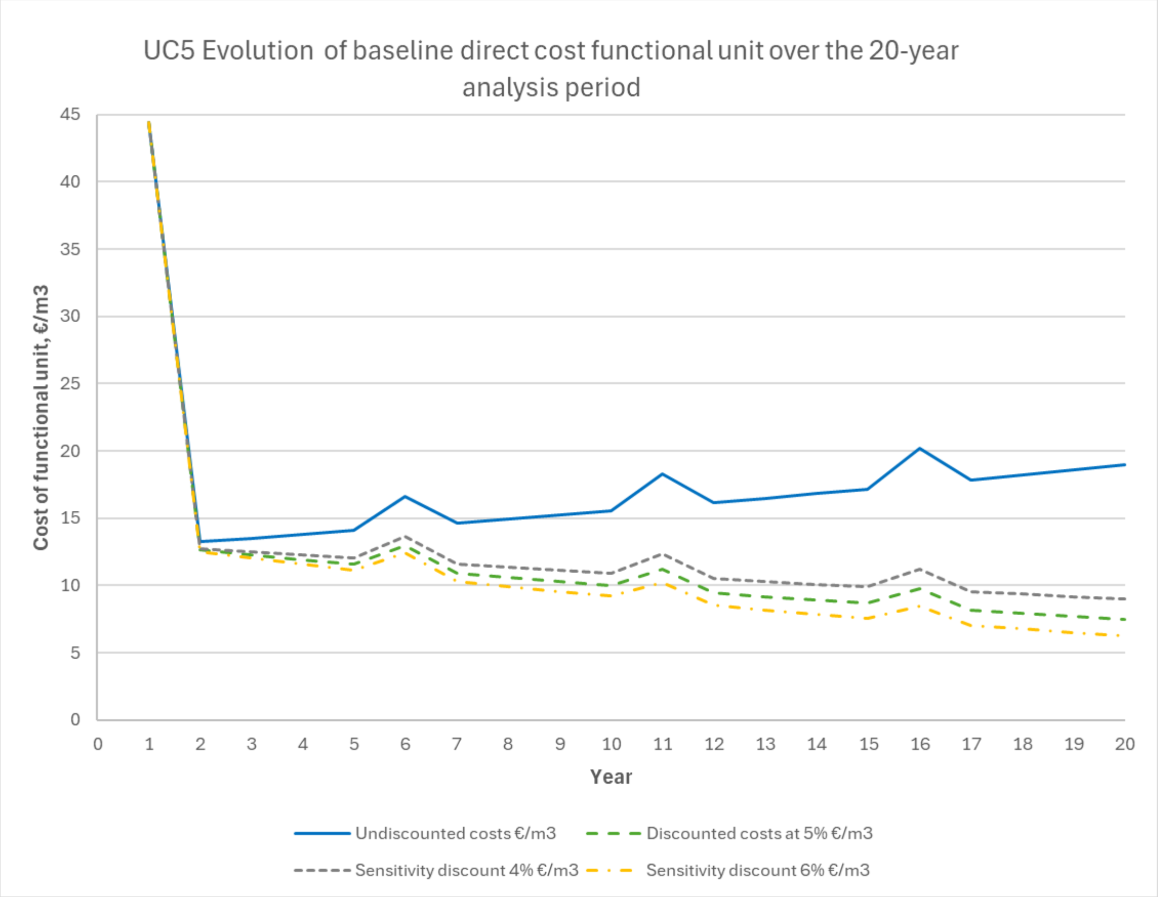

Figure 19: Evolution of the direct cost per functional unit of the baseline scenario for Use Case 5 over the 20-year analysis period, expressed in EUR/m3 of treated wastewater. The figure compares the undiscounted annual cost profile with the discounted annual cost profiles obtained using discount rates of 4%, 5%, and 6%, under an inflation assumption of 2%.

The cumulative results for the selected analysis period of 20 years are summarised in Table 16. The total undiscounted cost over the 20-year analysis period is 4.0 MEUR, corresponding to a unit cost of 17.7 EUR/m^3 of input water. When future costs are discounted to present value at the discount rate of 5%, the baseline net present cost is 2.6 MEUR, equivalent to 11.8 EUR/m^3 input water. The sensitivity analysis indicates that the selected discount rate has a clear influence on the reported present-value results. At the lower discount rate of 4%, the discounted cost increases to 2.8 MEUR and the corresponding unit cost is 12.7 EUR/m^3 wastewater, whereas at the higher discount rate of 6% the discounted cost is 2.5 MEUR with a unit cost of 11.0 EUR/m^3 input water.

Table 16: LCC results for the Use Case 5 baseline scenario over the 20-year analysis period, under an inflation assumption of 2%.

For the selected analysis period of 20 a		Discount rate %	Cumulative cost MEUR	Cost per functional unit EUR/m^3
Total undiscounted costs		0 %	4.0	17.7
Total discounted costs (Net present costs, NPC)	Sensitivity low	4 %	2.8	12.7
	Baseline	**5 %**	2.6	11.8
	Sensitivity high	6 %	2.5	11.0

The highest uncertainty affecting the baseline results is the RO replacement interval. The replacement interval for the RO membranes was estimated to be 5 years. The RO membrane lifetime varies depending on many parameters e.g. feedwater quality, pretreatment and operation parameters, and may be up to 10 years with clean seawater in desalination plants.

3.4.2 Use Case 5 - iMERMAID LCC Results

In the iMERMAID scenario, the reverse osmosis (RO) stage is replaced by a combination of microfiltration (MF) and EDEN technology as an alternative tertiary treatment. In this Use Case, the purpose is to analyse the economic effect of replacing RO with EDEN microfluidic system over the 20-year analysis period. The scenario represents a technology substitution case in which the RO-related cost components are removed and replaced by the investment and operating costs associated with the iMERMAID scenario. These excluded RO related costs include RO investment, RO membrane replacement, chemical consumption, electricity demand and wastewater management costs. In their place, the assessment includes the costs associated with the EDEN microfluidic system, including investment, electricity consumption, maintenance and retrofitting costs. Labour cost is assumed to remain same, as well as other fixed cost except additional maintenance cost for the EDEN microfluidic system.

One of the key technical assumptions in the iMERMAID scenario is that the wastewater stream is significantly reduced in comparison with the RO-based alternative. The residual wastewater stream is assumed to decrease from 35% of input to approximately 1% of input, which indicates a substantial reduction in reject volume.

The LCC results presented in Table 17 indicate a total undiscounted cumulative cost of 4.7 MEUR over the 20-year analysis period, corresponding to 21.3 EUR/m^3 wastewater. At the baseline discount rate of 5%, the net present cost is 3.0 MEUR, or 13.7 EUR/m^3 wastewater, while the sensitivity cases yield 3.2 MEUR at 4% and 2.8 MEUR at 6%. As expected, higher discount rates reduce the present value of future costs.

Table 17: LCC results for the Use Case 5 iMERMAID scenario.

For the analysis period of 20 a		Discount rate %	Cumulative cost MEUR	Cost per functional unit EUR/m^3
Total undiscounted costs		0 %	4.7	21.3
Total discounted costs (Net present costs, NPC)	Sensitivity low	4 %	3.2	14.8
	Baseline	5 %	3.0	13.7
	Sensitivity high	6 %	2.8	12.6

Table 18 and Figure 20 present the annual direct cost per functional unit for the iMERMAID scenario over the 20-year analysis period. The results show clearly the investment cost of EDEN microfluidic system at Year 1 and retrofitting every third year. The discounted results follow the same overall pattern as the undiscounted values, but future costs decrease in present-value terms as the discount rate increases.

Table 18: Direct cost per functional unit of the iMERMAID scenario for Use Case 5 over the 20-year analysis period, expressed in EUR/m3 of treated wastewater under undiscounted conditions and under discount rates of 5%, 4%, and 6%.

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Undiscounted cost	37.6	12.2	11.8	32.4	11.7	9.7	33.7	12.4	12.7	35.8	12.4	13.4	38.0	14.0	14.3	37.6	14.8	15.1	42.8	15.8
Discounted cost at 5%	37.6	11.6	10.7	28.0	9.6	7.6	25.2	8.8	8.6	23.1	7.6	7.9	21.1	7.4	7.2	18.1	6.8	6.6	17.8	6.2
Discounted cost at 4%	37.6	11.8	10.9	28.8	10.0	8.0	26.7	9.4	9.3	25.1	8.3	8.7	23.7	8.4	8.2	20.9	7.9	7.8	21.1	7.5
Discounted cost at 6%	37.6	11.5	10.5	27.2	9.3	7.3	23.8	8.3	7.9	21.2	6.9	7.1	18.9	6.6	6.3	15.7	5.8	5.6	15.0	5.2

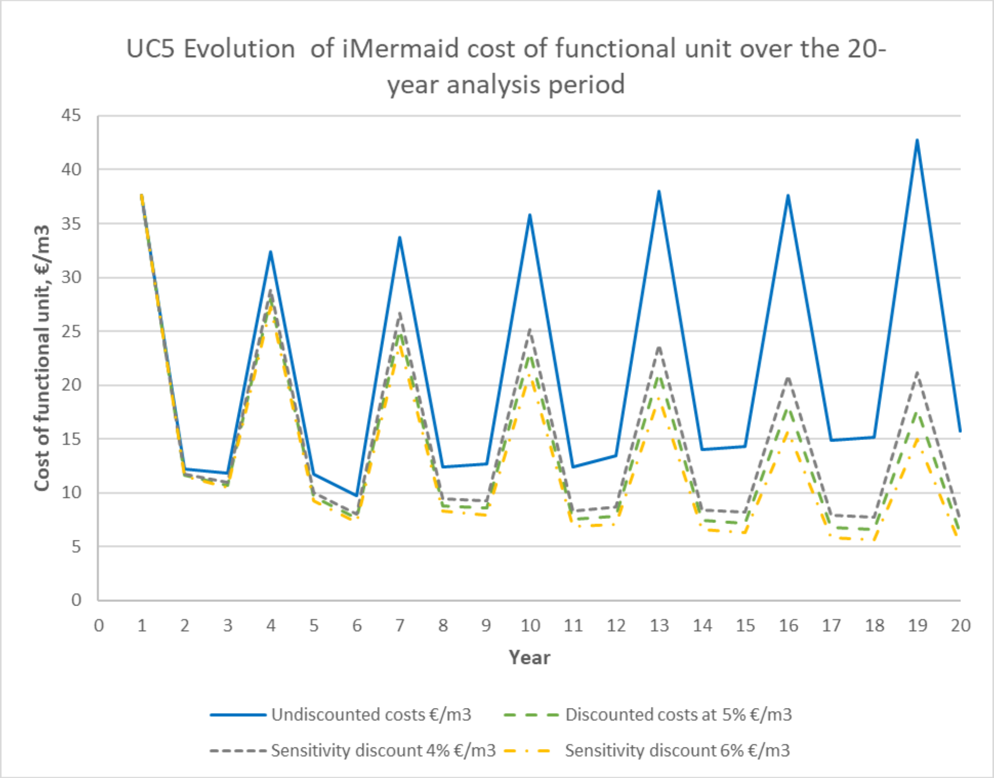

Figure 20: Evolution of the direct cost per functional unit of the iMERMAID scenario for Use Case 5 over the 20-year analysis period, expressed in EUR/m3 of treated wastewater. The figure compares the undiscounted annual cost profile with the discounted annual cost profiles obtained using discount rates of 4%, 5%, and 6%, under an inflation assumption of 2%.

Cost distribution is presented in Figure 21 for the selected years, taking into consideration annual inflation but not discounting. Year 1 represents the start-up year of iMERMAID scenario, Year 8 represents a basic year and Year 13 a retrofitting year of the EDEN microfluidic system. The figure illustrates the cost escalation by inflation during the years. It also shows the cost distribution during a basic year, Year 14 as an example, in which 98% of total cost consists of the baseline costs.

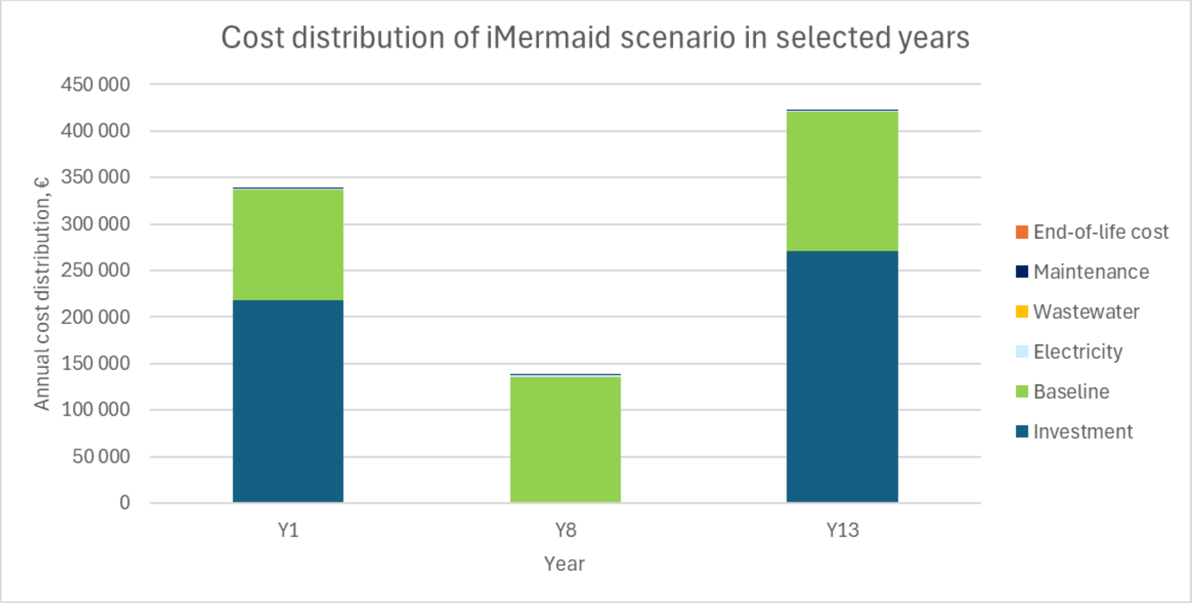

Figure 21: Distribution of annual costs for selected years in iMERMAID scenario for Use Case 5.

3.4.3 Use Case 5 - Cost-benefit analysis

The contaminants for emerging concerns (CoEC) to be removed using the EDEN microfluidic technology in Use Case 5 were organic contaminants in leachate. Specifically, the measured metals were bisphenol A (BPA), bentazone (BTZ) and propamocarb (PCR). The contents of these organic compounds in the treated water exiting the leachate treatment plant is in compliance with current regulations. However, the aim of iMERMAID in this Use Case was to compare the new technology (EDEN microfluidic system) to the state-of-the art technology (reverse osmosis membrane filtration).

In addition to the economic cost calculation, this assessment includes monetarised externalities or in other words environmental pricing, based on the CE Delft's Environmental Prices Handbook 2024: EU27 version. Although environmental quality has no explicit market price, environmental pricing aims to make environmental externalities such as impacts on human health, ecosystems, buildings, and well-being comparable with financial costs and benefits. In other words, it represents the loss of social welfare resulting from the environmental impact into the environment. Environmental prices are calculated values, derived from scientific cause–effect models linking emissions to impacts, and economic valuation methods that convert those impacts into monetary welfare losses. In practise, environmental pricing allocates a monetary value to environmental impact, expressed as a cost per unit of emission. The environmental prices in CE Delft publication are in euros of year 2021 and thus they were updated to year 2026 euros.

Monetarisation of externalities was limited in Use Case 5 to impact categories for which environmental price factors were available in the adopted methodology. Consequently, the reported monetised external costs represent only a partial environmental profile of the baseline and iMERMAID scenarios. It covers only impact categories that can be consistently translated into monetary values. These categories are climate change, ozone depletion, ionising radiation, oxidant formation affecting human health, particulate matter formation, acidification, freshwater eutrophication, marine eutrophication, and terrestrial eutrophication.

The results from monetarisation of externalities are presented in Table 19 and in Figure 22 for both the baseline scenario and iMERMAID scenario. The cost of monetised externalities per functional unit is 2.27 EUR/m^3 for the baseline scenario and 1.36 EUR/m^3 for the iMERMAID scenario. The monetarised externalities of the iMERMAID scenario are 60% in comparison to the baseline. This is mainly due to lower electricity demand and significant decrease in chemical consumption. The highest contributor is climate change for both cases: the baseline scenario 75% and iMERMAID 84%. The other significant contributors are acidification (the baseline scenario 13%, iMERMAID scenario 5%) and marine eutrophication (the baseline scenario 7%, iMERMAID scenario 6%). Other categories have insignificant effect to the total cost.

Table 19: Environmental price factors and resulting monetized environmental costs for Use Case 5, expressed in EUR2026 per unit of impact and in EUR/m3 of treated wastewater for the baseline and iMERMAID scenarios.

Impact category	Unit	Environmental prices per unit, EU27	Externalities	
		EUR (2026)	Baseline	iMERMAID
Climate change	kg CO2-eq.	0.159	1.70	1.13
Ozone depletion	kg CFC-11-eq.	35.58348	0.00	0.00
Ionising radiation	kBq U235-eq.	0.000868188	0.00	0.00
Oxidant formation, human health	kg NMVOC-eq.	1.59	0.05	0.02
Particulate matter formation	Disease incidence	934.986	0.00	0.00
Acidification	mol H+-eq.	2.494512	0.29	0.07
Freshwater eutrophication	kg P-eq.	4.573272	0.05	0.04
Marine eutrophication	kg N-eq.	17.4249	0.16	0.08
Terrestrial eutrophication	mol N-eq.	0.4047468	0.03	0.01
TOTAL costs			2.27	1.36

The results indicate that the EDEN microfluidics system contributes a lower external environmental burden than the RO system.

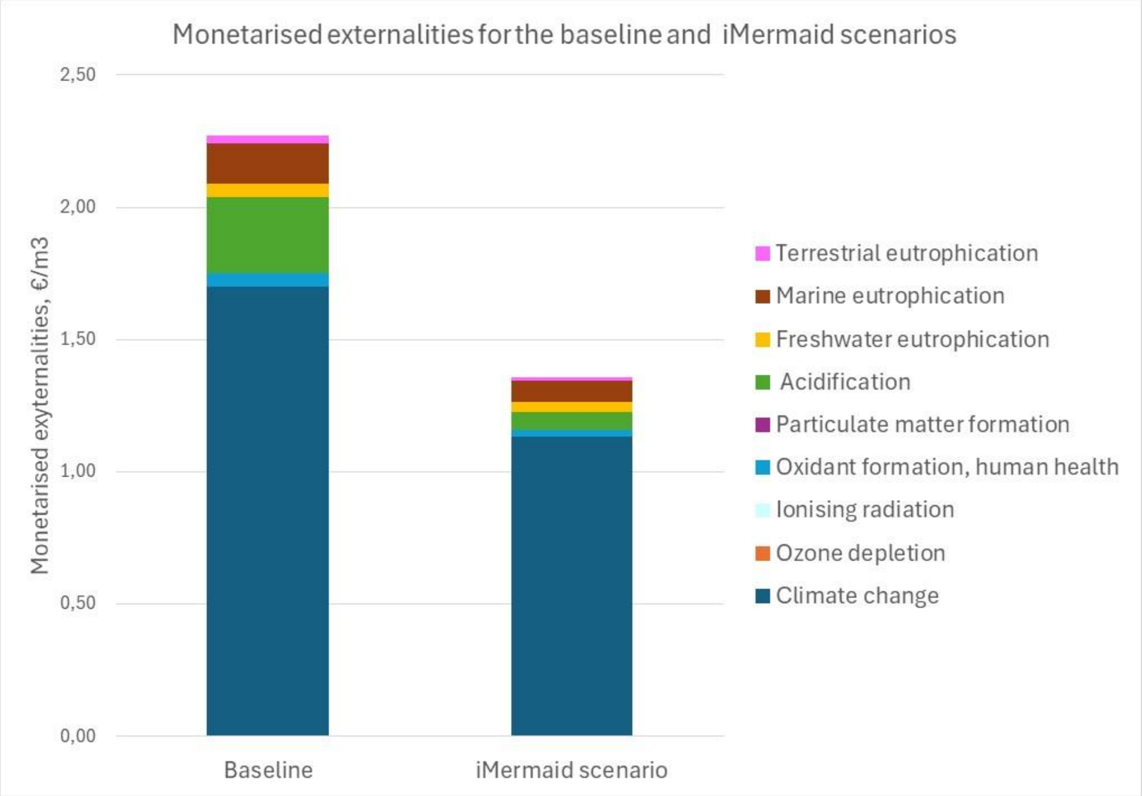

Figure 22: Monetized environmental costs for Use Case 5, expressed in EUR2026 per unit of impact and in EUR/m3 of treated wastewater for the baseline and iMERMAID scenarios.

To evaluate the results of monetarised externalities, they were added to the conventional LCC results. A summarised comparison of the conventional LCC results and the LCC results with addition of monetarised externalities are presented in Table 20. Adding the monetarised externalities to the baseline scenario increased it 16%, to the total undiscounted cost of 4.6 MEUR and to the cost per functional unit of 20.5 EUR/m^3. In case of the iMERMAID scenario, the addition of monetarised externalities caused 13% increase in cost, to the total undiscounted cost of 5.0 MEUR and to the cost per functional unit of 23.0 EUR/m^3. Although the monetarised externalities are lower for the iMERMAID case than the baseline case, the undiscounted cost including the externalities are still higher for the iMERMAID case.

Table 20: LCC results with externalities (discount rate 5%) for Use Case 5.

For the analysis period of 20 years	Cumulative cost	Cost per functional unit
	MEUR	EUR/m^3
Baseline		
Total undiscounted costs	4.0	17.7
Total undiscounted costs incl. externalities	4.6	20.5
iMERMAID scenario		
Total undiscounted costs	4.7	21.3
Total undiscounted costs incl. externalities	5.0	23.0

The selected method for monetarisation of externalities causes limitation to the analysis because does not include all LCA impact categories. Specifically, it does not include freshwater ecotoxicity, which in sustainability impact assessment of the iMERMAID scenario showed potential for beneficial environmental impact due to the decrease in the concentration of bisphenol A, bentazone and propamocarb. A total remediation performance of the iMERMAID scenario based on the inlet and outlet concentrations of the selected contaminants was 5.19 CTUe/m^3 or 25% from the inlet to outlet. In addition, there was 89% decrease in cradle-to-gate freshwater ecotoxicity footprint when replacing the current technology in place with the EDEN microfluidic technology. The analysis resulted in a net handprint of 15% meaning the remediation benefits outweigh the added life cycle burdens of the microfluidic system. Thus, these results indicate that EDEN microfluidic technology may provide substantial remediation benefit. The effect is shown in the monetized environmental cost indicator and also in not monetized freshwater ecotoxicity impact category.

3.4.4 Use Case 5 – Comparative analysis of the economic results of the baseline and iMERMAID scenarios

The assessment evaluated life cycle costs of replacing reverse osmosis membrane filtration with EDEN microfluidic system to the existing leachate treatment plant in Pera Galini, Crete. The baseline scenario included two stage physicochemical treatment consisting of coagulation and flocculation at first stage and biochemical (MBR) treatment at second stage, followed by Reverse Osmosis (RO) unit and dichlorination. The iMERMAID scenario replaced reverse osmosis unit with microfiltration and EDEN microfluidic system. Life cycle cost comparison was performed for 20-year analysis period, considering the operational cost of the whole treatment processes but investment cost of only RO, MF and EDEN microfluidic system.

Both the baseline scenario and the iMERMAID scenario had the investment cost at the year 1, leading to the functional cost of 44.4 EUR/m^3 in the baseline scenario and 37.6 EUR/m^3 in case of the iMERMAID scenario. The total undiscounted cost at year 1 was 0.49 MEUR for the baseline scenario and 0.34 MEUR for the baseline scenario, respectively. The higher cost of the baseline scenario was due to both higher investment cost and higher annual operational cost. At the Year 2, the functional cost based on undiscounted cost was decreased to 13.3 EUR/m^3 for the baseline scenario and 12.2 EUR/m^3 for the iMERMAID scenario, as there were no investment costs.

During the analysis period a higher annual cost occurred for the iMERMAID scenario every third year, as the lifetime of EDEN microfluidic system was assumed to be 3 years, leading to dismantling of the old system and purchasing a new one. On the other hand, in the baseline scenario it was assumed that the RO system requires replacement of membranes after 5 years utilisation. Cumulative cost comparison over the 20-year analysis period shows the impact of this assumption to the total cost of the scenarios in Figure 23.

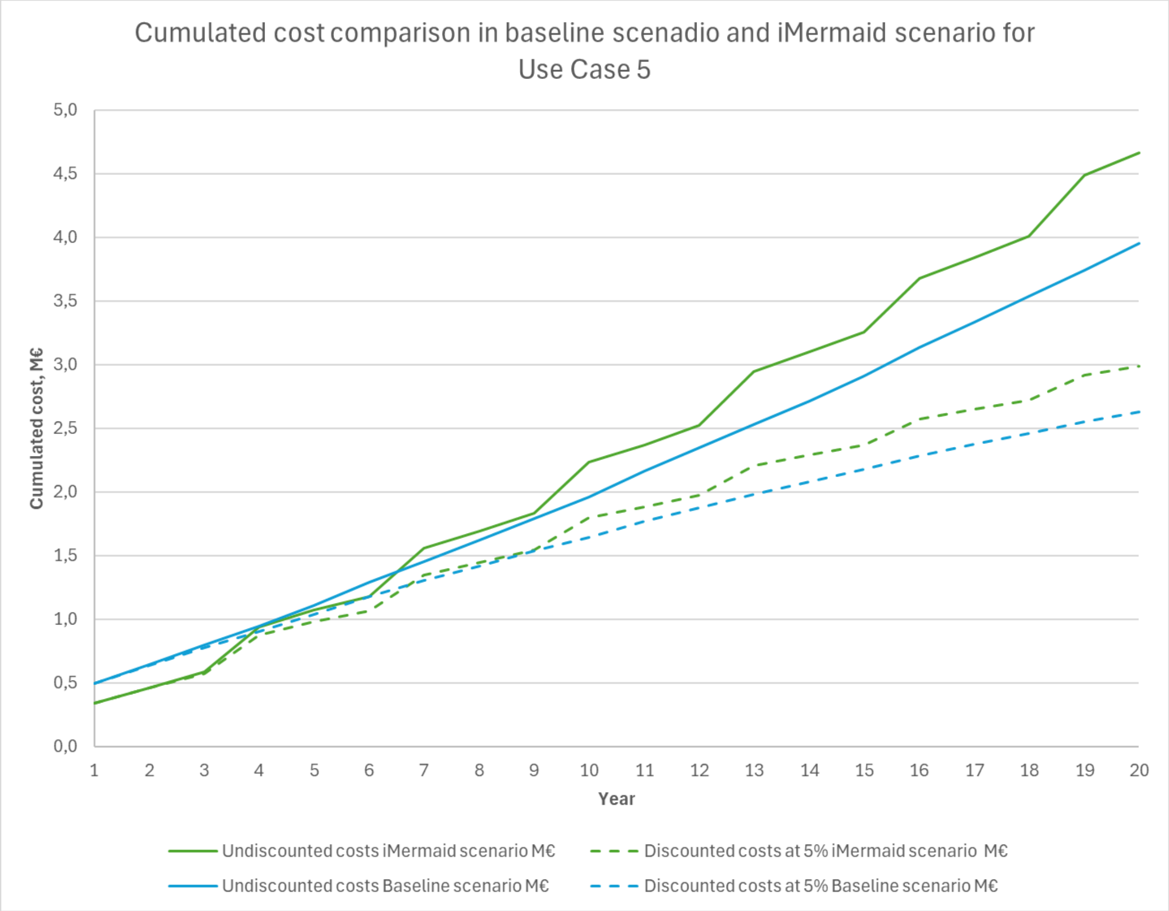

Figure 23: Comparison of cumulative costs of the baseline scenario and the iMERMAID scenario for Use Case 5.

Over 20 years, the total cumulative undiscounted costs reach 4.0 MEUR for baseline scenario and 4.7 MEUR for iMERMAID scenario, while discounted costs amount to 2.6 MEUR and 3.0 MEUR, respectively. The cost of the functional unit based on total undiscounted cumulative cost versus total treated water volume was for the baseline scenario 17.7 EUR/m^3 and for the iMERMAID scenario 21.3 EUR/m^3. Similarly, the cost of the functional unit based on total at 5% discount rate discounted cumulative cost versus total treated water volume was for the baseline scenario 11.8 EUR/m^3 and for the iMERMAID scenario 13.7 EUR/m^3. The results are summarised in Figure 24 and in Table 28.

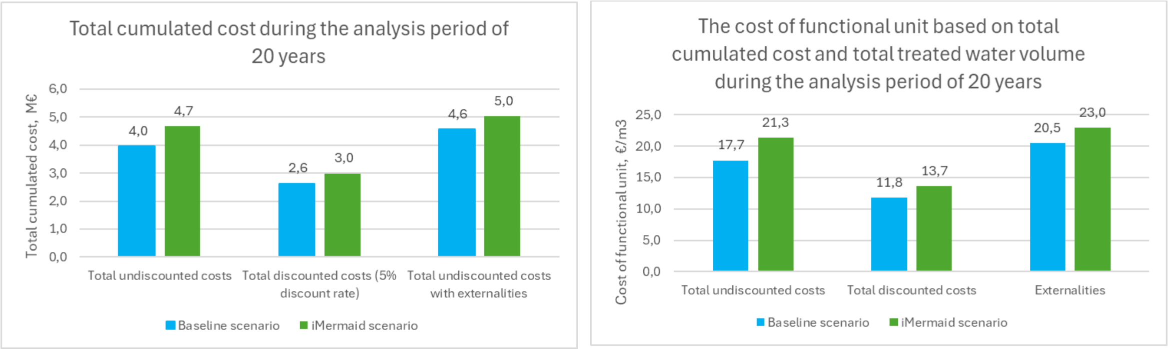

Figure 24: Summary of the comparison between the baseline scenario and the iMERMAID scenario for Use Case 5.

Table 21: Summary of the comparison between the baseline scenario and the iMERMAID scenario for Use Case 5.

For the analysis period of 20 years	Unit	Baseline scenario	iMERMAID scenario
Total undiscounted costs	MEUR	4.0	4.7
- Cost per functional unit	EUR/m^3	17.7	21.3
Total discounted costs (5% discount rate)	MEUR	2.6	3.0
- Cost per functional unit	EUR/m^3	11.8	13.7
Monetarised externalities	EUR/m^3	2.27	1.36
Total undiscounted costs with externalities	MEUR	4.6	5.0
- Cost per functional unit	EUR/m^3	20.5	23.0

The monetarised externalities were defined for both the baseline scenario and the iMERMAID scenario to assess the monetarised environmental impact of replacing RO with EDEN microfluidic system. The benefit of reduced concentration of the selected compounds bisphenol A (BPA), bentazone (BTZ) and propamocarb (PCR) is not shown in the monetarised results, because the impact category of fresh water ecotoxicity, in which the remediation benefit affects directly, is not included into the monetarised subcategories by CE Delft. However, even without this effect, the comparison indicated beneficial impact for replacement. The monetarised externalities for the baseline scenario were 2.27 EUR/m3 and for the iMERMAID scenario 1.36 EUR/m^3. Comparing the results, the iMERMAID scenario indicates 40% decrease in monetarised externalities if replacing RO with EDEN technologies. Climate change was dominating in both the baseline scenario (75%) and in the iMERMAID scenario (84%), however the iMERMAID scenario increased notably the share of acidification and marine eutrophication. Although the externalities were smaller for the iMERMAID scenario, the total undiscounted cumulative cost including the externalities were still higher for iMERMAID scenario (5.0 MEUR or 23.0 EUR/m^3) than for the baseline scenario (4.6 MEUR or 20.5 EUR/m^3) (Table 28). The results indicate that the EDEN microfluidics system contributes a lower external environmental burden than the RO system.

As conclusion, the analysis shows that the replacing the baseline configuration (RO) to the iMERMAID configuration leads to higher life cycle costs. However, parameters used for the analysis include significant uncertainties. For that reason, a more detailed analysis was carried out, including only the investment and variable operating costs of RO and EDEN system, including a sensitivity analysis for the most important key factors affecting the economic feasibility.

3.4.5 Use Case 5 – Comparative analysis of the economic results of RO and EDEN microfluidic system

This chapter presents the life cycle cost (LCC) comparison of the state-of-the-art technology for leachate treatment (RO) with the iMERMAID technology (EDEN microfluidic system).

The leachate treatment plant has since 2024 operated a new parallel wastewater treatment line to the three-stage treatment followed by chlorination. This parallel treatment line consists of only so-called tertiary treatment, reverse osmosis (RO), followed by chlorination, and excludes the prior stages. The performance of this new treatment line has been considered good, and it is regarded as a state-of-the-art solution for the site.

This RO treatment line is compared with the EDEN microfluidic system to assess the cost difference of the two alternatives, although there is no experimental data from demonstration. EDEN microfluidic system requires a prefiltration step, in here it was assumed to be microfiltration.

The economic comparison between the EDEN microfluidic system and the RO treatment line focuses on a restricted cost boundary, including only chemical consumption, utilities, and waste management. Labour costs were excluded from the assessment because they were assumed to be similar for both alternatives. Likewise, chlorination costs were excluded, because disinfection is assumed to remain necessary after the EDEN microfluidic system. The purpose of this restricted cost assessment is not to represent the full treatment cost of the entire plant, but rather to identify the main operational cost differences between the two tertiary treatment alternatives and identify the significant cost drivers via sensitivity analysis of the parameters having high uncertainty.

A flow rate measured in March 2026 (1.35 m^3/h) was used as the basis for the comparison, corresponding to an annual leachate volume of 11 800 m^3. At the RO treatment system, 65% of the input is recovered as purified permeate, while the remaining 35% leaves the RO as a concentrated wastewater fraction (retentate) containing the rejected impurities. Thus, concentrated wastewater fraction requiring disposal is relatively large.

The RO scenario is associated with several cost drivers. Multiple chemicals are required to maintain stable operation, to clean membranes and to prevent membrane fouling. In addition, electricity consumption is a major contributor, as significant energy is needed for operating the system. In this assessment, the specific electricity demand was estimated to be 7.3 kWh/m^3 of input with ±10% uncertainty (ESDAK). Another important factor in the RO-only scenario is the relatively high volume of concentrated residual wastewater, to which all rejected contaminants are accumulated. The replacement interval for the RO membranes has also an impact on cost. For this assessment, a five-year Ro membrane lifetime was selected, but as the installed system has been operated only since 2024 and has thus operated for approximately two years without replacement, this parameter has relatively high uncertainty. RO membrane lifetime varies depending for example on feed-water quality, fouling tendency and overall system design and operation, up to 10 years for seawater in desalination plants.

The EDEN microfluidics cost scenario includes prefiltration, from which 1% waste stream is assumed. In addition, LEDs consumes electricity. The electricity demand was defined by EDEN for industrial scale operation with optimised design of the system. Maintenance cost is estimated based on flowrate by EDEN. The significant cost is derived however from the retrofit of the system after three years lifetime. The investment cost is also an estimate. There is potential for further decrease in investment by both R&D but also if proceeding to large scale mass manufacturing of the discs.

The results for this comparison are summarized in Table 22. Over the 20-year analysis period, the total cumulative undiscounted cost is 1.1 MEUR for RO, corresponding to 4.82 EUR/m^3 inlet wastewater. At the discount rate of 5%, the total discounted cost is 0.85 MEUR, or 3.59 EUR/m^3 wastewater. EDEN microfluidics system results higher cost structure, the total cumulative undiscounted cost is 1.88 MEUR, corresponding to 8.10 EUR/m^3 inlet wastewater. At the discount rate of 5%, the total discounted cost is 1.22 MEUR, or 5.26 EUR/m^3 wastewater.

Table 22. Comparison of RO and EDEN microfluidic system for Use Case 5.

For the analysis period of 20 years	Unit	RO	EDEN microfluidics
Total cumulative undiscounted cost	MEUR	1.14	1.88
- Cost per functional unit	EUR/m^3	4.82	8.10
Total cumulative discounted cost (5% discount rate)	MEUR	0.85	1.22
- Cost per functional unit	EUR/m^3	3.59	5.26
Monetarised externalities	EUR/m^3	1.31	0.39
Total undiscounted cumulative cost incl. externalities	MEUR	1.52	1.99
- Cost per functional unit	EUR/m^3	6.41	8.58

Cost distribution over the 20-year analysis period is presented in Figure 25. It shows that while most of the RO cost factors are related to the operation, the most significant cost factor in EDEN scenario is the investment cost. In the RO scenario the chemical cost, electricity cost and the investment cost have each approximately 30% share, while the membrane cost and wastewater cost are both around 7%. In case of EDEN microfluidic system scenario, 97% of the total cost is derived from investment and retrofitting, whereas electricity cost accounts for 2% and maintenance cost for 1%.

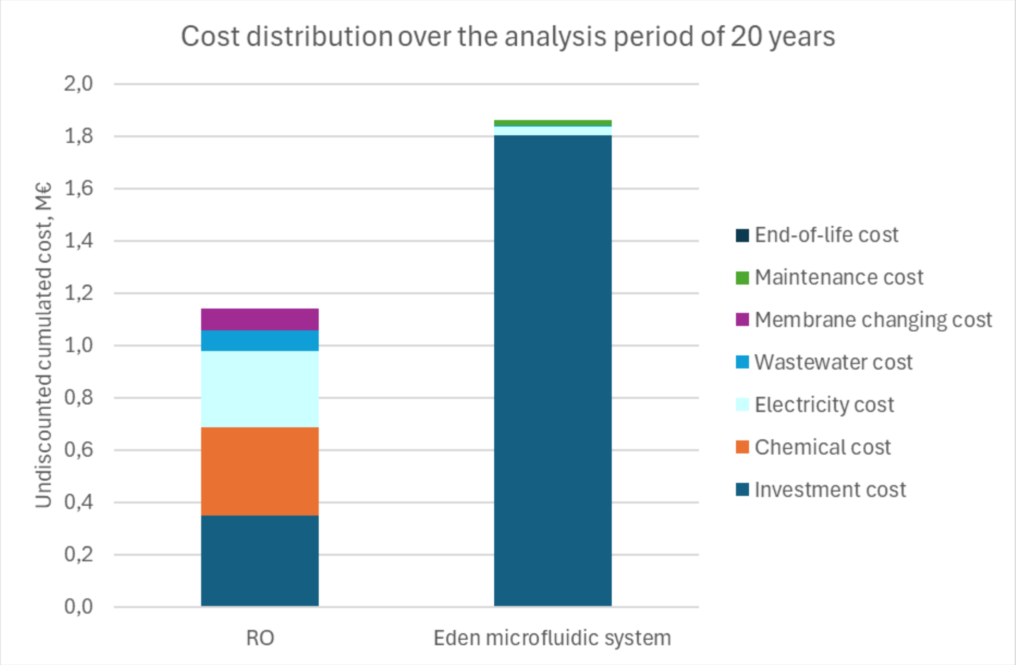

Figure 25: Cost distribution for the RO system and the EDEN microfluidic system (Use Case 5).

Sensitivity analysis was conducted for both RO and EDEN scenarios. Selected parameters were those having high uncertainty or high effect on the cost of functional unit. One parameter was varied at time in the analysis. The result for EDEN is presented in Figure 26 and for RO in Figure 27. In case of EDEN, the results showed that the investment cost is very significant: both decrease in investment cost but also increasing lifetime (e.g. from 3 to 5 years) would have a strong effect on cost. In case of RO, the RO membrane lifetime was assumed to be 5 years in this assessment but in reality, is not yet known, as the treatment line has been operated only 2 years. The analysis showed that the lifetime of RO membrane has a clearly noticeable effect to costs. On the other hand, increasing the estimated electricity demand of RO 10% or decreasing it 10% has only very minor effect to the cost. Electricity price change has in fact higher effect to the cost of the functional unit than the 10% consumption change. Summarising the sensitivity analysis of the comparison: decrease in either investment cost or the lifetime of the system has very positive effect to the cost of the functional unit, and would enable reaching the same cost level as RO.

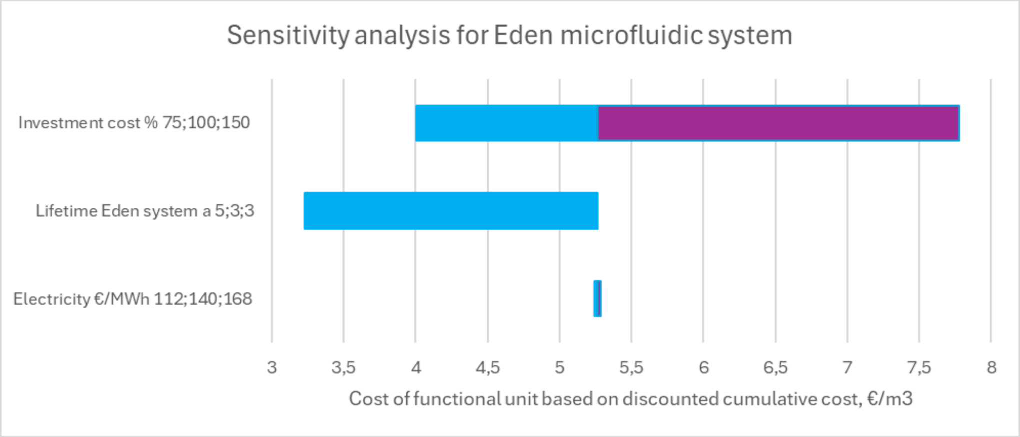

Figure 26: Sensitivity analysis for EDEN microfluidic system (Use Case 5).

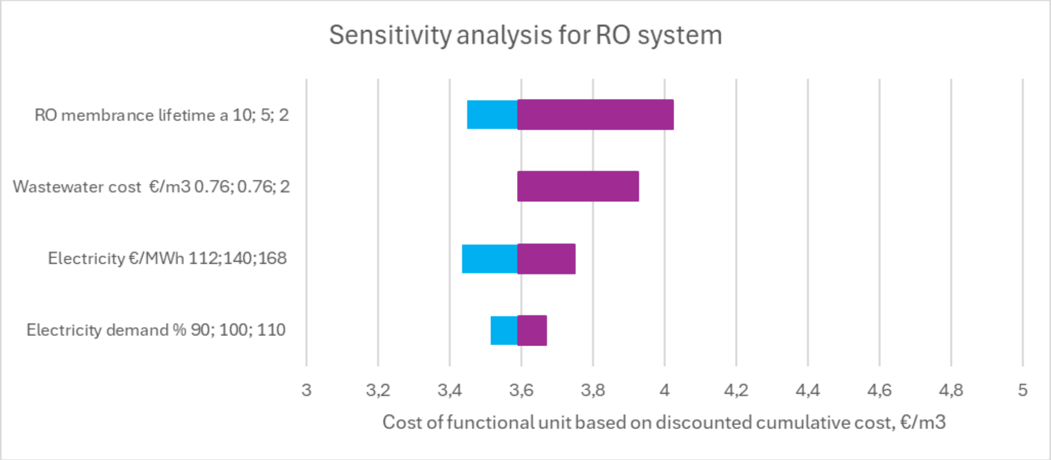

Figure 27: Sensitivity analysis for RO system (Use Case 5).

4.0 Conclusions

The aim of this study was to assess life cycle costing at industrial scale for the new technologies demonstrated at real wastewater treatment plants in the iMERMAID project. In Use Case 1, Use Case 2 and Use Case 3 the existing wastewater treatment system at the demonstration site represented first- and second-stage treatment but not tertiary treatment. In these Use Cases, the iMERMAID technology was an additional tertiary treatment, and there was no comparable technology. The tertiary treatment provided by the new technology would not provide any additional revenues, as there is currently no regulation requiring additional purification. However, Use Case 5 differed from the other use cases because the existing treatment plant already had a tertiary treatment in place (reverse osmosis membrane filtration, RO). Thus, in Use Case 5 the assessment consisted of a comparison of the technology in place (RO) with the new iMERMAID technology and evaluated the benefits and drawbacks of the replacement.

The assessment of Use Cases 1, 2 and 3 shows that the introduction of the iMERMAID treatment configurations as an additional treatment leads to a higher economic burden than the corresponding baseline scenarios over the 20-year horizon considered. This result is consistent for both direct life cycle costs and monetized environmental costs within the subset of impact categories for which environmental prices were available. In this respect, the analysis confirms that, under the system boundaries and assumptions adopted, the innovative configurations represent an additional cost for the treatment systems. This outcome is consistent with the role of the Life Cycle Costing in the present study. The purpose of the LCC is not to demonstrate financial attractiveness, short term economic superiority, or payback potential, since no direct revenue stream, tariff adjustment, or quantified operational saving is attributed to implementation of the additional treatment technologies within the assessed boundary. Rather, the LCC is applied as a cost of function assessment, intended to quantify the incremental economic burden associated with introducing an enhanced treatment step for contaminants of concern into an already operating system. In this context, the LCC provides a structured basis to identify the magnitude, composition, and timing of the additional costs required to deliver the improved treatment function.

At the same time, the results show that this additional burden is structured differently across the use cases 1, 2, and 3. In Use Case 1, the increase is driven mainly by recurring operational and maintenance requirements of the IRIS system, together with periodic replacement events. In Use Case 2, the increase remains strongly influenced by the acquisition and renewal of the ENIG and EDEN technologies; while recurring annual costs also represent a visible part of the overall cost profile once the system is in operation. In Use Case 3 most of the increase is derived from operational costs of the Weeefiner's 4D scavenger, specifically from replacing filter material and disposal of wastewater rich in heavy metals. The discounted analysis supports this interpretation by showing how the burden is distributed over time and how the present value of the scenarios is influenced by the timing of recurring costs and replacement events. In this respect, discounting and sensitivity analysis are useful not as indicators of profitability, but as tools to support a consistent long-term comparison of scenarios with different temporal cost structures and to clarify how strongly the overall burden depends on the treatment of future costs within the 20-year assessment horizon.

However, the economic interpretation cannot rely on Life Cycle Costing and monetized externalities alone. In Use Cases 1, 2 and 3, the monetized environmental costs capture the additional upstream burdens associated with technology deployment and operation, but they do not capture the avoided freshwater ecotoxicity linked to the removal of the selected substances of concern from the treated effluent. For this reason, the Cost Benefit Analysis must be interpreted together with the handprint assessment. In Use Case 2 and 3, this complementary perspective is particularly clear, as the enhanced treatment train achieves substantial reductions in the freshwater ecotoxicity potential of the discharged stream. In Use Case 1, the quantified handprint is smaller in absolute terms, which should be interpreted in light of the low concentrations observed in the assessed effluent, while the experimental results nevertheless showed complete degradation of the three selected substances under the tested conditions.

The set-up of the Use Case 5 differed greatly from the other use cases. In Use Case 5 a state-of-the-art tertiary treatment (RO) was already operating on site, thus enabling a comparison of the economic feasibility of the alternative tertiary treatment technologies. Replacing RO with EDEN technology increased costs, although the uncertainty associated with the estimate remains relatively high. Approximately 97% of the total cost was attributed to investment and equipment retrofit. However, the scenario in Use Case 5 showed a clear benefit in terms of environmental pricing, probably due to the negligible consumption of chemicals and electricity compared with RO. The sensitivity analysis further indicated that the EDEN technology could potentially approach the cost level of RO if the EDEN technology lifetime were extended from three to five years or if the investment cost were reduced by 25%.

For Use Case 5, the comparison of the new technology with reverse osmosis (RO) yielded informative results. A broader comparison of other new technologies against RO would also be of interest, but this would require at least experimental data on the performance of the RO membrane for specific wastewater to support the estimation of the relevant technical parameters. While new technologies may not achieve the same level of purification as RO, they may be more suitable in certain applications, as they can generate less wastewater and consume lower amounts of chemicals and electricity. Overall, the results indicate that the iMERMAID configurations represent tertiary wastewater treatment options that provide an additional remediation function.

5.0 Anthropogenic noise pollution evaluation

Acoustic monitoring was conducted on 2 October 2025, during the operation of the oil sensor on the buoy, off the coast of Limassol, Cyprus, as part of Use Case 4. Recording was made using an icListen Kayak hydrophone (Ocean Sonics). A 15-minute segment from the central part of the recording was analysed to minimise noise associated with deployment and retrieval activities and to better represent normal buoy and sensor operating conditions. The assessment included analysis of band levels over time and spectrogram interpretation. Results showed that low-frequency sound (10–200 Hz) constituted the dominant component of the recorded acoustic environment. Background noise levels in this frequency range initially increased and then stabilised, indicating the presence of a relatively continuous sound source during the monitoring period. In contrast, the mid-frequency (200–2000 Hz) and high-frequency (2–10 kHz) bands displayed smaller and less systematic variations, indicating a more limited contribution to overall acoustic conditions. The spectrogram confirmed persistent low-frequency acoustic energy, with sound levels decreasing substantially above 200–300 Hz and without evidence of tonal signals or short-duration events such as vessel pass-bys. More information and results can be found in D4.3, section 4.3.4. The observed acoustic pattern is considered consistent with normal buoy operation, including buoy motion, chain friction, and potentially the electricity generator supplying power to the oil sensor hence no significant noise pollution can be attributed to the oil sensor operation.

6.0 References

1. CE DELFT, 2024: Environmental Prices Handbook 2024: EU27 version | CE Delft https://cedelft.eu/wp-content/uploads/sites/2/2024/12/CE_Delft_230107_Environmental-Prices-Handbook-2024-EU-version_def_V1.1.pdf-
2. Cottes M., Mainardis M., Simeoni P., 2023: Assessing the Techno-Economic Feasibility of Waste Electric and Electronic Equipment Treatment Plant: A Multi-Decisional Modeling Approach. Sustainability 2023, 15, 16248. https://doi.org/10.3390/su152316248
3. Cronimet, 2026: Vantaa scrap yeard. Retrieved 13.4.2026 from https://www.cronimet.fi/en/scrap-yards/vantaa/
4. EU project NONTOX, 2021: Project data.
5. European Commission, 2025: Better Regulation Toolbox. Retrieved 13.4.2026 from https://commission.europa.eu/law/law-making-process/better-regulation/better-regulation-guidelines-and-toolbox_en
6. European Commission, 2014: Guide to Cost-Benefit Analysis of Investment Projects. Economic appraisal tool for Cohesion Policy 2014-2020. December 2014. Retrieved 7.4.2026 from https://ec.europa.eu/regional_policy/sources/studies/cba_guide.pdf
7. Ianes J., Piraldi S., Cantoni B., Antonelli M., 2025: Micropollutants removal, residual risk, and costs for quaternary treatments in the framework of the Urban Wastewater Treatment Directive. Water Research X, Volume 29, 1 December 2025, 100334.

7.0 Technical Note I – Note on updated electricity consumption data for the IRIS PDP system in Use Case 1

The economic assessment of Use Case 1 was developed using the electricity consumption value for the IRIS PDP system that had been previously shared and applied consistently in the modelling of the iMERMAID scenario. The value used in the report was approximately 9 to 10 kWh/m3, in line with the information available during the development of the study and used in the LCC calculations for the PDP operation phase.

At the final stage of report preparation, IRIS communicated an updated electricity demand of approximately 2.4 kWh/m3 for the PDP system. This revised value is about one quarter of the electricity consumption previously used in the assessment. Due to the timing of this clarification, and in the absence of sufficient time for validation and full recalculation, the updated figure could not be incorporated into the LCC, or the comparative scenario results presented in the current version of the report.

This update is economically relevant because electricity consumption is a significant contributor to the cost profile of the IRIS-based iMERMAID scenario. Under the value currently used in the report, IRIS operational electricity cost accounts for about 23.5% of the total annual cost in years dominated by initial investment or major replacement events, and about 37.5% in years dominated by recurring operation. If the updated electricity demand were applied as a simple proportional adjustment, the contribution of IRIS operational cost would decrease to about 7.1% and 13.0%, respectively. Accordingly, the total annual cost of the iMERMAID scenario would decrease from 334,575.08 EUR/year to 275,703.77 EUR/year in Year 1, and from 213,766.58 EUR/year to 153,717.84 EUR/year in Year 2, with similar proportional changes across the remaining years of the analysis horizon. At the aggregated level, the total undiscounted cost of the iMERMAID scenario over 20 years would decrease from 8,670,261.59 EUR to 7,239,843.70 EUR. Based on the total treated volume over the same period, this would reduce the undiscounted cost of the functional unit from 7.92 EUR/m3 to 6.61 EUR/m3. The revised electricity demand would therefore materially reduce the cost profile of the iMERMAID scenario, although it would remain above the baseline value of 4.62 EUR/m3 under the same calculation approach.

This means that the current report is likely conservative with respect to the burden associated with PDP operation, and that the LCC results for the iMERMAID scenario are expected to overestimate the contribution of IRIS electricity use to the total cost profile. At the same time, the updated value does not invalidate the overall interpretation of the assessment. The iMERMAID scenario would still represent an additional treatment step introduced into the baseline configuration and would therefore remain associated with an additional economic burden under the current project boundary. What changes is primarily the magnitude of the operational burden attributed to IRIS, not the general interpretation of the use case.

These updated values should be regarded as indicative only, since no full recalculation of the integrated economic assessment was carried out. A proper update would require the consistent revision of all affected LCC results, including the annual cost profile, discounted cost results, and the comparison between baseline and iMERMAID scenarios. The purpose of this note is therefore to transparently document the discrepancy between the value used in the report and the updated information shared by IRIS after the economic analyses had already been completed.

8.0 Annex 1: Basis for Use Case 3

Flowsheet definition

Based on the Use Case 3 demonstration, a simplified flowsheet was drawn, and it is presented in Figure 28. The wastewater is directed first through the Brandizzo wastewater treatment plant. After that, the treated wastewater is prefiltered in a filter. In the demonstration, the prefiltration media was glass particles. However, it became clear during the demonstration that filtration using glass particles was not sufficient, and thus in the LCC a sand prefiltration unit was considered. After the prefiltration, the treated wastewater is directed to the scavenger unit, which is operating in the metal removal mode. At least two parallel reactors are needed, as the other one is being evaluated and regenerated while the other is in the metal removal operation mode. Eluent (acid solution) is partly recycled before it is directed out from the system. Eluent (acid solution) exiting the system is thus concentrated in heavy metals and will be treated as wastewater concentrated with metals. Used regenerate (base solution) contains mainly dilute dissolved NaOH and salts, and the rinsing water contains only traces of impurities. Due to their dilute concentrations, the base solution and the rinsing water are combined to the treated water entering to the sand filter.

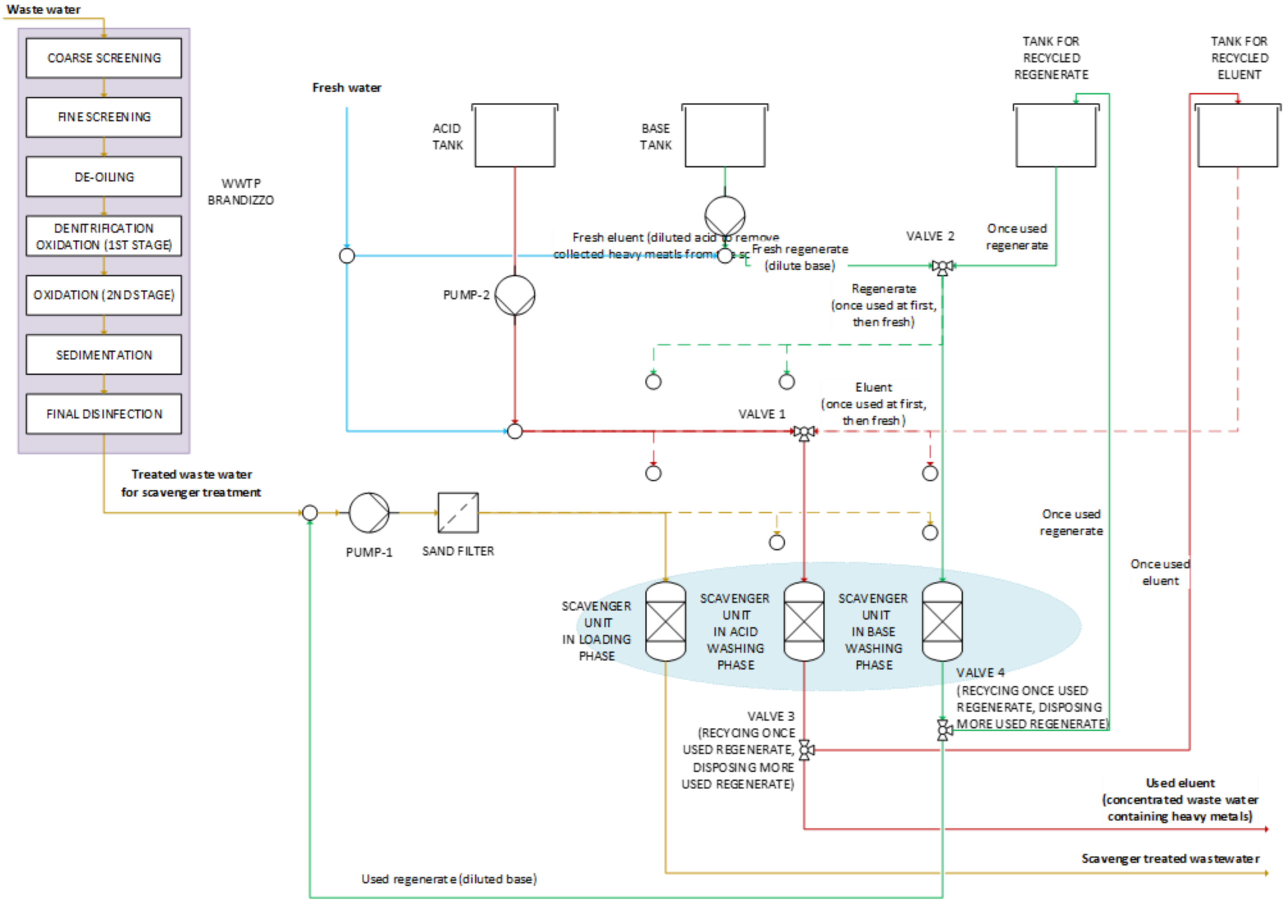

Figure 28: Simplified process flow diagram of Use Case 3. Scavenger system has at least two parallel units which operate in cycles. In blue background parallel scavenger units in at various stages of the operational cycle (rinsing with water was excluded in the simplified process flow diagram).

Mass and energy balances based on experimental data

Technology and the equipment used for demonstration were described in D3.3. Demonstration has been described in detail in D4.3. Due to equipment breakdown while in demonstration, the removal efficiency of heavy metals was defined by experiments carried out for industrial wastewater in Finland. The data was provided by Weeefiner. The experiments showed removal efficiency above 95%, however, the calculations are based on 95% removal rate for all heave metals.

The overall mass balances of the heavy metal removal system are presented in Table 23 including all internal recycling). The volumes of eluent and regeneration solution are small compared to the treated wastewater, 0.005 wt% and 0.003 wt% respectively. Rinsing and dilution water consumption is also minor, 0,3 wt%.

Table 23: Calculated mass balances based on the experimental performance data from Finland applied to iMERMAID scenario in Brandizzo Use Case 3.

			Industrial scale	Pilot scale (demonstration)		Functional unit
IN	**TOTAL**	**t/a**	**729 985**	**8 735**		
	Treated wastewater	t/a	727 687	8 707	m3/m3	1.0
	Sulphuric acid (95%)	t/a	33	0.39	t/m3	0.0003
	Sodium hydroxide (50%)	t/a	25	0.30	t/m3	0.0001
	Water (dilution, rinsing)	t/a	2 240	27	m3/m3	0.0038
OUT	**TOTAL**	**t/a**	**729 985**	**8 735**		
	Heavy metals depleted treated wastewater (including dilute base solution and rinsing water)	t/a	729 358	8 727	m3/m3	1. 00
	Acid concentrate solution (rich in heavy metals)	t/a	627	7.50	t/m3	0.0015

Compositions of heavy metals in treated wastewater at inlet and outlet, and the concentration of the eluent (acid outlet solution rich in heavy metals) at outlet are presented in Table 24. In these calculations it was assumed that all heavy metals removed from treated wastewater are dissolved in the eluent. Acid solution was considered as wastewater to be landfilled.

Table 24: The heavy metal concentrations of the treated wastewater inlet and outlet and of the acid eluent outlet (rich in heavy metals) in Use Case 3.

Treated wastewater IN					
Total, of which		t/a	727 687		
	Water	t/a	727 687		
	Al	t/a	0.291	mg/l	0.4
	Zn	t/a	0.058	mg/l	0.08
	Cu	t/a	0.0073	mg/l	0.01
Treated wastewater OUT					
Total, of which		t/a	729 358		
	water	t/a	729 346		
	Al	t/a	0.015	mg/l	0.020
	Zn	t/a	0.003	mg/l	0.004
	Cu	t/a	0.0004	mg/l	0.0005
Acid solution concentrated with heavy metals OUT					
Total, of which		t/a	627		
	water	t/a	595		
	Al	t/a	0.28	mg/l	441
	Zn	t/a	0.06	mg/l	88
	Cu	t/a	0.007	mg/l	11
	H2SO4	t/a	31	mg/l	49 973
	pH				0.3

Energy demand consisted only of electricity demand. The estimated electricity demand is presented in Table 25.

Table 25: Energy demand of Use Case 3.

			Industrial scale		Pilot scale (demo)		Functional unit
Electricity total, of which		MWh/a	109	MWh/a	1.3	kWh/m3	0.15
	pump	MWh/a	84	MWh/a	1.0	kWh/m3	0.11
	other	MWh/a	25	MWh/a	0.3	kWh/m3	0.03

Economic parameters and investment cost estimation

Unit costs of chemicals, utilities and waste fractions for iMERMAID scenario are presented in Table 26, as well as the operational cost of the baseline scenario (Brandizzo wastewater treatment plant).

Table 26: Prices of chemicals, utilities and waste fractions for Use Case 3.

		Baseline	Min	Max	Reference
Sulphuric acid (95 wt%)	EUR/t	200	150	1000	Weeefiner E.L. email 28.1.2026
Sodium hydroxide (50wt%)	EUR/t	500	450	1300	Weeefiner E.L. email 28.1.2026
Water (dilution, rinsing)	EUR/t	1	0.75	1.25	Weeefiner E.L. email 28.1.2026
Electricity	EUR/MWh	100	93	151	SMAT
Changing of filter material	EUR/m^3	0.122	0.098	0.146	Weeefiner E.L. email 28.1.2026
Maintenance	EUR/m^3 treated wastewater	0.0122			Weeefiner E.L. email 28.1.2026
Wastewater rich in heavy metals - landfilling	EUR/m^3	200	150	600	Nontox, Italian data
Incineration -non-hazardous waste	EUR/t	420			Nontox, Italian data
Revenue for Electric and electronic equipment waste (WEEE) (Supporting components)	EUR/t	-50			Cottes et al. 2023
Revenue for recycled stainless steel 304	EUR/t	-830			Cronimet 2026
Labour cost for employer, per person	EUR/a	40 000			SMAT
Operational cost for the baseline scenario	EUR/m^3 treated water	0.5853			SMAT

*supporting components

Investment cost was estimated using capacity scaling based on reference system investment cost and reference capacity provided by the technology owner. Parameters are presented in Table 27.

Table 27: Investment cost estimation.

Parameters for investment cost estimation	Unit	Value
Reference system investment cost Co	kEUR	700
Reference system water inlet So	m^3/h	50
coefficient k	-	0,77
System water inlet Si	m^3/h	83

System investment cost Ci	kEUR	1035
Sensitivity -min	%	93 %
Sensitivity – max	%	114 %
Economic lifetime	a	12

9.0 Annex 2: Basis for Use Case 5

9.1.1 Flowsheet definition

A simplified flowsheet of the Pera Galini leachate treatment plant is presented in Figure 29, including also the demonstration of Use Case 5. Figure 29 shows the old process line consisting of physical and chemical treatment, followed by MBR and RO. A parallel line illustrates a new RO (operating since 2024) without any pre-treatment. It also shows the location of EDEN microfluidic system in the Use Case 5 demonstration.

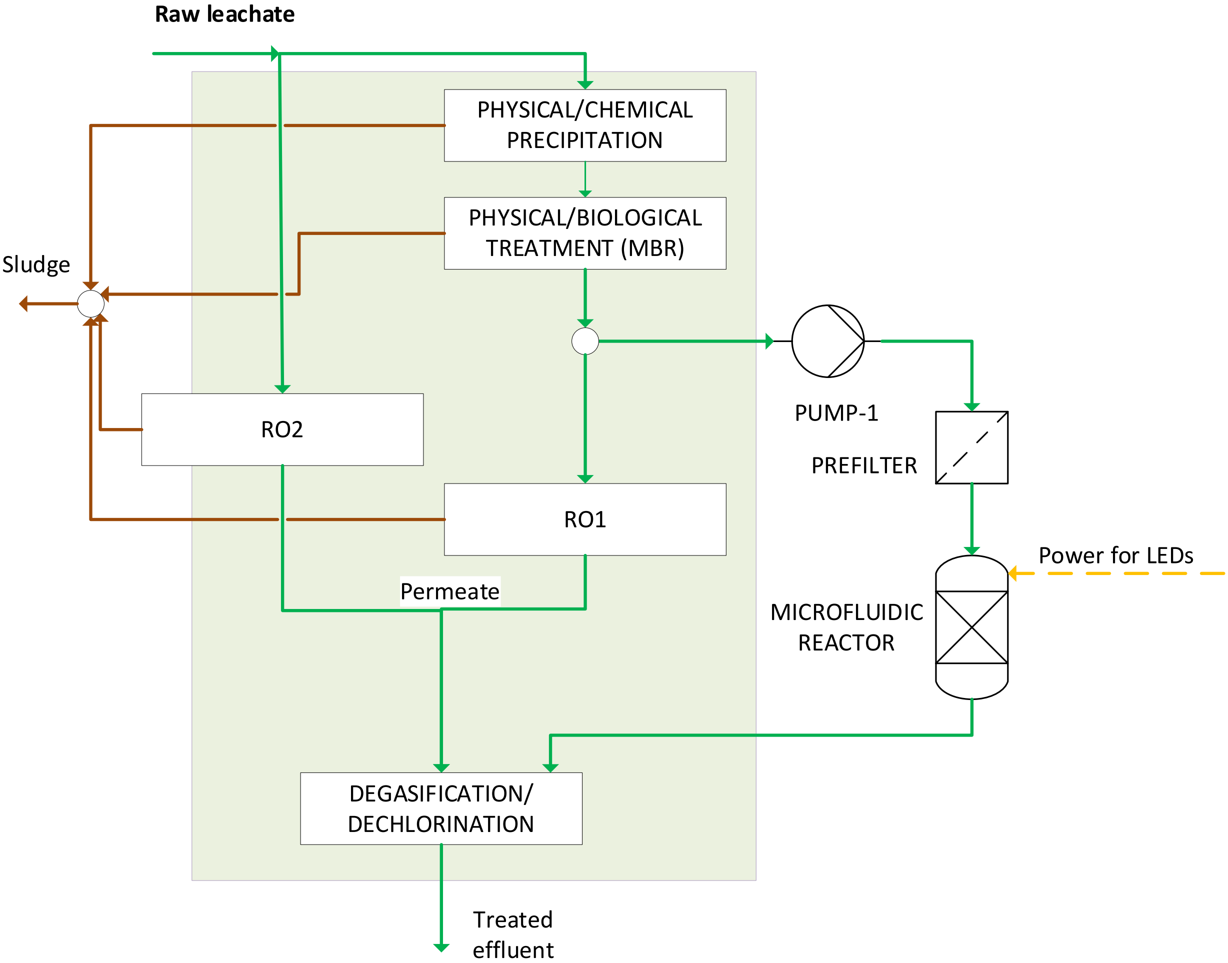

Figure 29: Flowsheet of Use Case 5.

9.1.2 Mass and energy balances based on experimental data

Industrial scale mass and energy balances for the new RO system and EDEN microfluidic system based on experimental and ESDAK data are presented in Table 28. Table 28 indicates the benefits if microfluidic system in comparison to RO regarding the chemical and energy consumption.

Table 28: Comparison of the state-of-the-art technology and iMERMAID technology (EDEN microfluidics).

		RO		EDEN microfluidic system	
		Industrial scale	Functional unit	Industrial scale	Functional unit
IN		t/a	m3/m3	t/a	m3/m3
	TOTAL	**11 149**		**11 149**	
	Treated wastewater	11 149	1	11 149	1
	Chemicals	t/a	kg/m3	t/a	kg/m3
	Sulphuric Acid H2SO4 98%	27.08	2.43	-	-
	Antiscalant	0.18	0.02	-	-
	Polyelectrolyte	0.18	0.02	-	-
	PAC 18%	2.35	0.21	-	-
	Sodium hydroxide NaOH	0.11	0.01	-	-
OUT		t/a	m3/m3	t/a	m3/m3
	TOTAL	**11 149**		**11 149**	
	Treated wastewater	7 247	0,65	11 037	0,99
	Wastewater (outlet retentate)	3 902	0,35	111	0,01
Energy		MWh/a	kWh/m3	MWh/a	kWh/m3
	Electricity	81,21	7,28	10,26	0,92

The selected model compounds to demonstrate the remediation potential were bisphenol A, bentazone and propamocarb. The tests prior demonstration indicated good remediation potential but in the demonstration the results were confusing. The remediation potential in this assessment was based on the test results at 11th March (Table 29).

Table 29: Remediation potential of the target compounds.

Remediation potential	Inlet concentration	Outlet concentration	Reduction
	kg/m3	kg/m3	
Bisphenol A (BPA)	4,00E-03	2,99E-03	25 %
Bentazone	6,60E-06	5,00E-06	24 %
Propamocarb	2,53E-05	1,97E-05	22 %

9.1.3 Economic parameters and investment cost estimation

Unit costs of chemicals, utilities and waste fractions for iMERMAID scenario are presented in Table 30, as well as the operational cost of the baseline scenario (Pera Galini leachate treatment plant).

Table 30: Prices of chemicals, utilities and waste fractions for Use Case 5.

	Unit	Baseline	Min	Max	Reference
Sulphuric Acid H2SO4 98%	EUR/t	350			ESDAK
Antiscalant	EUR/t	3 600			ESDAK
Polyelectrolyte	EUR/t	4000			ESDAK

PAC 18%	EUR/t	650			ESDAK
NaOH 50%	EUR/t	600			Estimate
Electricity cost	EUR/MW	140			ESDAK
Maintenance cost (EDEN)	EUR/a (m3 treated wastewater)	0.075	0.05	0.1	EDEN
Wastewater cost	EUR/t	0.76			ESDAK
Labour cost for employer, per person	EUR/a	30 000			ESDAK

Investment cost estimates are based on the reference costs presented in Table 31. RO cost estimate is used in the baseline scenario and RO scenario. MF filtration was selected for pre-filtration system in the iMERMAID scenario, as the hollow fiber membrane system was considered unsuitable based on the demonstration.

Table 31: Investment cost estimation for EDEN microfluidic system, RO filtration and MF filtration.

	Reference Investment cost	Reference capacity	Lifetime of system	Lifetime of membranes	Replacement cost of membranes	Reference
	EUR	m^3/h	a	a		
RO	350 000 EUR	5	20	5	22 500 EUR	ESDAK
EDEN microfluidic system	120 000 EUR	2	3	-		EDEN
MF*	4000 EUR/ (m^3/h permeate)	-	20	3	20 EUR/m2	VTT inhouse estimation

*assumption flux 650 l/m^2h

The Mediterranean Sea and its surrounding regions support a diverse variety of essential socioeconomic activities. It is one of the highly exploited water ways and the influence of anthropogenic activities on its marine habitats and ecosystems has grown significantly since the industrial revolution. Because of this, the Mediterranean Sea basin is very vulnerable to chemical contamination and build-up. To safeguard the Mediterranean Sea basin from contaminants for emerging concerns (CoEC), iMERMAID will integrate, coordinate, and synergize innovative preventive, monitoring, and remediation solutions. iMERMAID will build an evidence-based multidimensional framework that will guide policymaking and transform societal perceptions to reduce CoEC usage, emissions, and pollution. Furthermore, next generation sensor and remediation solutions will be developed within iMERMAID to monitor and remove prioritized chemicals from its source while reducing upstream pollution. iMERMAID builds an ideal interdisciplinary team by bringing together prominent SMEs, researchers, regulators, and innovation professionals who have been essential in improving the knowledge and awareness of CoEC. Beyond state-of-the-art techniques, iMERMAID will strive to strengthen regulations against CoEC, expand economic possibilities and competitiveness, improve the standard of living for EU residents, while preventing the accumulation of chemical pollution in the Mediterranean Sea basin. iMERMAID will empower the efforts to create a zero pollution, contaminant free waters by enabling the Chemical Strategy's goals to become a practical reality.

iMERMAID

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