Project acronym	Life Bitmaps
Project full title	Pilot technology for aerobic Biodegradation of spent TMAH Photoresist solution in Semiconductor industries
Project Number	**LIFE15 ENV/IT/000332**

Deliverable C1	Action C1 – Environmental assessment of the project and of impact indicators
Annex - Document title	ANNEX C1_3_Environmental impact assessment including LCA and LCC results conclusions and recommendations
Revision no.	2
Document date	28 march 2020
Due date of deliverable	30 November 2019
Dissemination level	Consortium
Responsible partner	UNIVAQ
Contributing partners	All partners
Reviewing partners	All partners

Dissemination level		
PU	Public	
PP	Restricted to other programme participants (including Commission Services)	
RE	Restricted to a group specified by the consortium (including Commission Services)	
CO	Confidential, only for members of the consortium (including Commission Services)	

Revision Chart and History Log		
Version	Date	Comment
1		Rev 1 submitted to partners for internal review
2		Approved

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Sommario

1. Introduction

This deliverable provides the Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) for the treatment of residual effluents produced by LFoundry srl and developed within Life Bitmaps project. The input of the study are the mass and energy balances coming from the process analysis considering the pilot and full- scale Life Bitmaps plant. Simulations have been arranged taking into account the data obtained from experimental activity. A Life Bitmaps plant has the capability to treat three type of wastewater:

- TMAH and photoresist wastewater
- BOE wastewater
- SEZ wastewater

The first effluent is treated by biological process, instead the other two wastewaters are treated by chemical/physical ones adding lime in the presence of coagulant to remove the impurities.

LCA has been performed in order to assess the environmental impacts associated with all stages of the lifecycle of the studied processes and for comparison with the current disposal approach.

LCC has been performed to estimate the total cost of a plant using the Life Bitmaps processes. It takes into consideration all cost including first costs, such as capital investment costs, purchase and installation costs, operating cost including also the disposal.

LIFEBITMAPS

2. Goal and scope of the LCA study

2.1 Goal of the study

The main goal of the present document is that to investigate the environmental assessment and the economic convenience of the Life Bitmaps processes. The results for the pilot and full-scale plant have been reported considering the mass and energy balances of the processes in pilot and full scale, respectively.

In particular the LCA study has the aim to identify the main process criticalities by a life cycle impact assessment (LCIA), which includes both the classification and characterization steps and the normalization and weighting phases. The study is carried out by the thinkstep GaBi software-System and Database for Life Cycle Engineering (compilation 7.3.3.153; DB version 6.115), used for the production processes of energy and raw materials and the quantification of the environmental impact of the treatments, following the recommendation of ISO 14040:2006 norm. In particular LCIA is starting from the preliminary analysis made to catch the LCI (Life Cycle Inventory) which was a previous deliverable of the BITMAPS project (ANNEX C1_2_ LCI definition of flows of all inputs and outputs of the structured system).

The impact categories and the related characterization methods are selected in agreement with the Product Environmental Footprint (PEF) guidelines and the ILCD recommendation. A further normalization and weighting step allows the determination of the relevance of the different environmental impact categories. The analysis is useful for both the audience within the project and the external stakeholders, as a support tool for future decisions.

2.2. Scope of the study

2.2.1 Functional unit

The adoped processes allow the treatment of three kinds of wastewater, characterized by a different composition, that need specific treatment, before the final disposal. The functional unit chosen for the analysis is 1 kg of wastewater for pilot scale analysis and the current annual production for each considered wastewater for the full-scale analysis. More in detail, the streams are the following:

Wastewater with TMAH and photoresist

Wastewater with NH4F (BOE)

Wastewater with nitrates, fluorides, phosphoric acid and acetic acid (SEZ)

2.2.2. System boundaries

Fig. 1 describes the system boundaries considered for the innovative LFOUNDRY technology, including the three lines of interest. The first flow is treated by a neutralization with sulfuric acid, followed by a biological treatment, that represents an innovation introduced by the project. Moreover, the innovative treatment of the second and the third lines consists of a precipitation using lime, with the addition of $Al_2(SO)_4 {}^* 18H_2O$, as coagulant. Both operations include the final filtration for the separation of solid and liquid products. The water supply is included for the raw materials dilution and the liquid flows produced at the end of the three lines are treated in the biological reactor already available within the applicant facilities, before the final discharge. An average Italian power mix is chosen as energy source to feed all the main process blocks. As concerns the solid waste produced by the second and the third lines, the classification as not hazardous was confirmed by the pilot plant tests.

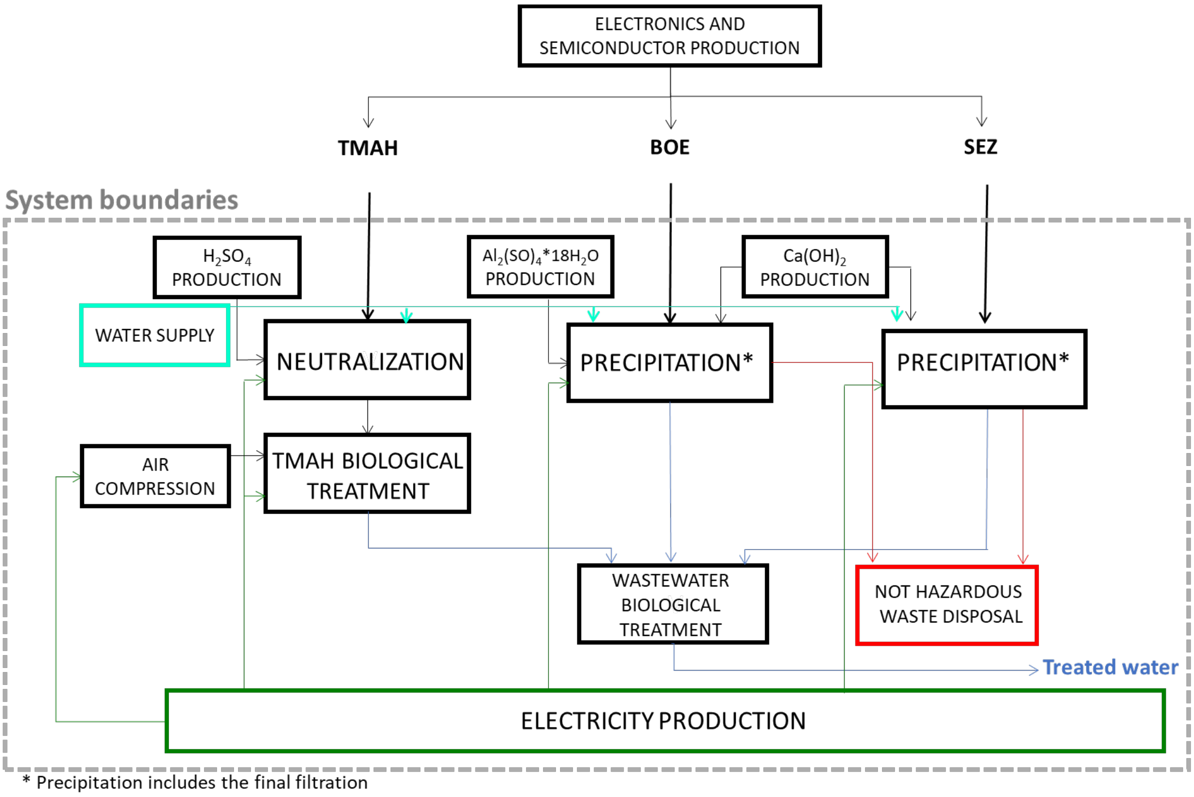

Figure 1: System boundaries for the Life Bitmaps processes

On the other hand, Fig. 2 shows the system boundaries for the wastewater management strategy currently applied by the project applicant, selected for the final comparison with the innovative approaches. The TMAH flow is treated by ion exchange and discharged; the resin is regenerated by a sulfuric acid solution, that is then neutralized with sodium hydroxide, and managed as not hazardous wastewater by external companies. The resin regeneration can be carried out for two year at most, thereafter the material is disposed as hazardous waste. On the other hand, BOE and SEZ flows are not processed inside the facilities of the applicant, and they are managed as hazardous wastewater, also in this case by external companies. In order to have an overview of current option environamental loads, the transport toward these companies is included within the system boundaries.

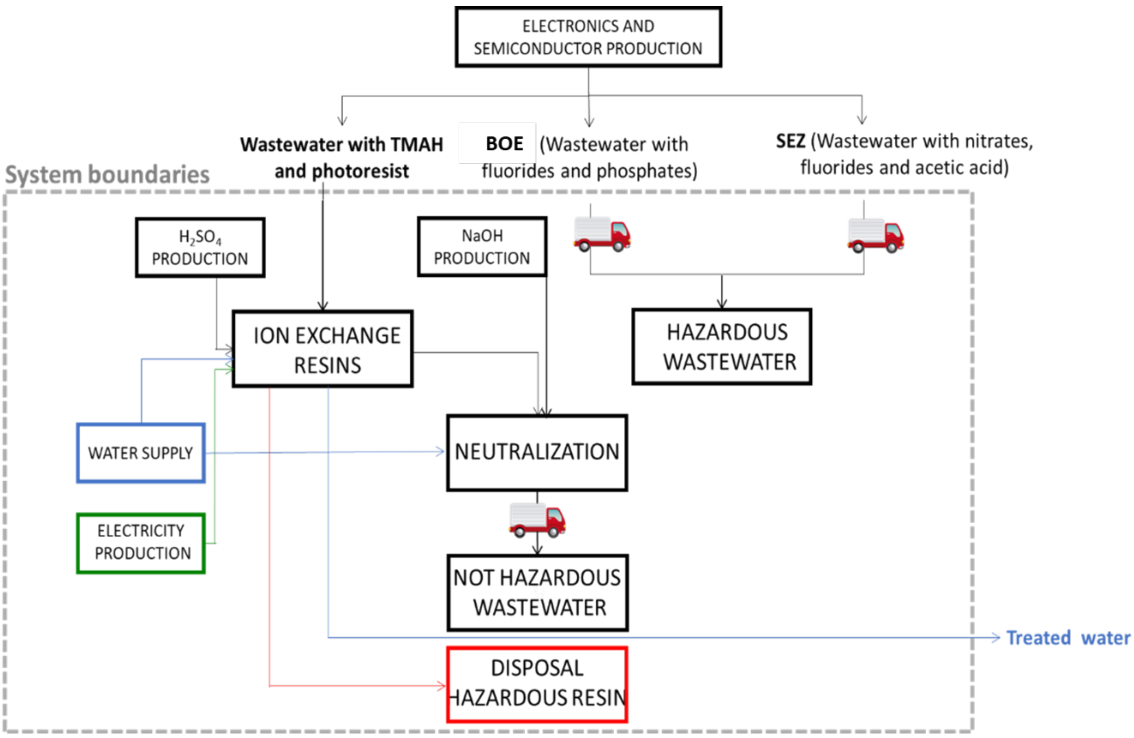

Figure 2: System boundaries for the current wastewater treatment

2.2.3. Assumptions and allocations

In order to solve the lack of details related to the production process of $Al_2(SO)_4*18H_2O$ (used in both BOE and SEZ lines) within the reference database, we considered the synthesis reaction reported in Eq. 1, substituting the $Al(OH)_3$ with the origin mineral bauxite. To overcome the problem of the impurities content, that makes less concentrated than a pure raw material, we assumed double the stoichiometric amount of aluminum hydroxide.

$2Al(OH)_3 + 3H_2SO_4 + 12H_2O \rightarrow Al_2(SO_4)_3 *18H_2O$ (Eq.1)

3. Life Cycle assessment and Life cycle cost of the pilot scale LIFEBITMAPS plant

3.1. Life Cycle inventory: mass and energy balances

Data reported in Table 1 summarize material and energy balances used as input for the inventory analysis.

Input	Output
Line 1: Wastewater with TMAH and photoresist	
Wastewater, 7 kg/h	Treated wastewater, 7 kg/h
Sulfuric acid (98%), 0.013 kg/h	
Water, 0.030 kg/h	
Electricity, 2.7 kW	
Line 2: Wastewater with NH4F (BOE)	
Wastewater, 33 kg/h	Treated wastewater, 77 kg/h
Lime, 10 kg/h	Solid waste, 7 kg/h
Water 40 kg/h	
$Al_2(SO)_4 \cdot 18H_2O$, 1 kg/h	
Electricity, 4.5 kW	
Line 3: Wastewater with nitrates, fluorides and acetic acid (SEZ)	
Wastewater, 33 kg/h	Treated wastewater, 72 kg/h
Lime, 9 kg/h	Solid waste, 5 kg/h
Water, 34 kg/h	
$Al_2(SO)_4 \cdot 18H_2O$, 1 kg/h	
Electricity, 4.5 kW	

Table 1. Input and output involved within the LIFE BITMAPS innovative processes (data based on the pilot plant capacity)

These quantities are used as input for the assessment. The achieved results are reported and discussed below.

3.2. Life cycle impact assessment

3.2.1. Classification and characterization

Fig. 3 reports the environmental load of the innovative LIFE BITMAP processes, for the three lines, estimated for 1 kg of wastewater. The impact was estimated in the most relevant categories, following the guidelines of the European Commission. As concerns the global warming potential, emissions of 0.1, 0.45 and 0.4 kg/CO2/kg wastewater have been estimated for TMAH, BOE and SEZ, respectively. According to the results achieved in most of the categories, the treatment of BOE and SEZ was more impacting than the TMAH, mainly due to the use of lime in the precipitation operation and to the solid waste disposal. Energy consumption was also responsible for the impact in relevant categories, such as ozone depletion and resources depletion potential.

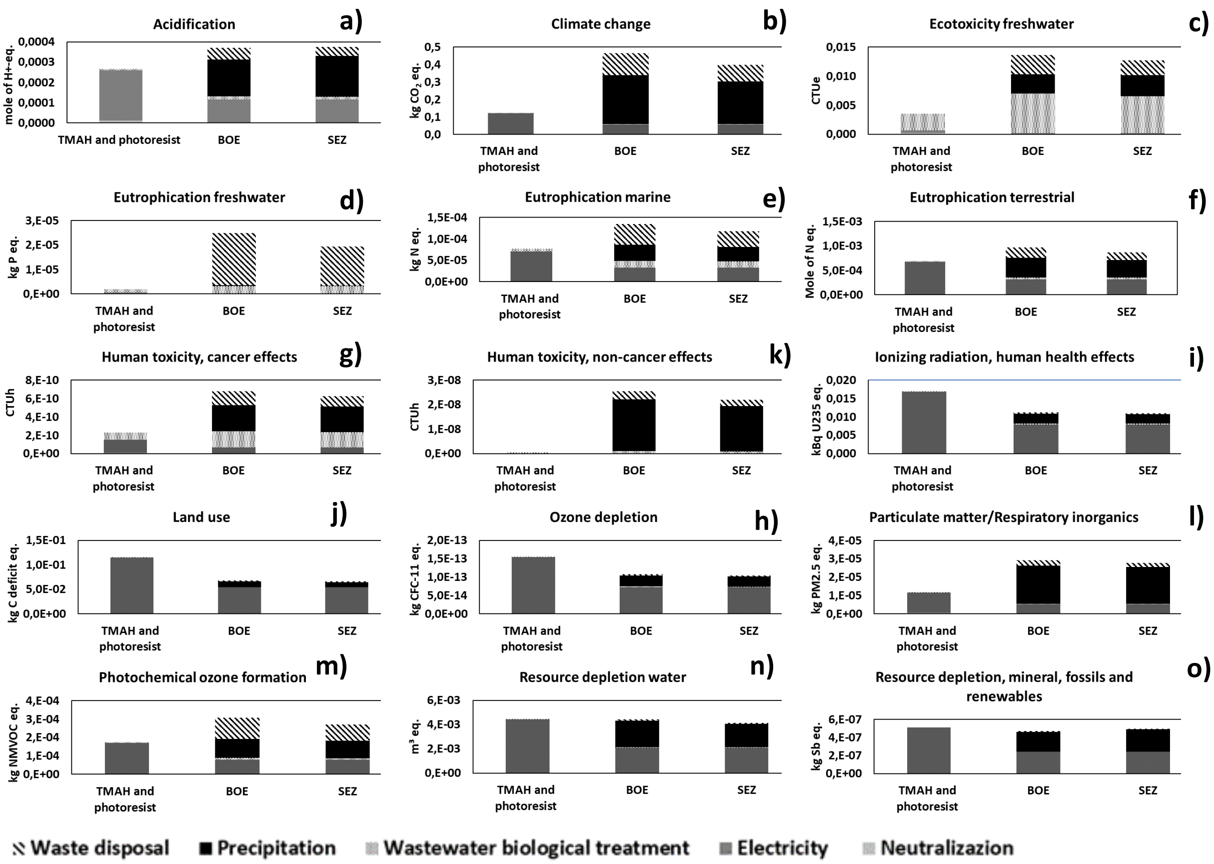

Figure 3: Environmental impact of the LIFE BITMAP processes (Functional unit: 1 kg wastewater).

3.2.2. Normalization and weighting

In order to have an overview of the environmental load of the three lines, Fig. 4 shows the normalized and weighted results, that allow to compare the three innovative technologies and to identify the most critical impact category. It can be observed that the treatment of BOE is the most impacting for the environment, followed by the SEZ and the TMAH treatment. Moreover, the climate change results to be the most affected category.

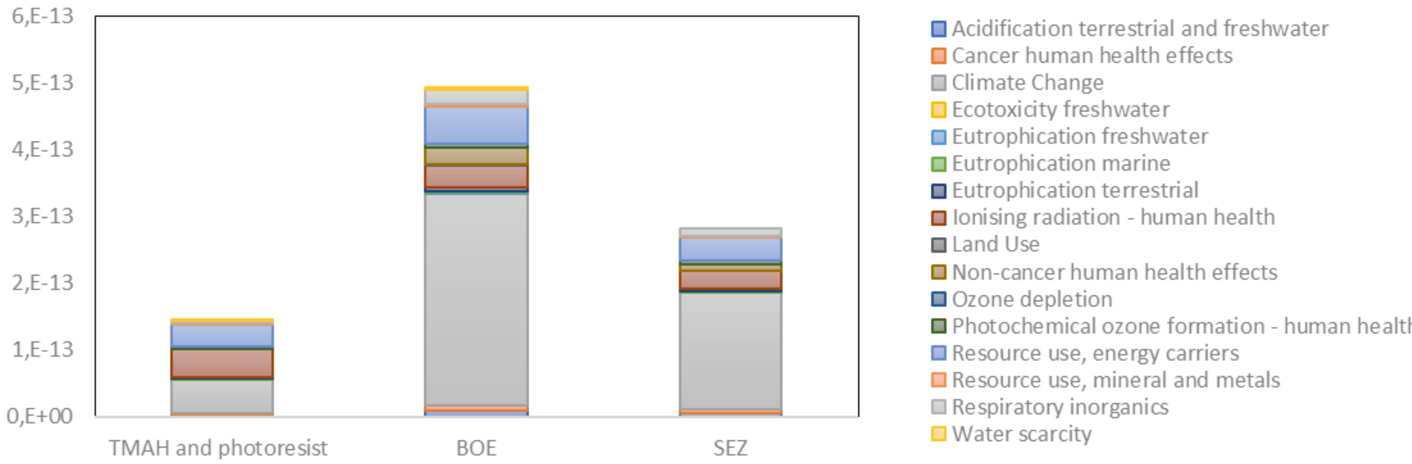

Figure 4: Output of the normalization and weighting step of LCIA (Functional unit: 1 kg of wastewater).

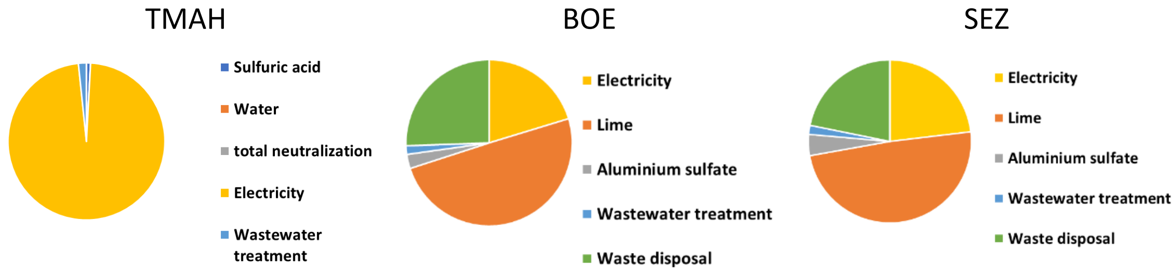

Figure 5: Relative contribution to the total environmental impact of each process in the system boundaries

As displayed by the pie charts in Fig. 5, the electricity production is the main critical issue for the TMAH, while the use of lime and the solid waste disposal (as not-hazardous waste) represents a significant contribute for both the BOE and SEZ treatments.

3.3. Life Cycle Cost analysis

3.3.1. Material and methods

In this section, the results about the life cycle cost analysis (LCC) based on the mass and energy balances defined for the pilot-scale facility are reported. In according to ISO 14040 (2006)[1], the first phase of life cycle cost analysis (LCC) is to define the goal and scope of the study including the description of the product or process system, the function of the operations, the functional unit, the system boundary, data requirements, assumptions and limitations. All that information are above reported (*see Section 2*).

Summarizing the functional unit chosen for the analysis is 1 kg of wastewater, irrespective of the annual stream production at L-Foundry facility, for each considered wastewater:

1) Wastewater with TMAH and photoresist (PR)
2) Wastewater with NH_4F (BOE)
3) Wastewater with nitrates, fluorides, phosphoric acid and acetic acid (SEZ)

The main item costs considered for the analysis were: (1) equipment cost, (2) raw material purchase, (3) energy cost and (5) transport and disposal of solid waste.

LCC are those incurred over the life span of a process system, including costs required to construct, equipment, and operate the system. For each treatment process, a general, annual cost estimation was developed consisting of the recurring costs (RC), also known as operation and maintenance costs, and the non- recurring costs (NRC), otherwise known as capital costs, converted to an annual cost basis ([2]Dhillon 2010). Moreover, it has been considered 5% of contingency applied to the overall annual. The general equation used for the analysis model is:

Annual LCC = RC + NRC (1)

More in details, RC include annual labor costs, operational energy costs and maintenance (repair) cost and purchase cost for the chemicals and disposal costs for the produced waste. Non recurring costs (NRC) include the capital investment like the equipment cost, piping, engineering, that are amortized in X years.

Swarr et al. (2011)[3] reports the following methodological framework for the estimation of LCC costs:

LCC = CC +IRC + FC + VC + WMC + TC – S (€/functional unit) (2)

Where

LCC total life cycle costs

CC capital costs (plant infrastructure, equipment cost and supporting parts)

IRC infrastructure replacement costs (In the specific case is not considered because the LCC costs is considered for 5 years that is the period of depreciation of the equipment, hence in this period it has been assumed that not replacement of infrastructure is necessary)
FC fixed operating costs (is the cost of materials and energy which are used regardless of the level of treatment or sludge. In the specific case is not considered)
VC variable operating costs (is the cost of materials and energy whose usage varies depending on the level of wastewater treatment. In VC, the labour cost is also considered). In this specific analysis, it has assumed that one worker can manage the pilot plant, considering that the biological section is almost completely automatic, and the chemical section can work in batch/mode. The annual cost of the personnel has been assumed of 50,000 €/year.

WMC waste management costs (include landfill and incineration of waste. In the specific case it has been considered the cost of disposal of solid in landfill)
TC transport costs (in the specific case TC is included on WMC)
S revenue (in this specific case, S is not considered).

3.3.2. Results and discussions

For LCC analysis it has been considered, the following operation mode:

- Continuous operation for TMAH/Photoresist wastewater treatment (7 kg of effluent/batch, a basis of 330 days per year, 7920 h operating rime)
- Batch mode for BOE treatment, 33 kg of effluent/batch of BOE per 150 batch per year
- Batch mode for SEZ treatment, 33 kg of effluent/batch of SEZ per 50 batch per year

Note: it has been assumed that the pilot plant can work as an industrial full scale plant.
The main equipment for TMAH treatment is represented by the neutralization reaction and three biological reactors in series and a clarification step; instead for BOE and SEZ treatment the main equipment are a chemical reactor and a filter press.
The main item costs considered for the analysis were: (1) equipment cost, (2) raw material purchase, (3) energy cost (4) labour cost and (5) disposal of solid waste that include also the transport cost.
The Direct Fixed Capital (DFC) is fixed to 446,000 € (equipment cost, piping, engineering, …) (real quotation of the pilot plant). Straight line depreciation over 5 years is considered with an index of 7.7. Each data is reported per kg of residual effluents (sum of TMAH, BOE and SEZ) that could be treated in one year.
The life cycle costs (*See Eq. 2*) during the depreciation time (5 years) of the wastewaters are summarized in *Fig. 6.* Capital cost includes also the contingency.

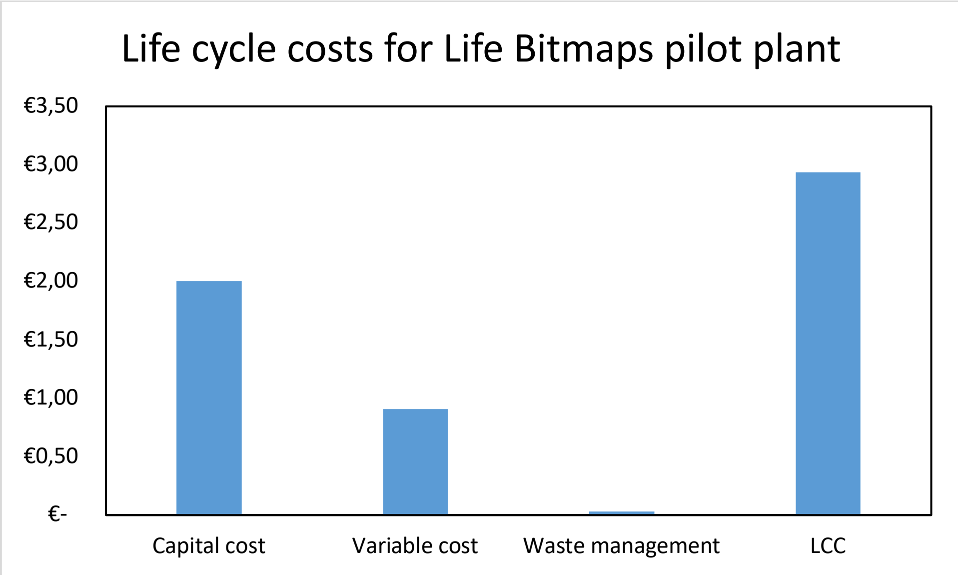

Figure 6: Life cycle costs of TMAH, BOE and SEZ treatment during depreciation time (€/kg of effluent)

The total cost is estimated to be the 2.94 €. The main contributor to the total LCC are the capital costs (more in details the investment for the purchase and commissioning of the pilot plant), that is near to 68% to the total costs, followed by the variable operating ones (30%). Personnel cost represent about 85% of variable operating costs (*Fig. 7*), other costs are less important under the considered assumption described above.

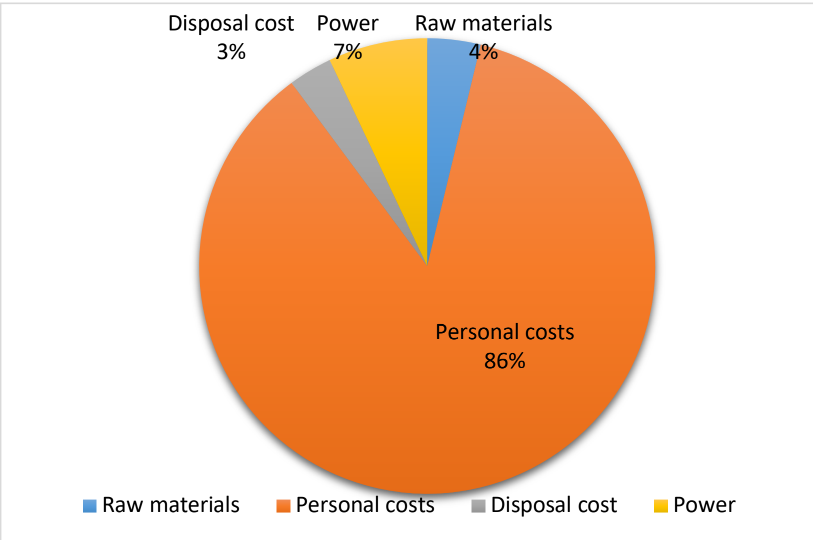

Figure 7: Contribution of different issue to the variable operating costs of TMAH, BOE and SEZ effluent treatment

Excluding the personal cost, it is possible to highlight the incidence of the other voice on OPEX.

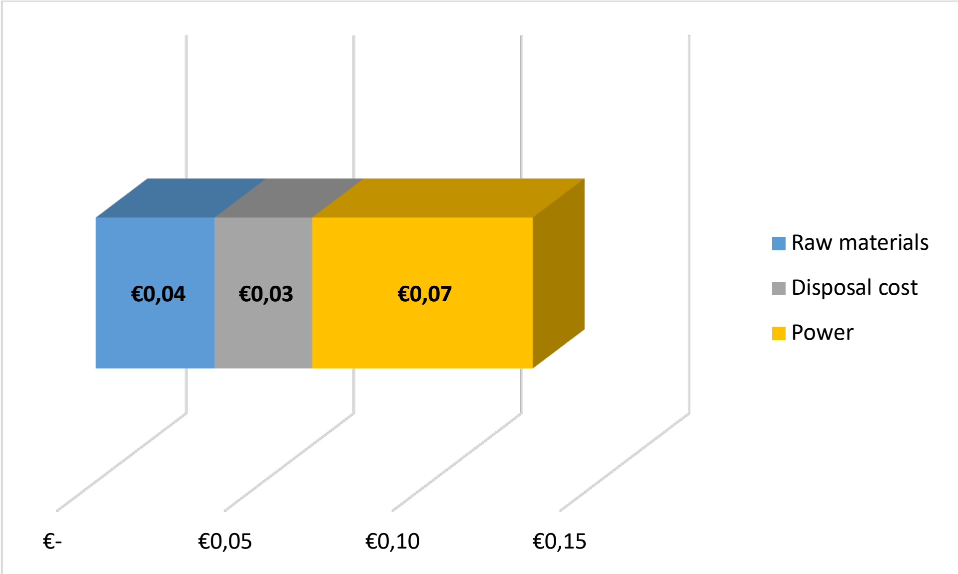

Figure 8: Contribution of different issue to the variable operating costs of TMAH, BOE and SEZ effluent treatment excluding the personnel cost (€/kg of effluent)

Raw materials cost includes the purchase of reagent, sulfuric acid for the neutralization operation, lime and aluminium sulphate for chemical precipitation.
The following tables report the details of the cost for each treatment: TMAH and photoresist, BOE and SEZ.

Variable cost for 1 kg of TMAH/Photoresist wastewater				
Issue		Unit	**Unit cost**	**€/kg of TMAH/PR wastewater**
TMAH/PR in	1	kg		
Sulfuric acid 98%	0.0019	kg/kg of TMAH	0.15 €/kg of reagent	0.0003
Water	0.0043	kg/kg of TMAH	0.0001 €/kg of water	0.0000
Electricity	0.3857	kWh/kg of TMAH	0.1 €/kWh	0.0386

Table 2: Variable costs estimated considering the treatment of 1 kg of TMAH/PR wastewater

The operative cost for the treatment of 1 kg of TMAH/PR is 0.039 €, excluding the personal cost.

Variable cost for 1 kg of BOE wastewater				
Issue		Unit	**Unit cost**	**€/kg of BOE wastewater**
BOE in	1	kg di BOE		
Lime solid	0.30	kg/kg of BOE	0,05 €/kg of reagent	0,015
Water	1.21	kg/kg of BOE	0,0001 €/kg of water	0,000
Aluminium sulphate	0.03	kg/kg of BOE	0,1 €/kg of reagent	0,003
Electricity	0.14	kWh/kg of BOE	0,1€/kWh	0,014
Solid waste	0.21	kg/kg of BOE	0,08 €/kg of solid to disposal	0,017

Table 3: Variable costs estimated considering the treatment of 1 kg of BOE

The operative cost for the treatment of 1 kg of BOE is 0.049 €, excluding the personal cost.

Variable cost for 1 kg of SEZ wastewater				
Issue		Unit	**Unit cost**	**€/kg di SEZ wastewater**
SEZ in	1,00	kg		
Lime solid	0,27	kg/kg of SEZ	0,05 €/kg of reagent	0,014
Water	1,03	kg/kg of SEZ	0,0001 €/kg of water	0,000
Aluminium sulphate	0,03	kg/kg of SEZ	0,1 €/kg of reagent	0,003
Electricity	0,14	kWh/kg of SEZ	0,1€/kWh	0,014
Solid waste	0,15	kg/kg of SEZ	0,08 €/kg of solid to disposal	0,012

Table 4: Variable costs estimated considering the treatment of 1 kg of SEZ

The operative cost for the treatment of 1 kg of SEZ is 0.03 €, excluding the personal cost.

Electricity is the main operative cost (excluding personnel cost) for the treatment of TMAH/PR wastewater due to the energy consumption for mixing system and aeration system. For BOE, the main cost is the disposal cost, following by the lime consumption and electricity. Instead for SEZ, the main cost are the energy consumption and purchase of lime solid, followed by the disposal cost of the residual solid.

4. Life Cycle assessment and Life cycle cost of the full scale LIFEBITMAPS plant

4.1. Life Cycle inventory: mass and energy balances

Data reported in Table 5 summarize the input and output flows per hour involved within the three lines of interest. This information was used for both the classification and characterization step and the normalization and weighting phase. Furthermore, the final result was compared with the environmental load due to the current treatments (described in Table 6).

Input	Output
Line 1: Wastewater with TMAH and photoresist	
(continuous operation; plant capacity 800 kg/h; 7920 operating hours/year)	
Wastewater, 800 kg/h	Treated wastewater, 810 kg/h
Sulfuric acid (98%), 3 kg/h	
Water, 7 kg/h	
Electricity, 80 kW	
Line 2: Wastewater with NH4F (BOE)	
(batch operation; 150 batch/year; 2h per batch)	
Wastewater, 2900 kg/batch	Treated wastewater, 4968 kg/batch
Lime, 684 kg/batch	Solid waste (about 50% dry), 1470 kg/batch
Water 2737 kg/h	
$Al_2(SO)_4 * 18H_2O$, 116 kg/batch	
Electricity, 50 kWh/batch	
Line 3: Wastewater with nitrates, fluorides and acetic acid (SEZ)	
(batch operation; 50 batch/year; 2h per batch)	
Wastewater, 2900 kg/batch	Treated wastewater, 4874 kg/batch
Lime, 679 kg/batch	Solid waste (about 50% dry), 1535 kg/batch
Water, 2714 kg/batch	
$Al_2(SO)_4 * 18H_2O$, 116 kg/batch	
Electricity, 50 kWh/batch	

Table 5: Energy and mass balances involved within the LIFE BITMAPS innovative processes

Input	Output
Line 1: Wastewater with TMAH and photoresist	
Wastewater, 800 kg/h	Treated wastewater, 800 kg/h
Sulfuric acid (98%), 5 kg/h	Not haz. wastewater, 307 kg/h
Sodium hydroxide, 2 kg/h	Hazardous resin, 35 kg/year
Deionized water, 300 kg/h	
Electricity, 0.6 kWh	
Resin, 35 kg/h	
Line 2: Wastewater with NH4F (treated by external companies)	
	Hazardous wastewater, 60 kg/h
Line 3: Wastewater with nitrates, fluorides and acetic acid (SEZ), (treated by external companies)	
	Hazardous wastewater, 16.5 kg/h

Table 6: Energy and mass balances involved within the current processes (Functional unit: flow rate for hour, 800 kg/h TMAH, 720 kg/h BOE, 200 kg/h SEZ)

The current approach which requires the treatment of wastewater (flow from neutralization of line 1 and streams from lines 2 and 3) by external companies, causes an environmental load connected with the wastewater transportation. In this regard, Table 7 summarizes the number and the distance of the annual trips, used for the environmental assessment.

Line	Number of trips per year	Distances (km)
Line 1	50	366
Line 2	24	400
Line 3	7	230

Table 7: Annual number and distance of the trips towards the external companies for the current treatment of flow from neutralization of line 1 and streams from lines 2 and 3.

4.2. Life cycle impact assessment

4.2.1. Classification and characterization

Figure 9 reports the environmental load evaluated for the three lines of interest. Overall, it can be observed the highest impact connected with the TMAH line, due to the highest production of such wastewater. Electricity consumption has the highest contribution in most impact categories, as concerns the treatment of TMAH. On the other hand, the BOE and SEZ treatment have a quite high impact due to the lime use in precipitation. The most critical categories are: acidification, climate change, ecotoxicity freshwater, eutrophication marine and terrestrial, human toxicity, cancer and non-effects, particulate matter/respiratory inorganics, photochemical ozone formation, resource depletion water, resource depletion, mineral, fossils and renewables (Figures 3a, b, c, e, f, g, h, l, m, n, o).

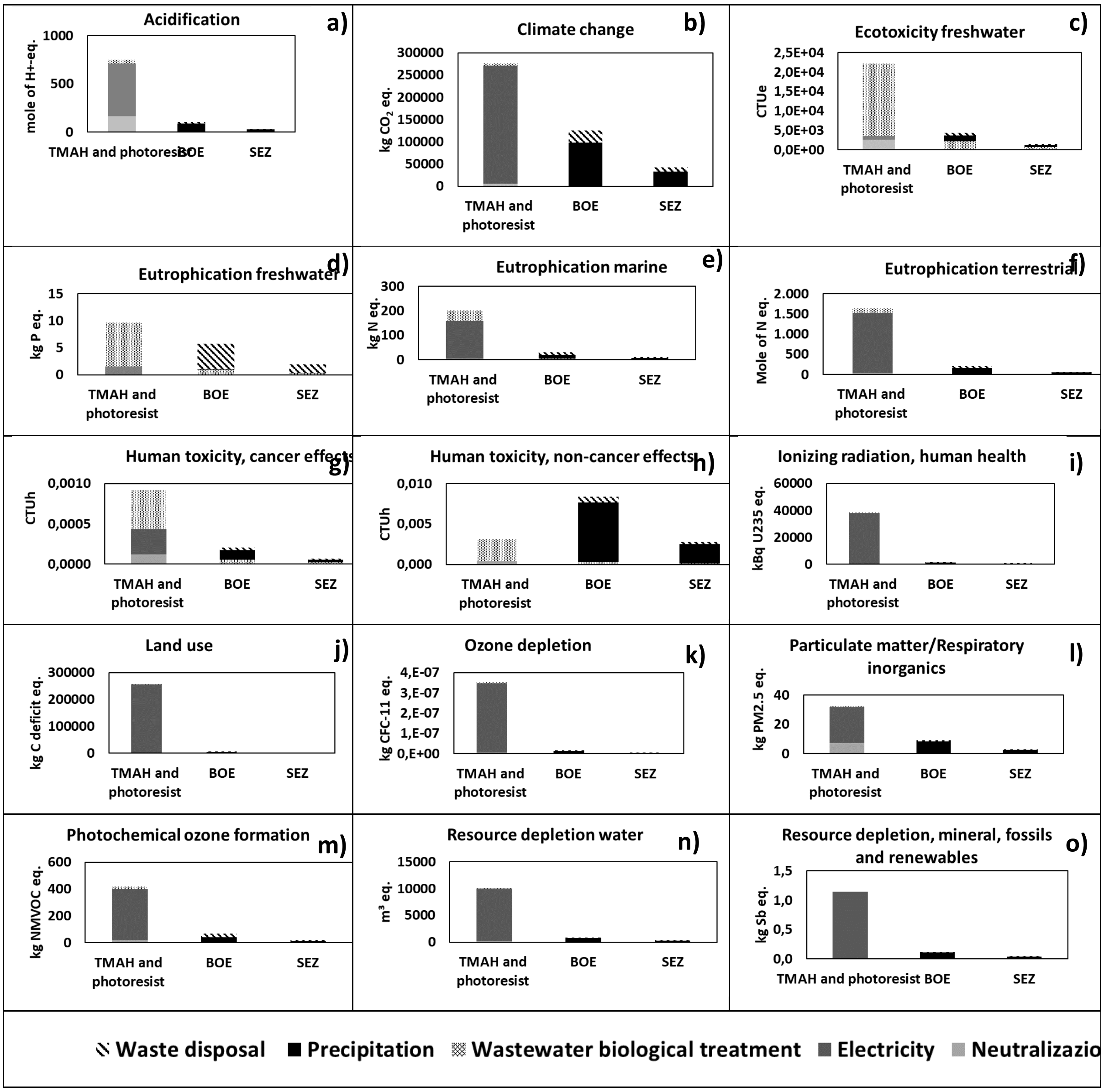

Figure 9: Quantification of the environmental impact of the innovative LIFE BITMAP technologies. (Functional unit: annual production of wastewater, 6300 t TMAH, 435 t BOE, 145 t SEZ)

4.2.2. Normalization and weighting

In order to have an overview of the environmental load of the three lines at issue, Figure 10 shows the normalized and weighted results, identifying the climate change as the most affected categories. As displayed by the pie charts, the lime use is the main critical issue for both the BOE and SEZ treatments (70% and 40%, respectively), in agreement with the results explained within the classification and characterization section.

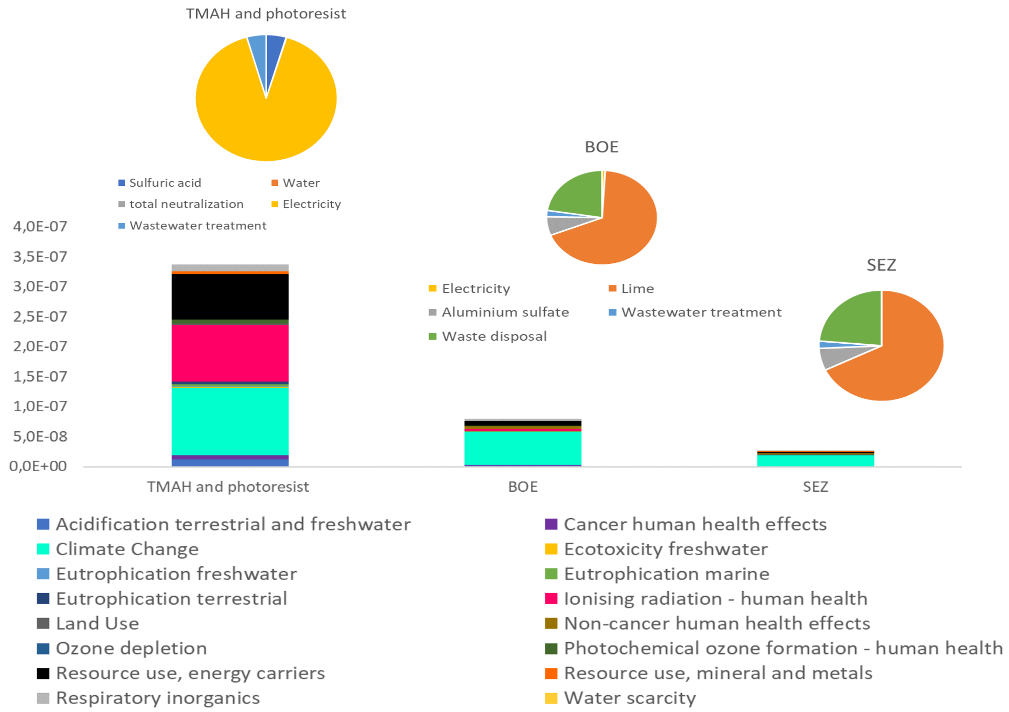

Figure 10. Output of the normalization and weighting step of LCIA. The pie charts show the detail of process contributions (Functional unit: annual production of wastewater, 6300 t TMAH, 435 t BOE, 145 t SEZ)

An interesting achievement is showed in Figure 11, which compares the innovative and the current options. In this case, the total environmental loads were assigned to each line for both the choices. The whole process improvement, with an impact decrease higher than 50%, is evident, mainly thanks to the TMAH process optimization. Comparable results are related to the other two lines, with the advantage of a process carried out within the same facility.

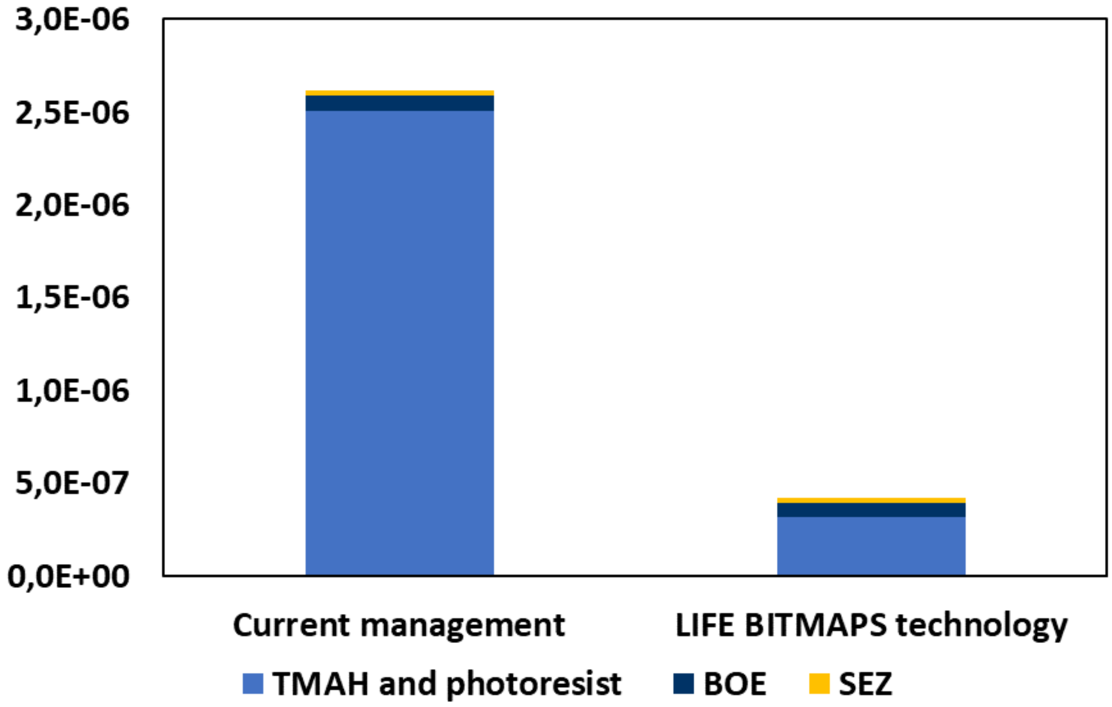

Figure 11: Comparison between the current and the innovative options considering the total normalized and weighted results (Functional unit: annual production of wastewater, 6300 t TMAH, 435 t BOE, 145 t SEZ)

4.3. Life Cycle Cost of the full scale LIFEBITMAPS plant

4.3.1. Material and methods

In this section, the results about the life cycle cost analysis (LCC) based on the mass and energy balances defined for the full-scale facility are reported.
In according to equation 2, Swarr et al. (2011)[3] :

LCC = CC +IRC + FC + VC + WMC + TC – S (€/functional unit) (2)

Where

LCC total life cycle costs

CC capital costs (plant infrastructure, equipment cost and supporting parts)

IRC infrastructure replacement costs (In the specific case is not considered because the LCC costs is considered for 10 years that is the period of depreciation of the equipment, hence in this period it has been assumed that not replacement of infrastructure is necessary)
FC fixed operating costs (is the cost of materials and energy which are used regardless of the level of treatment or sludge. In the specific case is not considered)
VC variable operating costs (is the cost of materials and energy whose usage varies depending on the level of wastewater treatment. In VC, the labour cost is also considered).

WMC waste management costs (include landfill and incineration of waste. In the specific case it has been considered the cost of disposal of solid in landfill)
TC transport costs (in the specific case TC is included on WMC)
S revenue (in this specific case, S is the gain on non-disposal of wastewater in the specific plant off-site)

4.3.2. Results and discussions

4.3.2.1. Economic Evaluation for the treatment of TMAH and Photoresist wastewater (S1) by biological process

A basis of 330 days per year (7920 h) operating time is used for economic analysis, and the nominal capacity of the plant is 800 L/h of TMAH wastewater. The block scheme is shown in *Fig.1*. The main equipment are the three biological reactors in series and a clarification step. The initial flowrate of TMAH wastewater is equal to 800 L/h. The main item costs considered for the analysis were: (1) equipment cost, (2) raw material purchase, (3) energy cost (4) labour cost and (5) disposal of solid waste that include also the transport cost.
The Direct Fixed Capital (DFC) is fixed to 900,000.00 € (equipment cost, piping, engineering, …) (real quotation). Straight line depreciation over 10 years is considered with an index of 7.7. Table 8 shows the operating and waste management cost for the TMAH and Photoresist wastewater treatment.

Item	**€/year**	**€/m^3**	**Note**
Raw materials	€ 3,570	€ 0.56	Sulfuric acid (0.15 €/kg); water 0.0001 €/kg.
Personal costs	€ 17,500	€ 2.76	Estimated
Disposal cost	€ -	€ -	No production of residual solid to disposal
Power	€ 63,360	€ 10.00	Energy cost (0.1 /kWh)

Table 8: Operating variable costs data for the treatment of TMAH and Photoresist wastewater (per m^3 of residual solution)

The life cycle costs (*See Eq. 2*) during the depreciation time (10 years) of the wastewater containing TMAH are summarized in *Fig. 12.*

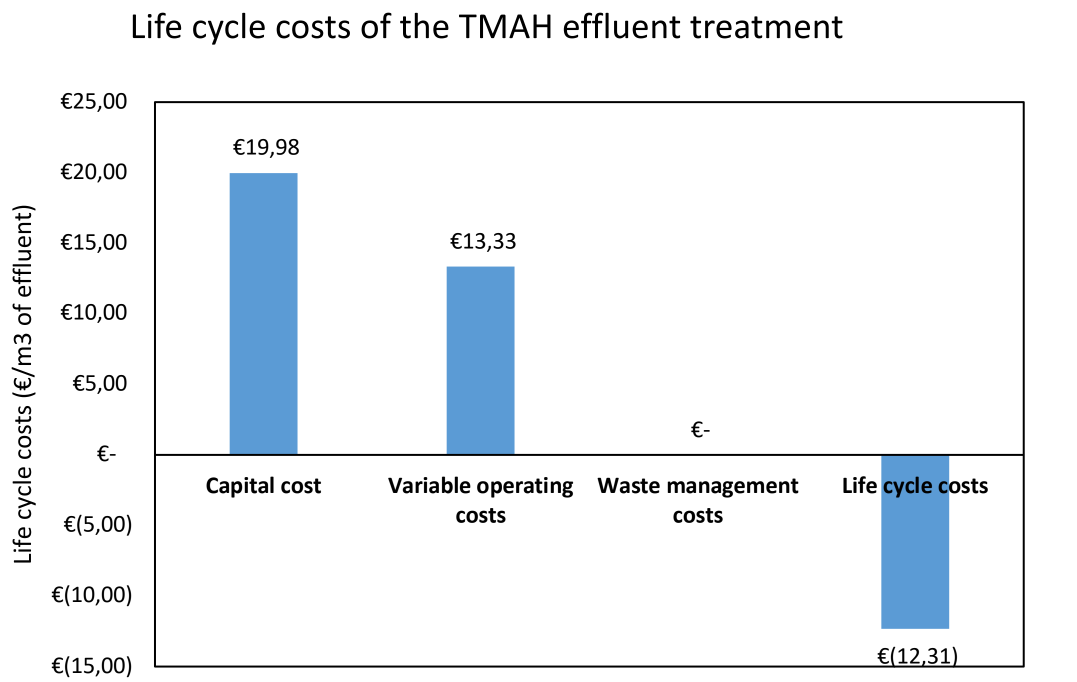

Figure 12: Life cycle costs of the TMAH residual solutions during depreciation time

The costs of biological treatment of TMAH are estimated to be -12.31 €/m^3. It is the net gain obtained by treating TMAH with Life Bitmaps process and avoiding the disposal of wastewater in the specific plant off-site. The main contributor to the total LCC are the capital costs (more in details the investment for the purchase and commissioning of the biological plant), that is near to 60% to the total costs, followed by the variable operating ones. Energy cost represent about 75% of variable operating costs (*Fig. 13*) and in this case are the power for the oxygen supply for the biological reactor, mixing system and pumping station.

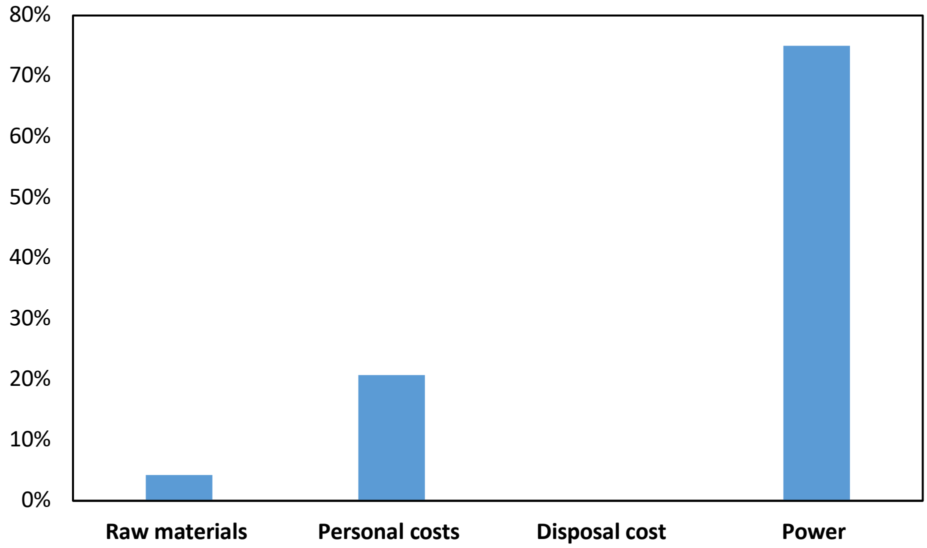

Figure 13: Contribution of different issue to the variable operating costs of TMAH effluent treatment

Fig. 14 describes the total annual costs (€/y) for the considered process. From this Figure, it is also possible to observe that amortization of the plant is the most relevant cost item, followed by the energy consumption.

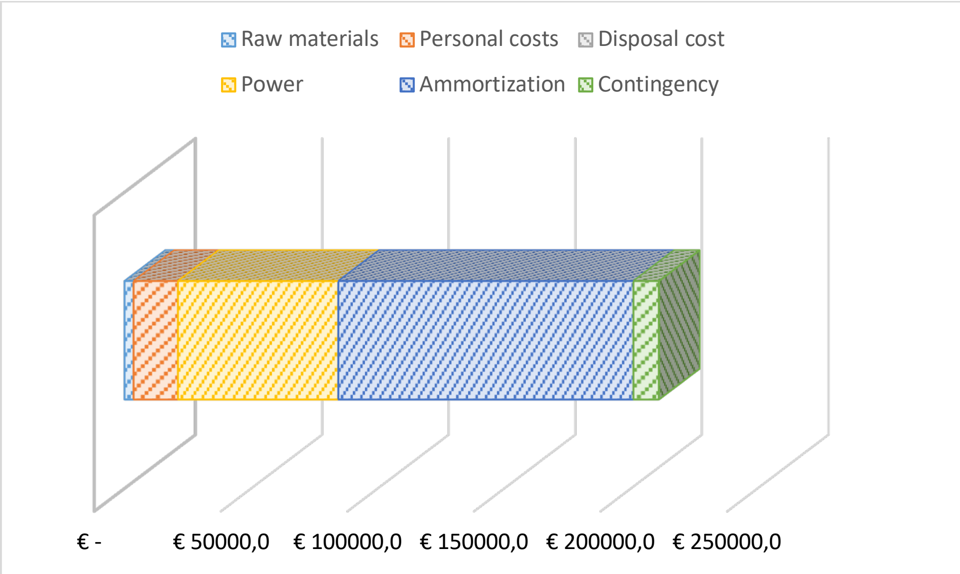

Figure 14: Contribution of different life cycle stages to the costs of TMAH wastewater treatment plant (€/y)

Operating cost (*Operating Expense*, OPEX) is reported in *Fig. 15.* Raw materials cost includes the purchase of reagent, mainly sulfuric acid for the neutralization operation. The main cost item is represented by power consumption, followed by the personal cost. The disposal cost is equal to zero as no waste is produced.

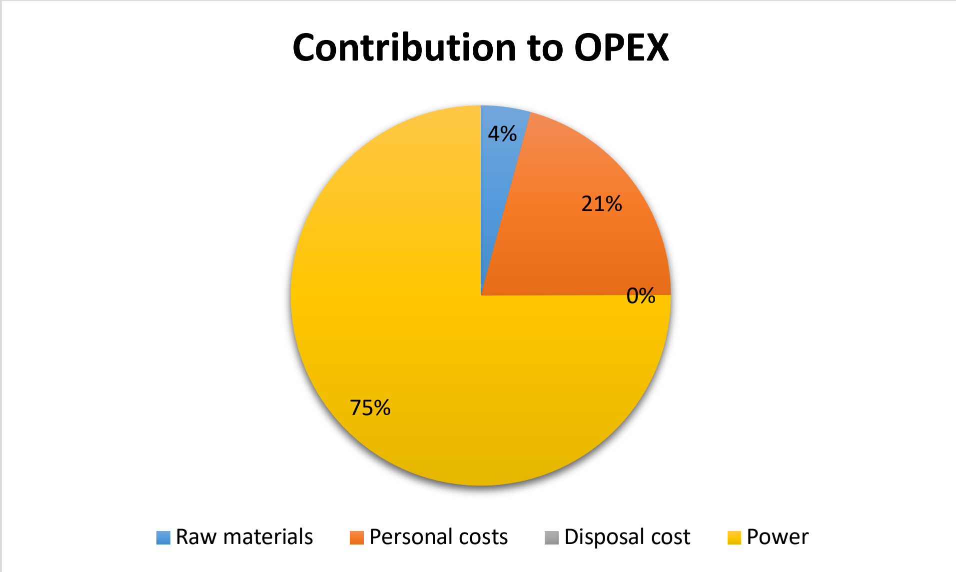

Figure 15: Operating cost for TMAH and Photoresist wastewater treatment

The total annual cost is to 33.31 €/m^3 of TMAH effluent including OPEX, depreciation and contingency, instead the actual disposal cost is 45.6 €/m^3.

4.3.2.2. Economic evaluation for the treatment of BOE wastewater by chemical process

The economic evaluation has been performed in according to the following considerations: batch operation mode, 2900 kg of BOE wastewater per batch and 150 batch/year, annual totaling of 435 ton of BOE. The block scheme is shown in Fig. 1. The main equipment are the chemical reactor and a filter press to separate the solid and liquid. The filtrate is sent to **existing active-sludge plant,** instead the solid is a residual non-hazardous waste that mainly contain CaF_2. This solid could be exploited but in the present analysis it has been considered that the solid is sent to disposal in a specific plant. The main item costs considered for the analysis were: (1) equipment cost, (2) raw material purchase, (3) energy cost (4) labour cost and (5) disposal of solid waste that include also the transport cost. In this case it has been considered a disposal cost of 80 €/ton of solid waste.
The Direct Fixed Capital (DFC) is fixed to 400,000.00 € (equipment cost, piping, engineering, …) (real quotation). Straight line depreciation over 10 years is considered with an index of 7.7. Table 9 shows the operating and waste management cost for the BOE wastewater treatment.

Item	**€/year**	**€/m^3**	**Note**
Raw materials	€ 6,911	€ 15.89	Lime solid (0.05 €/kg); water 0,0001 €/kg; aluminium sulfate (0.1 €/kg)
Personal costs	€ 17,500	€ 40.23	Estimated
Disposal cost	€ 17,640	€ 40.55	CaF_2 – non- hazardous waste
Power	€ 750	€ 1.72	Energy cost (0.1 /kWh)

Table 9: Operating variable costs data for the treatment of TMAH wastewater (per m^3 of residual solution)

The life cycle costs (*See Eq. 2*) during the depreciation time (10 years) of the wastewater containing TMAH are summarized in *Fig. 16.*

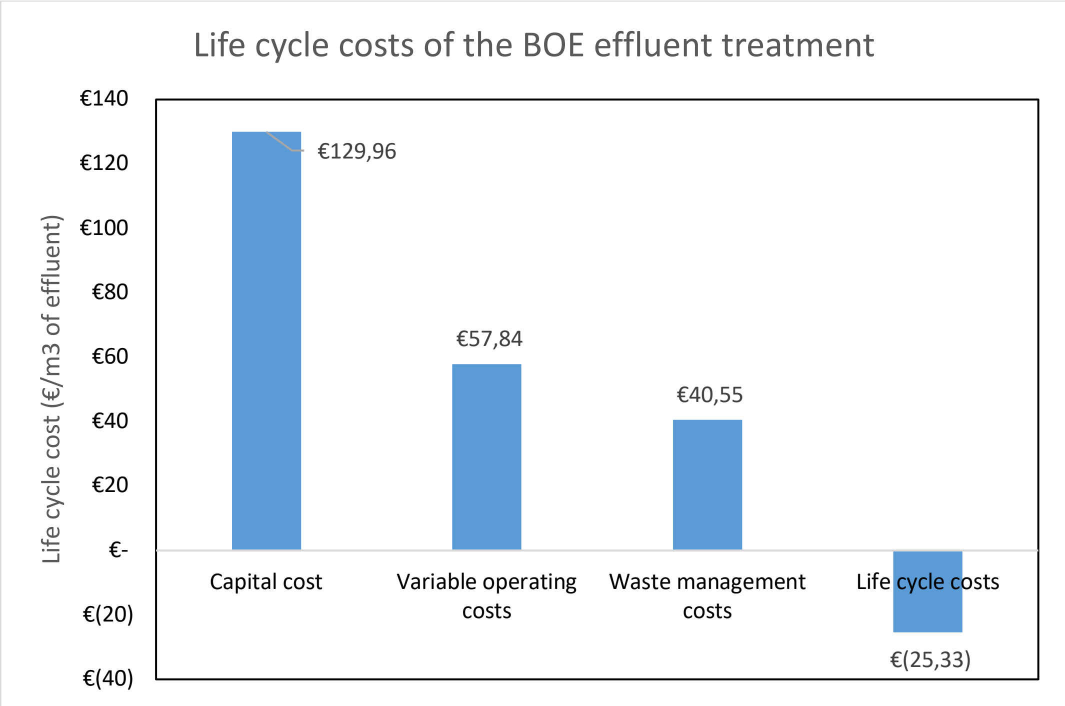

Figure 16: Life cycle costs of the BOE residual solutions during depreciation time

The costs of chemical treatment of BOE are estimated to be -25.33 €/m³. It is the net gain obtained by treating BOE with Life Bitmaps process and avoiding the disposal of wastewater in the specific plant off-site. The main contributor to the total LCC are the capital costs (more in details the investment for the purchase and commissioning of the chemical equipment), that is near to 60% to the total costs, followed by the variable operating ones and disposal cost. Personal cost represents about 66% of variable operating costs (*Fig. 17*), followed by the disposal cost.

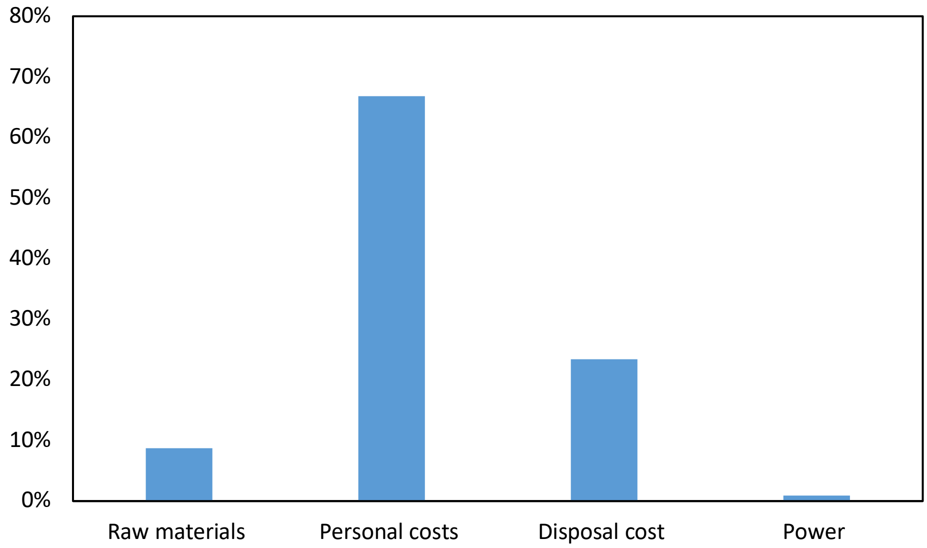

Figure 17: Contribution of different issue to the variable operating costs of BOE effluent treatment

Fig. 18 describes the total annual costs (€/y) for the considered process. Also in this Figure, it is possible to observe that amortization of the plant is the most relevant cost item, followed by the personal and disposal cost.

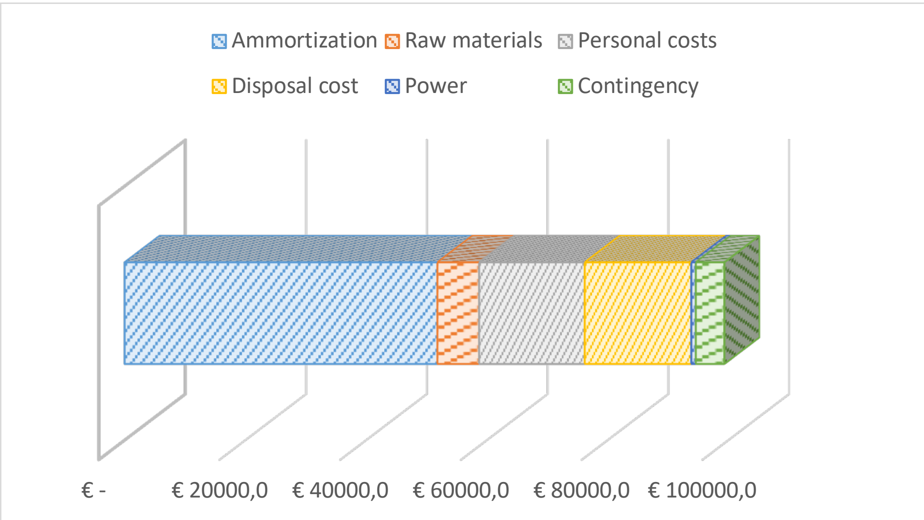

Figure 18: Contribution of different life cycle stages to the costs of BOE wastewater treatment plant (€/y)

Operating cost (*Operating Expense*, OPEX) is reported in *Fig. 19*. Raw materials cost includes the purchase of reagent, mainly lime and aluminium sulfate required for the precipitation of pollutants from aqueous solutions.

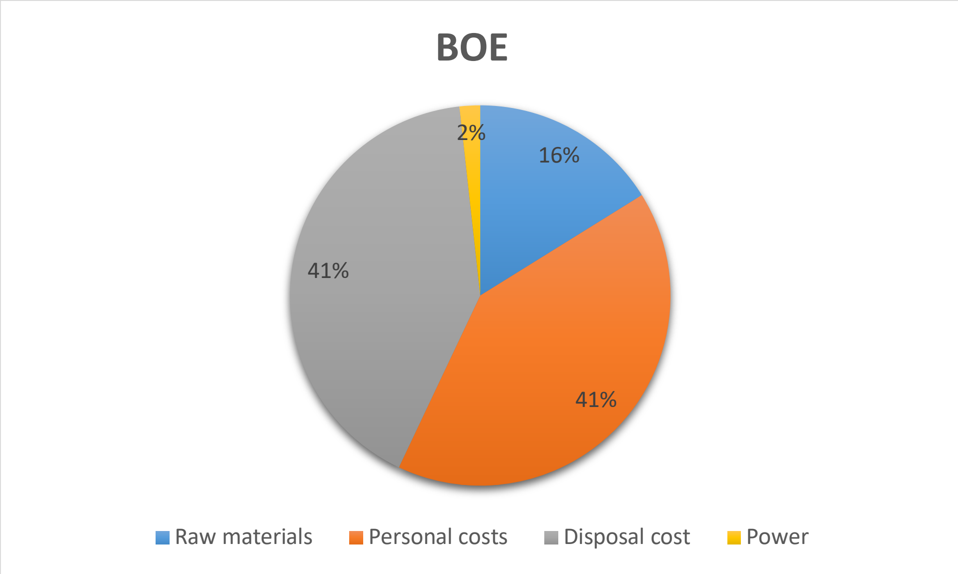

Figure 19: Operating cost for BOE wastewater treatment

The total annual cost is to 228.35 €/m^3 of BOE effluent including OPEX, depreciation and contingency, instead the actual disposal cost is 253.68 €/m^3.

4.3.2.3. Economic evaluation for the treatment of SEZ wastewater by chemical process

The economic evaluation has been performed in according to the following considerations: batch operation mode, 2900 kg of SEZ wastewater per batch and 50 batch/year, annual totaling of 145 ton of SEZ. The block scheme is shown in Fig. 1. The main equipment are the chemical reactor and a filter press to separate the solid and liquid. The filtrate is sent to existing active-sludge plant, instead the solid is a residual non-hazardous waste that mainly contain CaF_2. This solid could be exploited but in the present analysis it has been considered that the solid is sent to disposal in a specific plant. The main item costs considered for the analysis were: (1) equipment cost, (2) raw material purchase, (3) energy cost (4) labour cost and (5) disposal of solid waste that include also the transport cost. In this case it has been considered a disposal cost of 80 €/ton of solid waste.

The Direct Fixed Capital (DFC) is fixed to 400,000.00 € (equipment cost, piping, engineering, …) (real quotation). Straight line depreciation over 10 years is considered with an index of 7.7.

Table 6 shows the operating and waste management cost for the BOE wastewater treatment.

Item	**€/year**	**€/m³**	**Note**
Raw materials	€ 2,291	€ 15.80	Lime solid (0.05 €/kg); water 0,0001 €/kg; aluminium sulfate (0.1 €/kg)
Personal costs	€ 17,500	€ 120.69	Estimated
Disposal cost	€ 6,140	€ 42.34	CaF_2 – non-hazardous waste
Power	€ 250	€ 1.72	Energy cost (0.1 /kWh)

Table 10: Operating variable costs data for the treatment of SEZ wastewater (per m³ of residual solution)

The life cycle costs (*See Eq. 2*) during the depreciation time (10 years) of the wastewater are summarized in *Fig. 20.*

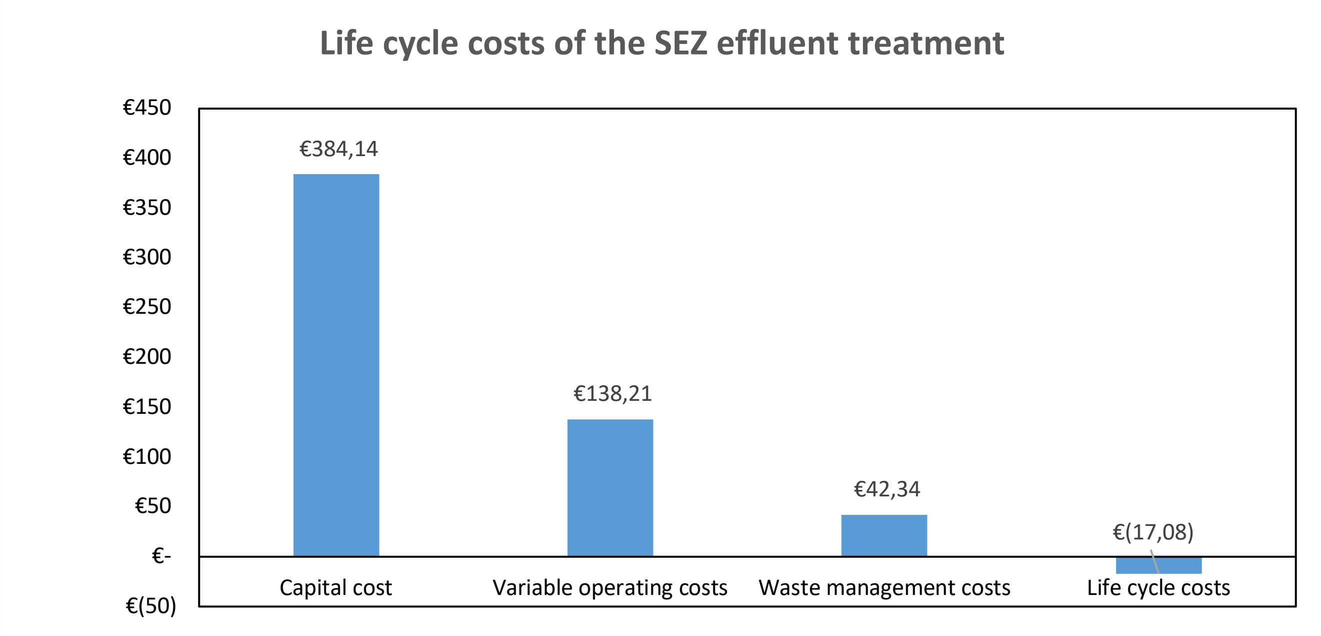

Figure 20: Life cycle costs of the SEZ residual solutions during depreciation time

The costs of chemical treatment of SEZ are estimated to be -17.08 €/m³. It is the net gain obtained by treating SEZ with Life Bitmaps process and avoiding the disposal of wastewater in the specific plant off-site. The main contributor to the total LCC are the capital costs (more in details the investment for the purchase and commissioning of the chemical equipment), that is near to 70% to the total costs, followed by the variable operating ones and disposal cost. Personal cost represents about 66% of variable operating costs (*Fig. 21*), followed by the disposal cost.

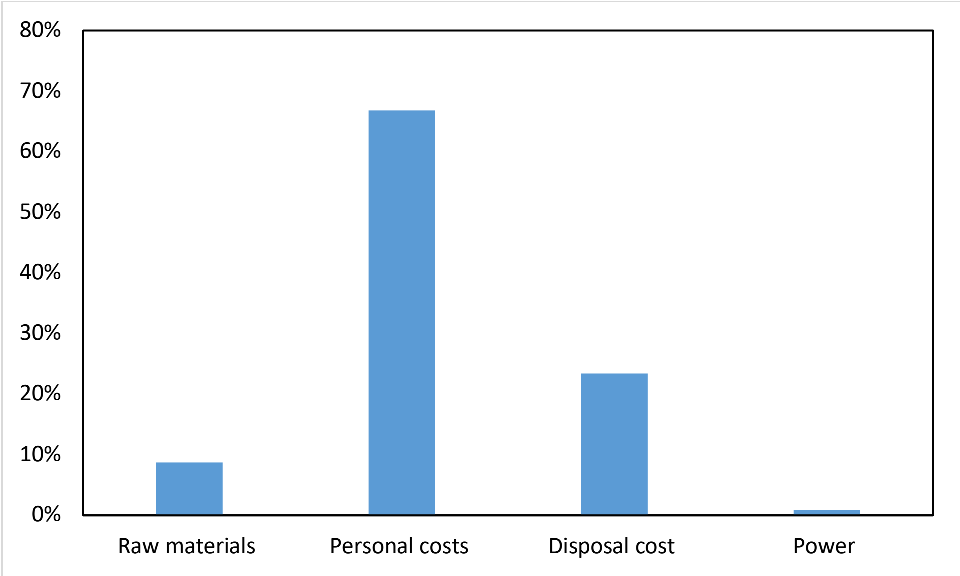

Figure 21: Contribution of different issue to the variable operating costs of SEZ effluent treatment

Fig. 22 describes the total annual costs (€/y) for the considered process. From this Figure, it is also possible to observe that amortization of the plant is the most relevant cost item, followed by the personal and disposal cost.

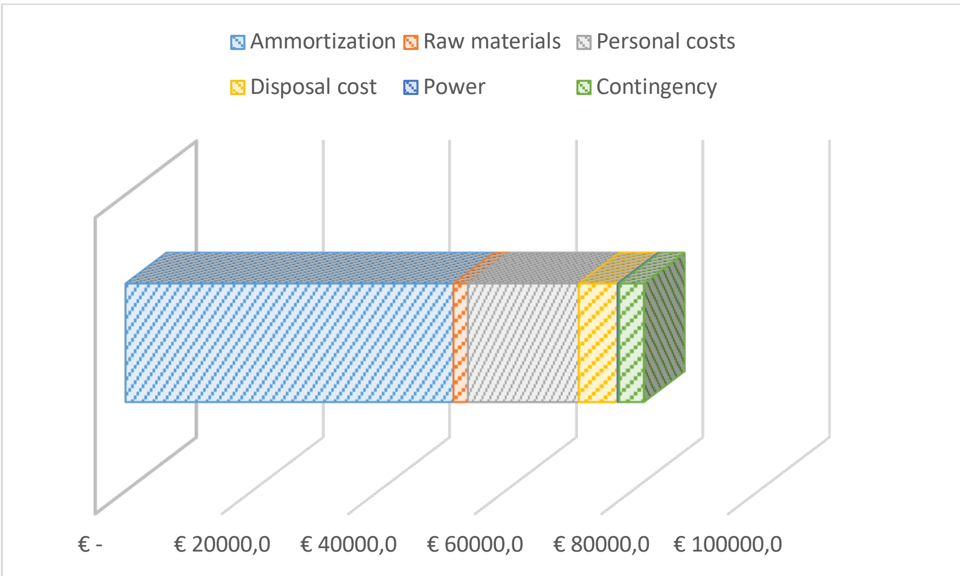

Figure 22: Contribution of different life cycle stages to the costs of SEZ wastewater treatment plant (€/y)

Operating cost (*Operating Expense*, OPEX) is reported in *Fig. 23*. Raw materials cost includes the purchase of reagent, mainly lime and aluminium sulfate necessary for the precipitation of pollutants from aqueous solutions.

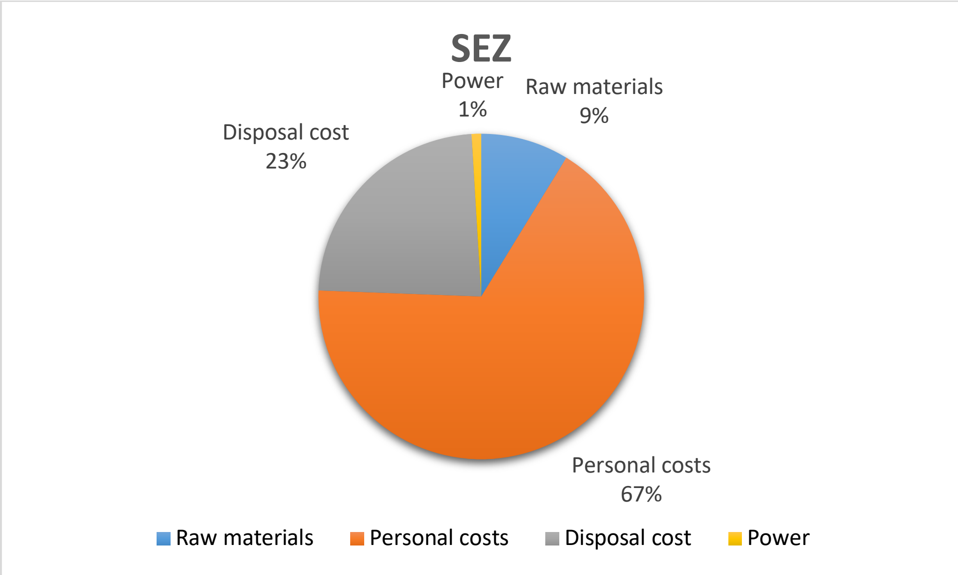

Figure 23: Operating cost for SEZ wastewater treatment

The total annual cost is to 564.70 €/m^3 of SEZ effluent including OPEX, depreciation and contingency, instead the actual disposal cost is 581.8 €/m^3.

4.3.2.4. Economic evaluation for the treatment of TMAH, BOE and SEZ wastewater

In this section the economic evaluation for the treatment of TMAH, BOE and SEZ are shown according to the operative conditions described before. Operating cost (*Operating Expense*, OPEX) is reported in *Fig. 24.* Raw materials cost includes the purchase of reagent, sulfuric acid, lime and aluminium sulfate required for the treatment of the wastewaters. The main contributor to OPEX are the energy consumption (mainly for the treatment of TMAH) followed by the disposal cost of the residual solid of SEZ and BOE. Personal cost represents about 15% of operating costs, instead 11% is the raw material purchase.

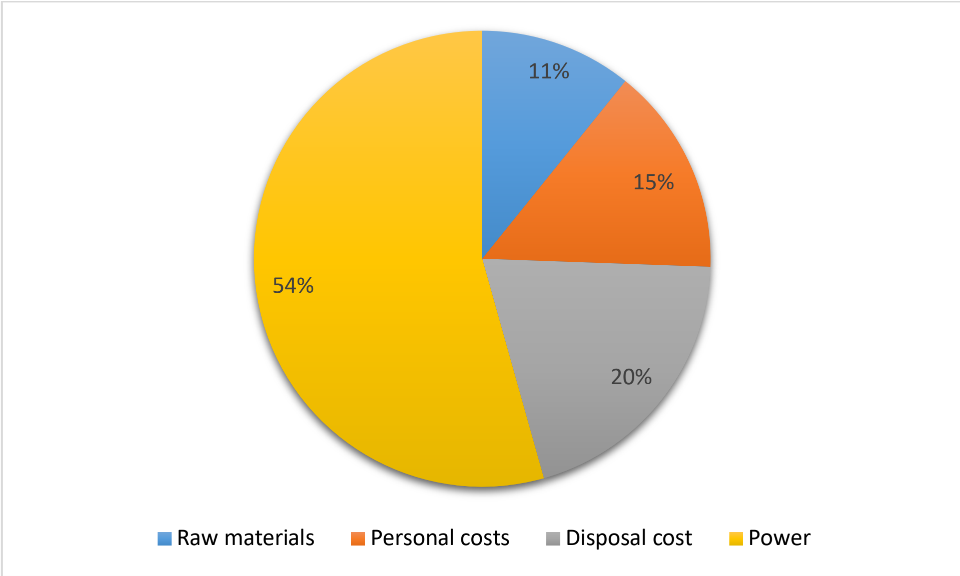

Figure 24: Operating cost for TMAH, BOE and SEZ wastewater treatment

5. Conclusions and recommendations

This study reports the LCA and LCC of the full scale Life Bitmaps processes. Three wastewaters are considered:

- TMAH and photoresist wastewater
- BOE wastewater
- SEZ wastewater.

Full scale plant includes: biological section for TMAH degradation and chemical/physical section for BOE and SEZ treatment. The first section is constituted of three biological reactors and a clarifies at it works in continuous mode. The nominal capacity is 800 L/h of TMAH and photoresist wastewater.

Instead the chemical section of the plant is mainly constituted of a chemical reactor and filterpress. It works in batch mode:

- 2900 kg of BOE wastewater per batch and 150 batch/year, annual totaling of 435 ton of BOE;
- 2900 kg of SEZ wastewater per batch and 50 batch/year, annual totaling of 145 ton of SEZ.

LCA analysis shows that the highest impact connected with the TMAH line, due to the highest production of such wastewater. Electricity consumption has the highest contribution in most impact categories, as concerns the treatment of TMAH. On the other hand, the BOE and SEZ treatment have a quite high impact due to the lime use in precipitation. The most critical categories are: acidification, climate change, ecotoxicity freshwater, eutrophication marine and terrestrial, human toxicity, cancer and non-effects, particulate matter/respiratory inorganics, photochemical ozone formation, resource depletion water, resource depletion, mineral, fossils and renewables

It has been demonstrated that the innovative processes compared to to the current disposal have a positive effect on environmental impact, mainly for the first effluent (TMAH and photoresist). The whole process improvement, with an impact decrease higher than 50%, is evident, mainly thanks to the TMAH process optimization. Comparable results are related to the other two lines, with the advantage of a process carried out within the same facility.

LCC analysis has been performed considering several scenarios: i) treatment of TMAH and photoresist; ii) BOE; iii) SEZ and finally (iv) the treatment of all three wastewaters.

The main item costs considered for the analysis were: equipment cost, raw material purchase, energy cost, labour cost and disposal of solid waste that include also the transport cost.

The following treatment cost have been estimated:

- The costs of biological treatment of TMAH are estimated to be -12.31 €/m^3. It is the net gain obtained by treating TMAH with Life Bitmaps process and avoiding the disposal of wastewater in the specific plant off-site. The main contributor to the total LCC are the capital costs (more in details the investment for the purchase and commissioning of the biological plant), that is near to 60% to the total costs, followed by the variable operating ones. Energy cost represent about 75% of variable operating costs and in this case are the power for the oxygen supply for the biological reactor, mixing system and pumping station.

- The costs of chemical treatment of BOE are estimated to be -25.33 €/m^3. It is the net gain obtained by treating BOE with Life Bitmaps process and avoiding the disposal of wastewater in the specific plant off-site. The main contributor to the total LCC are the capital costs (more in details the investment for the purchase and commissioning of the chemical equipment), that is near to 60% to the total costs, followed by the variable operating ones and disposal cost. Personal cost represents about 66% of variable operating costs followed by the disposal cost.
- The costs of chemical treatment of SEZ are estimated to be -17.08 €/m^3. It is the net gain obtained by treating SEZ with Life Bitmaps process and avoiding the disposal of wastewater in the specific plant off-site. The main contributor to the total LCC are the capital costs (more in details the investment for the purchase and commissioning of the chemical equipment), that is near to 70% to the total costs, followed by the variable operating ones and disposal cost. Personal cost represents about 66% of variable operating costs followed by the disposal cost.

For the last scenario, in which the treatment of the all wastewaters has been considered, the main contributor to OPEX are the energy consumption (mainly for the treatment of TMAH) followed by the disposal cost of the residual solid of SEZ and BOE. Personal cost represents about 15% of operating costs, instead 11% is the raw material purchase.

The obtained results for LCA show that the innovative Life Bitmpas processes have an environmental positive impact if compared with the current disposal.
Using LCC methodology the treatment cost has been estimated:

- 33.31 €/m^3 of TMAH effluent (actual disposal cost is 45.6 €/m^3)
- 228.35 €/m^3 of BOE effluent (actual disposal cost is 253.68 €/m^3)
- 564.70 €/m^3 of SEZ effluent (actual disposal cost is 581.8 €/m^3)

It is clear that the main advantage is associated to the TMAH treatment, hence it recommends to design the full scale plant to treat all considered wastewaters in order to make the most of the benefits of innovative processes.

References

[1] R. Theregowda, M-K- Hsieh, M. E. Walker, A.E. Landis, J. Abbasian, R. Vidic, D.A. Dzombak, Life cycle costs to treat secondary municipal wastewater for reuse in cooling systems, *Journal of Water Reuse and Desalination* (2013), 0.3.3, 224-238.

[2] B. S. Dhillon, Life Cycle Costing for Engineers, CRC Press. New York, Ch.4

[3] T.E. Swarr, D. Hunkeler, W. Klopffer, H.L. Pesonen, A. Ciroth et al., Environmental life cycle costing: a code of practice. *The International Journal of Life Cycle Assessment* (2011), 16, 389–391.