PORTABLECRAC

Portable Solution for the Electrochemical Regeneration of Activated Carbon

PORTABLE SOLUTION FOR THE ELECTROCHEMICAL REGENERATION OF ACTIVATED CARBON

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D6.1 LCA & LCCA of acquiring Virgin AC and of thermal regeneration

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TABLE OF CONTENTS

PROJECT INFORMATION

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4	Empresa mixta valenciana de aguas S.A.	EMIVASA	Spain
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DELIVERABLE DETAILS

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Abstract	This Deliverable is focused on the life cycle assessment (LCA) and the life cycle cost (LCC) analysis of the production and thermal regeneration of activated carbon and its usage in EMIVASA drinking water facilities. The main aim of the study is to stablish the current scenario for regeneration in order to compare these results with the future analysis of PORTABLECRAC solution. The LCA of activated carbon production from hard coal reveals that direct emissions represent more than half of global warming and terrestrial acidification, while hard coal management contributes close to 80% to eutrophication. On the other hand, for thermal regeneration the evaluation of global warming potential shows that direct emissions of CO_2cause 77% of the total impact. Also, as in the previous process, the direct emission of sulfur dioxide is the main responsible for terrestrial acidification. The study for EMIVASA facilities takes into accounta medium-large plant in which spent activated carbon is regenerated and a small one in which it is incinerated and replaced with new one. Accordingly, direct emissions and hard coal management are the main responsible to global warming, terrestrial acidification and eutrophication. Regarding toxicity related impact categories, incineration of spent activated carbon is the main responsible for the impacts. The economic assessment carried out for both EMIVASA scenariosshows that the present value of total costs per activated carbon volume is higher in small facilities,3,597.49 €/m^3 in the face of 1,733.23 €/m^3. In both plants, the operating and maintenance costs category, which includes the regeneration and replacement, represents more than 90 % of global costs.

1 SCOPE OF THE DOCUMENT

The present deliverable aims at performing the life cycle assessment (LCA) and the life cycle cost (LCC) analysis of the current processes involved in activated carbon production and thermal regeneration. The main objective of this evaluation is to obtain environmental burdens and economic indicators to be compared in further steps with the technology developed within the project PORTABLECRAC. Information and data related to the processes were taken frombibliography and revised and completed by EMIVASA.

Both processes of production and regeneration are also included in two real treatment scenarios: the use of activated carbon in medium-large and small drinking water facilities. The former regenerates spent activated carbon while for small volumes spent material is replaced by new one. The reason behind the evaluation of large filters is that thermal regeneration causes activated carbon losses, fact that could be overtaken in PORTABLECRAC. Accordingly, the environmental and economic consequences of replacing losses with virgin activated carbon are considered in the present study. Regarding small facilities, currently spent activated carbon is replaced by new material, but the PORTABLECRAC system could arise as a solution to consider in-situ regeneration. The development of both LCA and LCC will allow to establish the feasibility of the PORTABLECRAC technology considering not only technical but also environmental and economic performance.

2 PROCESSES DESCRIPTION

2.1 PRODUCTION OF VIRGIN ACTIVATED CARBON

Typically activated carbon is produced using carbonaceous materials such as hard coal, coconut husk or peat. The process consists of two steps: carbonization or devolatilization followed by anactivation stage. For this study, the process to producegranular activated carbon from hard coal was taken from the Ecoinvent Database(based on Bayer et al., 2005 and Muñoz et al., 2007). It is important to mention that typically activated carbon is produced in China and shipped to Europe to be distributed. Therefore, the European process included in the Ecoinvent Database was accordingly modified considering Chinese processes and activated carbon shipping from China to the distribution point was properly included in the assessment.

The production of 1 kg of granular activated carbon from 3 kg of hard coal is described, taking into account that 60% of the original weight is lost. The database includes electricity use, burning of natural gas for water vaporisation, water use and emissions from combustion of hard coal. Two main stages are comprised: carbonization and partial gasification to activate the carbon. Firstly, hard coal is heated to temperatures over 700°C. Regarding the activation stage, it is achieved through vaporisation at temperatures between 800°C and 1,000°C. Because of this step, a highly porous material is produced. It was estimated that the process consumes 1.6 kWh of electricity from grid and 0.33 m^3 of natural gas to heat 12 kg of water. Data for the carbonisation of 2 kg of hard coal were assumed as heat production at hard coal industrial furnace 1-10MW. The lifetime of the furnace is 20 years, which corresponds to 5,000 fully load hours per year. The heating value is 28.9 $MJkg^{-1}$ and the efficiency factor around 80%.

2.2 THERMAL REGENERATION OF SPENT ACTIVATED CARBON

PORTABLECRAC is mainly focused on regeneration processes to overcome the drawbacks associated with the current thermal process. Accordingly, thermal regeneration performed to reactivate carbon in industry nowadays needs to be well characterized. Similar to production, data gathering from real processes is a difficult task and the process was modelled following bibliographic data. The average European process detailed in the Ecoinvent Databasewas taken for the present study (Bayer et al., 2005; Muñoz et al., 2007).The process describesthe production of 0.9 kg of reactivated granular activated carbon from 1 kg of hard coal. It means that the percentage of losses was estimated ~10% which represents the most optimistic situation but losses up to 20% could be achieved during the process. This disadvantage is expected to be overcome with the new technology developed in PORTABLECRAC.

The process detailed in Ecoinvent Databases comprises drying and activation of spent activated carbon. Firstly, the spent activated carbon is dried at 100°Cand then heated to temperatures over 700°C. A reduction of water content up to 50% is achieved during the first stage of drying. The activation stage is carried out via vaporisation at temperatures between 800°C and 1,000°C. As explained for the productive process, burning of 3 kg of coal requires 1.6 kWh of electricity and 0.33 m^3 of natural gas to heat 12 kg of water. Moreover, direct emissions from reactivation are considered. It is important to highlight that the emissions from the reactivation of spent activated carbon depend on the contaminants adsorbed. Consequently, the process considered for the study does not include those contaminants but only the emissions from the reactivation process itself.

2.3 USE OF ACTIVATED CARBON IN DRINKING WATER FACILITIES

The main aim of this Deliverable is to quantify the environmental burdens related to production and regeneration of activated carbon following the current processes. Additionally, the evaluation of its use in a real facility is very interesting because it allows assessing the whole life cycle of the material. It means that important issues such as transportation of virgin and spent activated carbon and material losses due to thermal processes can be accounted for. With this objective, the use of activated carbon in real drinking water facilitiesoperated by EMIVASA in Valencia is evaluated. It should be highlighted that spent activated carbon is regenerated in medium-large size facilities while the smallest ones opt to replace it by new material.Both scenariosare evaluated considering that the PORTABLECRAC system is proposed as an alternative to the current thermal regeneration but also asan alternative to the replacement of spent activated carbon in small facilities.

The medium-large size target drinking facility located in Valencia uses 100 m^3(45 Ton)of activated carbon per filter and in total 1500 m^3 are used (680 Ton). Virgin activated carbon is brought from a distribution point in The Netherlands. However, the material is produced in China and then transported by sea to Europe.Transportation from The Netherlands is carried out in big bags of 500 kg by trucks of maximum capacity of 22 Ton (44 big bags per truck). Although the saturation period depends on each specific situation, stream or pollutants, 4 – 6 years is the average range reached in the target plant. Regarding spent activated carbon, thermal regeneration is performed in Italy up to 3 times. The material is transported in tanker trucks by road. The maximum capacity of the truck is 50 m^3 but 25-30 m^3 of wet spent activated carbon is the maximum load transported. Consequently, 3 trucks are necessary to transport the total amount of spent material. It should be mentioned the thermal process leads to 10% of losses and consequently only 90% of the regenerated carbon is used while the remaining 10% has tobe refilled with new activated carbon. Again, the regenerated material is transported by tanker trucks to the facility. After the third regeneration, spent activated carbon is incinerated by a specialized waste manager close to the facilities.

Regarding small facilities, a drinking water facility using 20 m^3 (9 Ton) of activated carbon per filter is assessed. The main difference with larger facilities is that spent activated carbon is not regenerated, but it is incinerated and replaced by new carbon.

3 LIFE CYCLE ASSESSMENT (LCA)

The LCA has been conducted according to the ISO 14040 Standard "Environmental management - Life cycle assessment - Principles and framework" (ISO, 2006). Figure 1 shows the steps to perform the LCA.

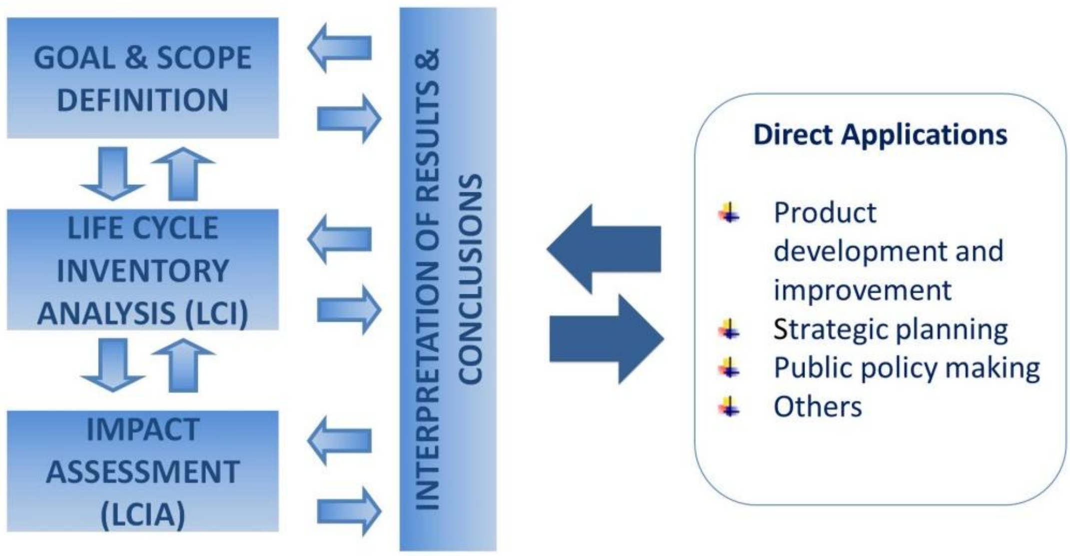


Figure 1. Framework for life cycle assessment (LCA) - adapted from ISO (2006).

The "goal and scope definition" is the first stage of the study and it includes the reasons that justify the analysis, the expected information, how it will be used, its potential availability to be public and the foreseen comparison with other results. Moreover, the study must be perfectly delimited and, consequently, the boundaries (geographical, conceptual and temporal), the quality of the data used, and the main hypothesis have to be defined (Baumann and Tillman, 2004).

The functional unit (FU) is also determined in this stage and it represents the function of the system under study. The adequate selection of the FU has been proved to be a key aspect in defining environmental profiles.

The next step, the life cycle inventory (LCI) is the most work intensive and time-consuming task of the different stages of an LCA study. It consists of data collection and interpretation of the inputs and outputs of the studied system, mainly referred to mass, energy, land use and transport (Baumann and Tillman, 2004). This phase comprises data collection and calculation. Additionally, allocation could be necessary: inputs and outputs are allocated to different products according to clearly stated procedures.

The life cycle impact assessment (LCIA) phase aims at converting the LCI into potential impacts associated with processes and products (ISO, 2006). Impact assessment in LCA generally consists of two mandatory steps: classification and characterization, as well as optional elements, normalization, weighting and data quality analysis. Classification consists of the assignment of LCI data to each impact category. Regarding characterization, all the inventory flows are converted into potential impacts. In this step, characterization factors (CFs) are applied and they are commonly considered as equivalency factors. Normalization links the environmental profile to a broader data set by its division by a selected reference value. By performing this step, the importance of each impact category can be compared, and the consequent optimization of the process can be focused. Another optional phase is the grouping of results, where the impact categories are ranked. Weighting is the third optional step where the environmental impact is summed up in a single impact score. This stage is not a scientific process, but it is based on stakeholder values, which can reflect the goal of the study.

Once the burdens are calculated, results are assessed in order to conclude and recommend actions according to the goal and scope definition (Baumann and Tillman, 2004). Here, the critical sources of impacts and the options to reduce them are presented. Additionally, the consistency of the assumptions and data quality must be checked by means of the evaluation of completeness, sensitivity and consistency of the data.

3.1 GOAL AND SCOPE DEFINITION

3.1.1 Objectives

- **Main objective**: The main objective of the Deliverable is to determine the environmental burdens related to production of new activated carbon and to thermal regeneration according to the current processes performed. Additionally, once both processes are defined, and their related impacts are determined, it is interesting to evaluate the impacts related to the use of activated carbon in real drinking water facilities. This option was decided considering that factors such as transportation to facilities and material losses could be key issues in the global evaluation.
- **Driving force**: In PORTABLECRAC, a novel system for activated carbon regeneration will be developed with the objective of reducing costs when compared to thermal regeneration. This new technology will overtake barriers such as off-site service

requirements, high energy input and carbon losses with negative environmental impacts. Therefore, the environmental and economic assessment of the current processes is essential to understand and demonstrate the benefits associated with the process developed in PORTABLECRAC.

- **Target audience**: The main sectors interested on this study comprise mainly drinking water and wastewater facilities but also other users with wastewater production such as food industry; industries with off-gas streams; public agents (ministries, council, EU Commission…) and pressure groups.

3.1.2 Functional unit

As mentioned in "Section 3.1.1. Objectives", three processes are evaluated in the present Deliverable:

1) Production of activated carbon which function is to produce virgin activated carbon from hard coal.
2) Regeneration of activated carbon which function is to reactivate spent activated carbon through a thermal process.
3) Treatment of water streams using activated carbon in which case the main function is to remove pollutants from the wastewater stream.

Accordingly, a different FU will be defined for each case:

1) **1 kg of virgin activated carbon** produced from hard coal.
2) **1 kg of activated carbon**treated in a thermal regenerationprocess.
3) **20 years** covering the whole cycle of 1 filter of activated carbon.

Regarding the latter FU, a temporal unit was agreed instead of focusing on removal of pollutants because the whole cycle of the carbon will deliver more reliable outcomes when both scenarios (current situation vs. PORTABLECRAC integration) are compared. The evaluation of complete life cycle of the activated carbon allows to consider transportation to and from regeneration point, losses of material during thermal regeneration and issues such as the final treatment of spent material in incinerators. Moreover, the analysis will be carried out for a single filter of the drinking water facilities, because the PORTABLECRAC technology will be also assessed per filter.

3.1.3 System boundaries

Background and foreground processes are considered for the environmental assessment. The system boundaries are established to produce virgin activated carbon, thermal regeneration and operation of activated carbon in industry (Figure 2). If the whole system is split into subsystems: activated carbon production includes from the transportation of hard coal from the Mine to the final packaging of final material to be delivered; thermal regeneration considers from the reception of spent material to the production of reactivated carbon; and the use of activated carbon in industry comprises all the processes and streams depicted in Figure 2.

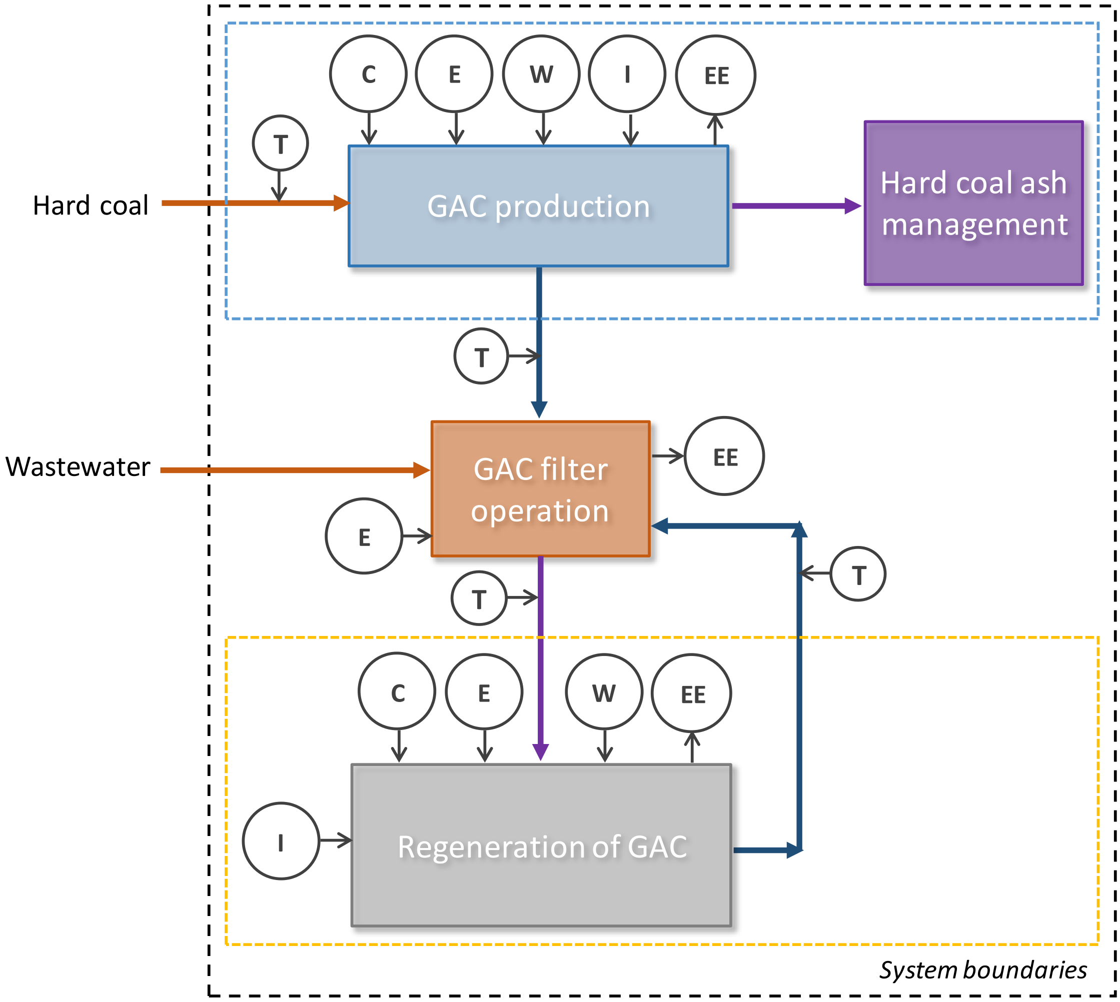


Figure 2. Processes included in the system boundaries to produce granular activated carbon (GAC) (blue line), regeneration (orange line) and use of activated carbon in industry (black line). Acronyms: C, chemicals; E, electricity; EE, direct emissions; I, infrastructure; W, water and T, transport.

3.2 LIFE CYCLE INVENTORY (LCI)

3.2.1 Production of virgin activated carbon

The inventory data related to the production of virgin activated carbon detailed in Table 1 correspond with the process described in section "2.1. Production of virgin activated carbon". Considering that the target virgin activated carbon is produced in China, inventory data were kept as in the original process of Ecoinvent Database for Central Europe ("Activated carbon, granular {RER}| activated carbon production, granular from hard coal"), but the specific Ecoinvent processes were changed and accordingly modified to consider the production in China.

The estimation of electricity use of 1.84 kWh is based on data taken from a heating plant located in Bern (Switzerland). On one hand, at full load 1.13% of the input energy is consumed as electricity. On the other hand, the installed capacity in auxiliary units is split into different inputs: induced draft fan (31%), primary air fan (13%), feed pump (39%), electric filter (11.8%), rust (0.8%), feeding (1.8%), slag chain (0.2%), oil supply control (0.9%) and secondary air (1.4%). It was considered that during load operation the use of electricity could be even higher. It was estimated that the heating plant has a capacity of about 38 MW. Therefore, it is assumed that 1.5% of the input energy is consumed as electricity. Finally, to the amount required for carbonisation, 1.6 kWh of electricity is added as an estimated requirement for activation (Bayer et al., 2005). In this case, the mix of energy market included in the process is replaced by the process “Electricity, medium voltage {CN}| market group” which includes specific energy profiles for China.

As abovementioned, 3 kg of hard coal are fed to produce 1 kg of activated carbon. The Ecoinvent Database considers that most of the raw material comes from Western Europe (~84%) while the remining 16% is transported from Poland. In this study it was assumed that activated carbon is produced in China and that the hard coal mine is also located in China with the process “Hard coal {CN}| market for”.

Around 0.33 m^3 of natural gas are necessary to produce 12 kg of water vapour and the activity is represented as 13.3 MJ of heat from natural gas. Concerning the use of water, it is assumed that 2% of the water fed is additionally required as decarbonised water. Water used for cleaning is out of the scope of the study due to the lack of information. Considering that no specific processes are detailed for China, global approaches were considered: “Heat, district or industrial, natural gas {GLO}| market group for”; “Industrial furnace, coal 1-10 MW {GLO}| market for” and “Water, completely softened, from decarbonized water, at user {GLO}| market for”.

Direct emissions to air account for more than 70 pollutants due to the process of production. The concentration of the trace elements was calculated considering the ash content in the coal and average transfer coefficients for coal power plants with ash retention of 98%. While all the compounds and concentrations were taken from the Ecoinvent process, the concentration of carbon dioxide emitted to air was modified according real data facilitated by the company: 7 Ton CO_2 emitted per Ton of activated carbon produced instead of 5.29 Ton CO_2 per kg reported in the baseline process of Ecoinvent. Regarding emissions to aquatic environment, no specific contaminants were measured and only water with no impact allocated is expected to be released ~0.01 m^3.

Finally, waste treatment considers that 100% of the hard coal ash is disposed in landfills. This alternative corresponds with the worst-case scenario because recycling is another possibility for this type of wastes.The Ecoinvent process “Hard coal ash {GLO}| market” was used to model this scenario.

Table 1. Life cycle inventory (LCI) related to the production of activated carbon from hard coal (FU: 1 kg of virgin activated carbon) (Bayer et al., 2005; Muñoz et al., 2007).

	Value	Units
Inputs from technosphere		
Electricity, medium voltage from grid	1.84	kWh
Hard coal	3.00	kg
Heat, district or industrial, natural gas	13.3	MJ
Industrial furnace, coal, 1-10 MW	$3.21{\cdot}10^{-8}$	p
Softened water from decarbonized water	12.43	kg
Outputs to technosphere: Waste treatment		
Hard coal ash	0.17	kg
Emissions to water		
Water	0.01	m^3
Emissions to air		
Aluminum	$6.18{\cdot}10^{-4}$	kg
Antimony	$9.13{\cdot}10^{-8}$	kg
Arsenic	$1.46{\cdot}10^{-6}$	kg
Barium	$7.28{\cdot}10^{-6}$	kg
Benzene	$2.89{\cdot}10^{-5}$	kg
Benzo(a)pyrene	$5.78{\cdot}10^{-10}$	kg
Beryllium	$7.28{\cdot}10^{-8}$	kg
Boron	$2.74{\cdot}10^{-5}$	kg
Bromine	$5.48{\cdot}10^{-7}$	kg
Cadmium	$9.13{\cdot}10^{-8}$	kg
Calcium	$7.28{\cdot}10^{-5}$	kg
Carbon dioxide, fossil	7.00	kg
Carbon monoxide, fossil	$5.78{\cdot}10^{-3}$	kg
Chromium	$1.30{\cdot}10^{-6}$	kg
Chromium VI	$1.61{\cdot}10^{-7}$	kg
Cobalt	$1.83{\cdot}10^{-7}$	kg
Copper	$9.60{\cdot}10^{-7}$	kg
Dinitrogen monoxide	$5.78{\cdot}10^{-5}$	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	$1.16{\cdot}10^{-12}$	kg
Ethane	$8.67{\cdot}10^{-5}$	kg
Ethene	$1.73{\cdot}10^{-4}$	kg
Ethyne	$2.89{\cdot}10^{-5}$	kg
Formaldehyde	$4.62{\cdot}10^{-6}$	kg
Hydrocarbons, aliphatic, alkanes, unspecified	$2.89{\cdot}10^{-5}$	kg
Hydrocarbons, aliphatic, unsaturated	$2.89{\cdot}10^{-5}$	kg
Hydrogen chloride	$2.34{\cdot}10^{-3}$	kg
Hydrogen fluoride	$7.28{\cdot}10^{-5}$	kg
Iodine	$6.59{\cdot}10^{-7}$	kg
Iron	$2.55{\cdot}10^{-4}$	kg
Lead	$4.38{\cdot}10^{-6}$	kg
Lead-210	$2.69{\cdot}10^{-3}$	kBq
Magnesium	$2.19{\cdot}10^{-4}$	kg
Manganese	$1.28{\cdot}10^{-6}$	kg
Mercury	$1.64{\cdot}10^{-7}$	kg
Methane, fossil	$5.78{\cdot}10^{-4}$	kg
Molybdenum	$2.74{\cdot}10^{-7}$	kg
Nickel	$1.10{\cdot}10^{-6}$	kg
Nitrogen oxides	$1.16{\cdot}10^{-2}$	kg
NMVOC, non-methane volatile organic compounds	$9.94{\cdot}10^{-5}$	kg

Table 1. *(Cont)*Life cycle inventory (LCI) related to the production of activated carbon from hard coal (FU: 1 kg of virgin activated carbon) (Bayer et al., 2005; Muñoz et al., 2007).

	Value	Units
Emissions to air		
Particulates < 2.5 um	$1.16 \cdot 10^{-3}$	kg
Particulates > 10 um	$5.78 \cdot 10^{-4}$	kg
Particulates > 2.5 um, and < 10um	$1.16 \cdot 10^{-3}$	kg
Phosphorus	$3.65 \cdot 10^{-6}$	kg
Polonium-210	$4.91 \cdot 10^{-3}$	kBq
Potassium	$7.28 \cdot 10^{-5}$	kg
Potassium-40	$7.80 \cdot 10^{-4}$	kBq
Propane	$5.78 \cdot 10^{-5}$	kg
Propene	$2.89 \cdot 10^{-5}$	kg
Radium-226	$6.94 \cdot 10^{-4}$	kBq
Radium-228	$3.76 \cdot 10^{-3}$	kBq
Radon-220	$5.78 \cdot 10^{-5}$	kBq
Radon-222	$5.78 \cdot 10^{-5}$	kBq
Scandium	$7.28 \cdot 10^{-8}$	kg
Selenium	$5.48 \cdot 10^{-7}$	kg
Silicon	$9.13 \cdot 10^{-4}$	kg
Sodium	$3.65 \cdot 10^{-5}$	kg
Strontium	$1.10 \cdot 10^{-5}$	kg
Sulfur dioxide	$2.89 \cdot 10^{-2}$	kg
Thallium	$9.13 \cdot 10^{-8}$	kg
Thorium	$1.10 \cdot 10^{-7}$	kg
Thorium-228	$3.18 \cdot 10^{-4}$	kBq
Thorium-232	$2.02 \cdot 10^{-4}$	kBq
Tin	$3.65 \cdot 10^{-8}$	kg
Titanium	$2.19 \cdot 10^{-5}$	kg
Toluene	$5.78 \cdot 10^{-6}$	kg
Uranium	$1.46 \cdot 10^{-7}$	kg
Uranium-238	$5.78 \cdot 10^{-4}$	kBq
Vanadium	$2.19 \cdot 10^{-6}$	kg
Water/m3	$1.86 \cdot 10^{-3}$	m3
Xylene	$5.78 \cdot 10^{-6}$	kg
Zinc	$1.83 \cdot 10^{-7}$	kg

3.2.2 Thermal regeneration of spent activated carbon

The inventory data related to the thermal regeneration (Table 2) is referred to the process described in “2.2. Thermal regeneration of spent activated carbon”. The Ecoinvent process used is “Activated carbon, granular {RER}| treatment of spent activated carbon, granular from hard coal, reactivation” and all the processes included were kept without modifications.

The estimated 0.61 kWh is based on data from a heating plant located in Bern. As abovementioned 1.13% of energy is used as electricity and the installed capacity in auxiliary units is split as indicated for production. In this case 1.6 kWh is divided by 3 (1 kg of feeding stead of 3 kg needed for production) and summed to consider reactivation. Considering losses around 10% produced during the thermal regeneration, 0.90 kg of reactivated carbon are obtained from 1 kg of dried spent activated carbon. Dry mass for spent activated carbon is 30%

of wet mass (Muñoz et al., 2007). The reference product is expressed as 1 kg of dry matter basis corresponding with 3.33 kg of spent activated carbon treated. Considering that 0.33 m^3 of natural gas are burned to produce 12 kg of water vapour in the production process, 4.93 MJ corresponds with 4 kg of vapour required for regeneration. Moreover, 2% of water fed is additionally needed as decarbonised water. Water for cleaning is out of the scope of the study.

Direct emissions to air include more than 70 pollutants. Trace elements concentration was calculated considering the ash content in the coal and average transfer coefficients for coal power plants with ash retention of 98%. Again, CO_2concentration emitted to air was changed according to data provided by the company: 2 Ton CO_2 emitted per Ton of activated carbon produced vs. 0.29 Ton CO_2 per kg reported in Ecoinvent. Regarding emissions to aquatic environment, only water is expected around3.80 L.Finally, disregarding solid waste recycling, 9.31 g of hard coal ash were estimated to be treated.

Table 2. Life cycle inventory (LCI) for the process of thermal regeneration of spent activated carbon (FU: 0.9kg of regenerated activated carbon)(Bayer et al., 2005; Muñoz et al., 2007).

	Value	Units
Inputs from technosphere		
Electricity, medium voltage from grid	0.61	kWh
Spent activated carbon	1.00	kg
Heat, district or industrial, natural gas	4.93	MJ
Industrial furnace, coal, 1-10 MW	$1.79 \cdot 10^{-9}$	p
Softened water from decarbonized water	4.47	kg
Outputs to technosphere: Waste treatment		
Hard coal ash	$9.31 \cdot 10^{-3}$	kg
Emissions to water		
Water	$3.80 \cdot 10^{-3}$	m^3
Emissions to air		
Aluminum	$3.44 \cdot 10^{-5}$	kg
Antimony	$5.07 \cdot 10^{-9}$	kg
Arsenic	$8.12 \cdot 10^{-8}$	kg
Barium	$4.05 \cdot 10^{-7}$	kg
Benzene	1.61E-06	kg
Benzo(a)pyrene	$3.21 \cdot 10^{-11}$	kg
Beryllium	$4.05 \cdot 10^{-9}$	kg
Boron	1.52E-06	kg
Bromine	$3.04 \cdot 10^{-8}$	kg
Cadmium	$5.07 \cdot 10^{-9}$	kg
Calcium	$4.05 \cdot 10^{-6}$	kg
Carbon dioxide, fossil	2.00	kg
Carbon monoxide, fossil	$3.21 \cdot 10^{-4}$	kg
Chromium	$7.23 \cdot 10^{-8}$	kg
Chromium VI	$8.93 \cdot 10^{-9}$	kg
Cobalt	$1.01 \cdot 10^{-8}$	kg
Copper	$5.33 \cdot 10^{-8}$	kg
Dinitrogen monoxide	$3.21 \cdot 10^{-6}$	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	$6.42 \cdot 10^{-14}$	kg
Ethane	$4.82 \cdot 10^{-6}$	kg
Ethene	$9.63 \cdot 10^{-6}$	kg
Ethyne	$1.61 \cdot 10^{-6}$	kg

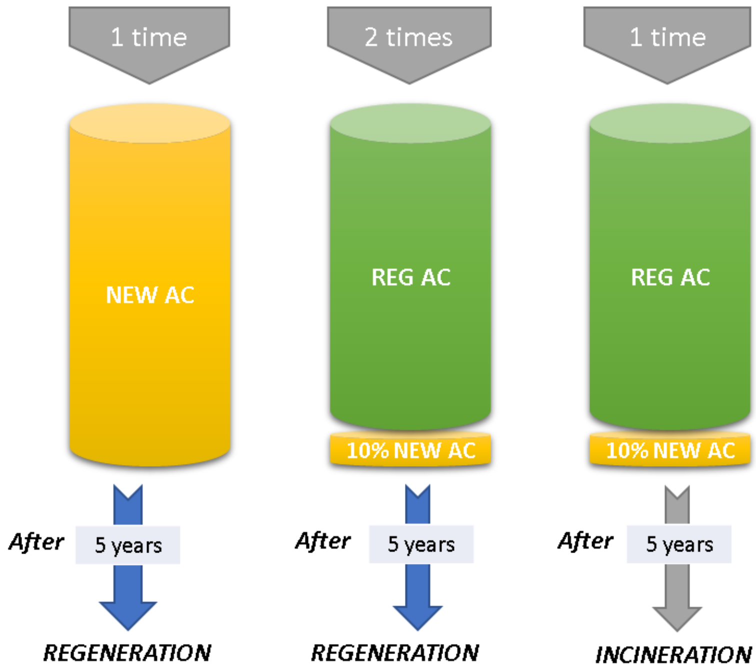
Table 2. Life cycle inventory (LCI) for the process of thermal regeneration of spent activated carbon (FU: 0.9kg of regenerated activated carbon) (Bayer et al., 2005; Muñoz et al., 2007).

	Value	Units
Formaldehyde	$2.57 \cdot 10^{-7}$	kg
Hydrocarbons, aliphatic, alkanes, unspecified	$1.61 \cdot 10^{-6}$	kg
Hydrocarbons, aliphatic, unsaturated	$1.61 \cdot 10^{-6}$	kg
Hydrogen chloride	$1.30 \cdot 10^{-4}$	kg
Hydrogen fluoride	$4.05 \cdot 10^{-6}$	kg
Iodine	$3.66 \cdot 10^{-8}$	kg
Iron	$1.42 \cdot 10^{-5}$	kg
Lead	$2.43 \cdot 10^{-7}$	kg
Lead-210	$1.49 \cdot 10^{-4}$	kBq
Magnesium	$1.22 \cdot 10^{-5}$	kg
Manganese	$7.10 \cdot 10^{-8}$	kg
Mercury	$9.12 \cdot 10^{-9}$	kg
Methane, fossil	$3.21 \cdot 10^{-5}$	kg
Molybdenum	$1.52 \cdot 10^{-8}$	kg
Nickel	$6.10 \cdot 10^{-8}$	kg
Nitrogen oxides	$6.42 \cdot 10^{-4}$	kg
NMVOC, non-methane volatile organic compounds	$5.52 \cdot 10^{-6}$	kg
Particulates < 2.5 um	$6.42 \cdot 10^{-5}$	kg
Particulates > 10 um	$3.21 \cdot 10^{-5}$	kg
Particulates > 2.5 um, and < 10um	$6.42 \cdot 10^{-5}$	kg
Phosphorus	$2.03 \cdot 10^{-7}$	kg
Polonium-210	$2.73 \cdot 10^{-4}$	kBq
Potassium	$4.05 \cdot 10^{-6}$	kg
Potassium-40	$4.34 \cdot 10^{-5}$	kBq
Propane	$3.21 \cdot 10^{-6}$	kg
Propene	$1.61 \cdot 10^{-6}$	kg
Radium-226	$3.85 \cdot 10^{-5}$	kBq
Radium-228	$2.09 \cdot 10^{-4}$	kBq
Radon-220	$3.21 \cdot 10^{-6}$	kBq
Radon-222	$3.21 \cdot 10^{-6}$	kBq
Scandium	$4.05 \cdot 10^{-9}$	kg
Selenium	$3.04 \cdot 10^{-8}$	kg
Silicon	$5.07 \cdot 10^{-5}$	kg
Sodium	$2.03 \cdot 10^{-6}$	kg
Strontium	$6.10 \cdot 10^{-7}$	kg
Sulfur dioxide	$1.61 \cdot 10^{-3}$	kg
Thallium	$5.07 \cdot 10^{-9}$	kg
Thorium	$6.10 \cdot 10^{-9}$	kg
Thorium-228	$1.77 \cdot 10^{-5}$	kBq
Thorium-232	$1.12 \cdot 10^{-5}$	kBq
Tin	$2.03 \cdot 10^{-9}$	kg
Titanium	$1.22 \cdot 10^{-6}$	kg
Toluene	$3.21 \cdot 10^{-7}$	kg
Uranium	$8.12 \cdot 10^{-9}$	kg
Uranium-238	$3.21 \cdot 10^{-5}$	kBq
Vanadium	$1.22 \cdot 10^{-7}$	kg
Water/m3	$3.23 \cdot 10^{-3}$	m3
Xylene	$3.21 \cdot 10^{-7}$	kg
Zinc	$1.01 \cdot 10^{-8}$	kg

3.2.3 Medium-large size drinking water facility

The assessment of the use of activated carbon is based on the total cycle of the material. It means, from the first use of virgin activated carbon to the final incineration of spent activated carbon taking into account intermediate regenerations and repositions of new material.

As abovementioned, the target drinking plant uses 100 m^3 of activated carbon (45 Ton) per filter and considering losses around 10% during regeneration, 4.5 Ton of new activated carbon are replaced. Moreover, the saturation period ranges between 4-6years and the material accepts up to 3 regenerations. After the whole cycle, spent activated carbon is incinerated and virgin activated carbon is placed again in the drinking water treatment. The total cycle (Figure 3) takes 20years for an average of 5years for saturation and comprises 58.5 Ton of new activated carbon, 135 Ton sent to regeneration and 45 Ton delivered to incineration (Table 3).



	AC	Units
Production of new activated carbon	58.5	Ton
Activated carbon to regeneration	135.0	Ton
Incineration of spent activated carbon	45.0	Ton
Period	20	years

Figure 3. Total cycle for the use of activated carbon in 1 filter of medium-large size facilities considering a lifespan of 5 years, up to 3 regenerations and 10% of losses during the thermal process.

In this process, transportation is a key issue because both processes of production and regeneration are performed abroad: virgin activated carbon is produced in China and distributed from The Netherlands and spent activated carbon is regenerated in Italy. Therefore, 1,902 km are gone down from The Netherlands while regeneration implies two travels (go and return) of 1,555 km, distance from Valencia to Italy. In both cases the Ecoinvent process selected is “Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for”. Moreover, virgin activated carbon is transported from China to The Netherlands sailing around 11,999 nm. Transportation by sea was included in the analysis as “Transport, freight, sea, transoceanic tanker {GLO}| market for”.Finally, it was assumed that the final spent material is incinerated close to the factory in Valencia,sotransportationis disregarded. Incineration is modelled following an average Ecoinvent process for municipal solid waste (“Hard coal ash {RoW}| treatment of hard coal ash, municipal incineration”)and modified considering emissions of CO_2provided by the company: 4 Ton CO_2 per Ton of activated carbon incinerated. Although the process selected is referred to hard coal ash incineration, no specific processes for spent activated carbon incineration were found in Ecoinvent Database or bibliography.

Considering that the present work is performed with the objective of establishing a comparison with the PORTABLECRAC technology, common inputs for both scenariossuch as energy used in the plant or wastewater characterization are disregarded.

Table 3. Life cycle inventory (LCI) for the use of 1 filter of 100 m^3 of activated carbon in medium-large drinking water facilities (FU: 20 years).

	Value	Units
Inputs from technosphere		
Virgin activated carbon	58.50	Ton
Truck > 32 ton for virgin activated carbon from The Netherlands to Spain	111,267	Ton·km
Shipping of virgin activated carbon from China to The Netherlands	1,299,987	Ton·km
Tank truck > 32 ton for spent and regenerated activated carbon	419,850	Ton·km
Tank truck > 32 ton for final spent activated carbon to incineration	Negligible	Ton·km
Outputs to technosphere: Waste treatment		
Spent activated carbon to regeneration	135.00	Ton
Spent activated carbon to incineration	45.00	Ton

3.2.4 Small size drinking water facility

Regeneration is not typically performed in small facilities because it is affordable to substitute spent material by new one at such small quantities. In this case, a unit of 20 m^3 (9 Ton) is operated for the set lifespan (5 years as determined for larger units) and after this period the spent carbon is incinerated and replaced by new material. To be consistent with the previous scenario, a time framework of 20 years is considered for the analysis (Figure 4) although in this case the cycle is completed every 5 years. Moreover, the system developed in PORTABLECRAC will be a suitable alternative for small facilities and the total cycle will go beyond 5 years considering regeneration.

	AC	Units
Production of new activated carbon	36.0	Ton
Activated carbon to regeneration	0	Ton
Incineration of spent activated carbon	36.0	Ton
Period	20	years

Figure 4. Total cycle for the use of 20 m^3 filters of activated carbon in small facilities considering a lifespan of 5 years and a total time framework of 20 years.

As explained for larger units, virgin activated carbon is produced in China, transported to the distribution point in The Netherland by sea (11,999 nm) and then carried to Spain for its use in the drinking water facility (1,902 km). The replacement of spent carbon by new material supposes that every 5 years the itinerary is carried out (Table 4). The PORTABLECRAC system will allow small facilities to perform the in-situ regeneration avoiding all the transportation stages every 5 years and all related environmental burdens. Keeping in mind that the present work is performed with comparative purposes when the PORTABLECRAC technology is developed, common inputs for both situations such as energy use in the plant or wastewater characterization are disregarded.

Table 4. Life cycle inventory (LCI) for the use of 1 filter of 20 m^3 of activated carbon in small drinking water facilities (FU: 20 years).

	Value	Units
Inputs from technosphere		
Virgin activated carbon	36.00	Ton
Truck > 32 ton for virgin activated carbon from The Netherlands to Spain	68,472	Ton·km
Shipping of virgin activated carbon from China to The Netherlands	799,992	Ton·km
Tank truck > 32 ton for final spent activated carbon to incineration	Negligible	Ton·km
Outputs to technosphere: Waste treatment		
Spent activated carbon to incineration	36.00	Ton

3.3 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

It was determined to perform the environmental evaluation at the midpoint level. ReCiPe is the methodology selected to evaluate global warming, terrestrial acidification, freshwater eutrophication and marine eutrophication while USEtox is used for toxicity related categories: human toxicity and freshwater ecotoxicity. ReCiPe is a method broadlyapplied which covers a wide range of impact categories at both midpoint and endpoint levels (Goedkoop et al., 2009). Concerning toxicity assessment, USEtox is a consistent method recommended by the ILCD Handbook (ILCD, 2011), which exclusively deals with toxicity categories (Rosenbaum et al., 2008).

3.3.1 Production of activated carbon

In the present section, the potential impacts related to the production of activated carbon according to the LCI described in Table 1 are calculated (Table 5). The impacts are referred to the production of 1 kg of virgin activated carbon following a conventional process. Among the impact categories evaluated global warming has been deeply studied in the bibliography considering its relevance for energy depending processes. In this study the use of activated carbon based on bituminous carbon was assumed but nowadays other raw materials such as coconut shells are also feasible. This approach is relevant under an environmental perspective considering that environmental burdens related to the production of granular activated carbon based on bituminouscarbon ranges from 10.33 to 19.60 kg CO_2 eq per kg ofGAC (Meier, 1997; Bayer et al., 2005) while more optimized processes using coconut shell lead to much lower impacts from 1 to 7 kg CO_2 eq per kg ofGAC (Arena et al., 2016; Paredes et al., 2018). It is also demonstrated that the potential global warming calculated, 13.16 kg CO_2 eq per kg ofGAC, is in accordance with bibliographic data for bituminous based activated carbon.

Table 5. Potential impacts related to the production of virgin activated carbon (FU: 1 kg of activated carbon)

Impact categories	Value	Units
Global warming	13.16	kg CO_2 eq
Terrestrial acidification	$5.53 \cdot 10^{-2}$	kg SO_2 eq
Freshwater eutrophication	$1.53 \cdot 10^{-3}$	kg P eq
Marine eutrophication	$9.27 \cdot 10^{-5}$	kg N eq
Human toxicity	$1.22 \cdot 10^{-6}$	cases
Freshwater ecotoxicity	53,152.70	PAF·m^3·day

The contribution of the different inputs and outputs (Table 1) to the total environmental burdens was evaluated with the aim of understanding their share in the global impacts (Figure 5). Direct emissions represent more than half of global warming and terrestrial acidification (Figure 5a and 5b) while hard coal management contributes close to 80% to eutrophication related categories (Figure 5c and 5d). When it comes to toxicity and ecotoxicity categories, electricity, hard coal management, incineration and direct emissions present significant shares (Figure 5e and 5f).

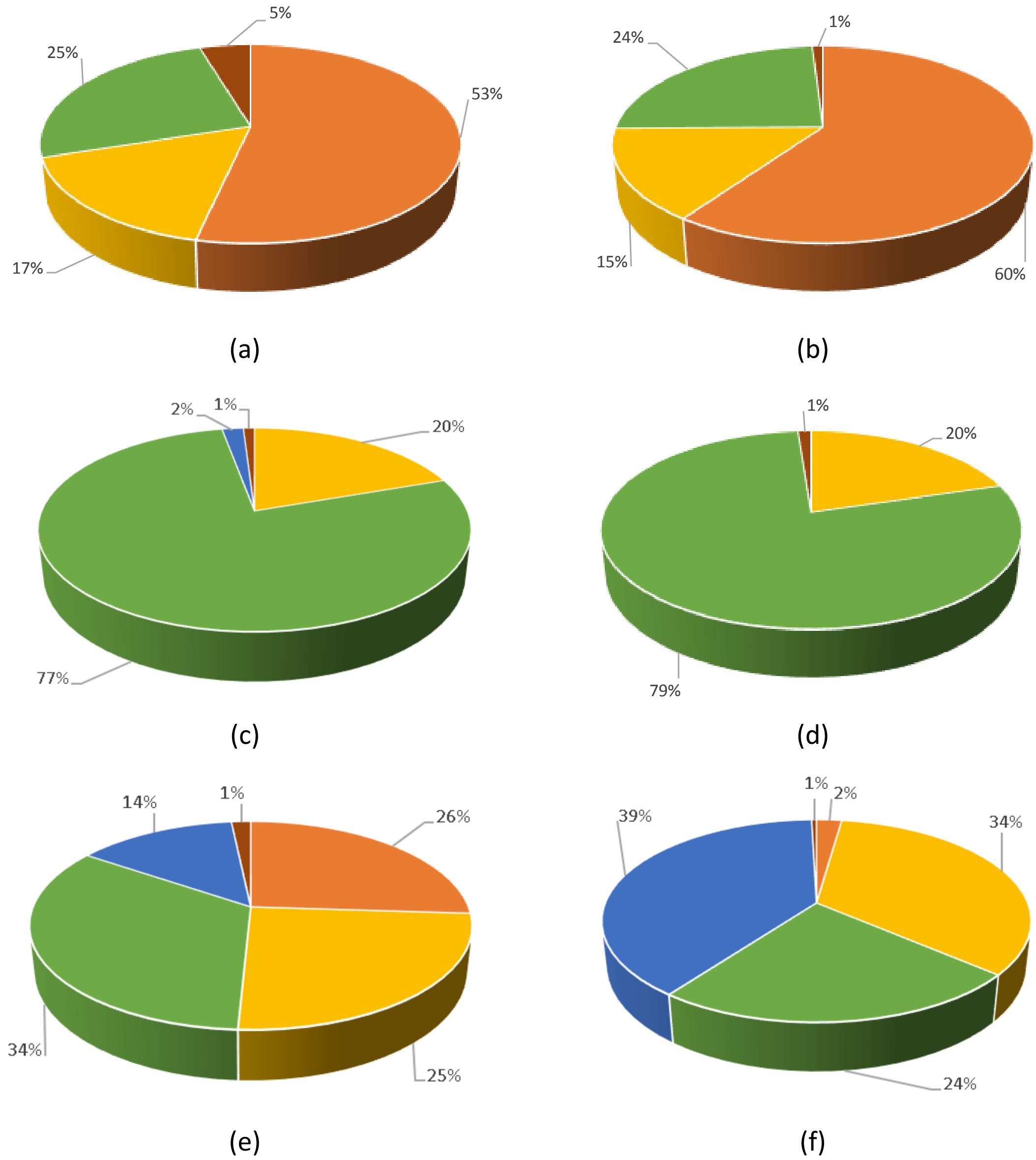


Figure 5. Relative contributions of processes and emissions to the general process of activated carbon production for (a) global warming, (b) terrestrial acidification, (c) freshwater eutrophication, (d) marine eutrophication, (e) damage to human health and (f) ecosystem diversity loss. Colors code: electricity (■), hard coal management (■), hard coal ash management (■), direct emissions (■) and others (■).

The value included in Table 1 for CO_2 emissions to air, 7 kg CO_2, is the main responsible for climate change impact with 7 kg CO_2 eq per kg of activated carbon considering that the characterization factor for this compound is 1 kg CO_2 eq per kg of CO_2 emitted. For terrestrial acidification, direct emissions represent 60% of the global impact mainly due to sulfur dioxide emissions during the productive process which lead to 0.0289 kg CO_2 eq per kg of activated carbon. Finally, 17% of human toxicity is caused by the emission of mercury to air. Therefore, the quantification of pollutants emitted to air is relevant in this study.

As explained in the process description, 3 kg of raw hard coal are necessary to obtain 1 kg of activated carbon. The process included in the analysis comprises sub-processes such as mine operation, hard coal preparation, transport and so on. The former sub-process is the main responsible for the impacts: 99% of the burdens calculated for hard coal management. Electricity leads to shares between 15% and 34% in the impact categories evaluated and treatment of ashes become relevant when it comes to ecotoxicity impact categories.

Although the potential impacts were calculated, and the corresponding shares determined, no specific improvements are here recommended because the analysis is mainly based on a bibliographic process. In case real scenarios are analyzed throughout the development of the PORTABLECRACproject, LCI will be accordingly modified and alternative scenarios will be proposed to improve the environmental profile.

3.3.2 Thermal regeneration of spent activated carbon

The environmental assessment of thermal regeneration was performed considering the LCI shown in Table 2. In this case, the analysis describes the treatment of 1 kg of spent activated carbon or, in other words the production of 0.9 kg of reactivated carbon. Although it was previously mentioned that similar processes are applied for production and regeneration, it is highlighted the difference in the feeding: 3 kg of coal in production vs. 1 kg of spent material for regeneration. Moreover, emissions to air show lower CO_2 release in this case: 2 kg CO_2 vs. 7 kg CO_2 emitted during the process of production.

The potential impacts obtained for thermal regeneration (Table 6) are much lower than those related to the process of activated carbon production. The main reason is the different between processes above-detailed: lower direct CO_2 emissions and treatment of 1 kg of material. For example, the treatment of 1 kg of spent activated carbon leads to 2.6 kg CO_2 eq while the potential impact to produce 1 kg of virgin material is much higher: 13 kg CO_2 eq. Moreover, this process considers the management of spent activated carbon instead of raw hard coal. This fact isespecially significant for the eutrophication potential (Figure 5c and 5d).

The shares related to the inputs included in the LCI of the process (Table 2) are depicted in Figure 6. Similar to Figure 5, direct emissions are the main responsible for global warming and terrestrial acidification potential impacts (Figure 6a and 6b). On the other hand, the large contribution of electricity over the rest of inputs is highlighted representing around 97% in eutrophication categories.

Table 6. Potential impacts related to the thermal regeneration of spent activated carbon (FU: 1 kg of spent activated carbon treated)

Impact categories	Value	Units
Global warming	2.599	kg CO_2 eq
Terrestrial acidification	$3.40 \cdot 10^{-3}$	kg SO_2 eq
Freshwater eutrophication	$2.69 \cdot 10^{-4}$	kg P eq
Marine eutrophication	$1.88 \cdot 10^{-5}$	kg N eq
Human toxicity	$1.18 \cdot 10^{-7}$	cases
Freshwater ecotoxicity	3,651.38	PAF·m^3·day

The evaluation of global warming potential shows that direct emissions of CO_2 during the thermal process cause 77% of the total impact (Figure 6a) mainly due to 2 kg CO_2 directly emitted to air (Table 2). Also, energy and natural gas contribute ~22% to the potential impact. On the other hand, as demonstrated in the process of production of virgin activated carbon, direct emissions of sulfur dioxide are the main responsible for terrestrial acidification: 47% of the global impact. The reason behind the freshwater ecotoxicity potential of hard coal ash management is like that explained in production: due to hard coal mine activities.

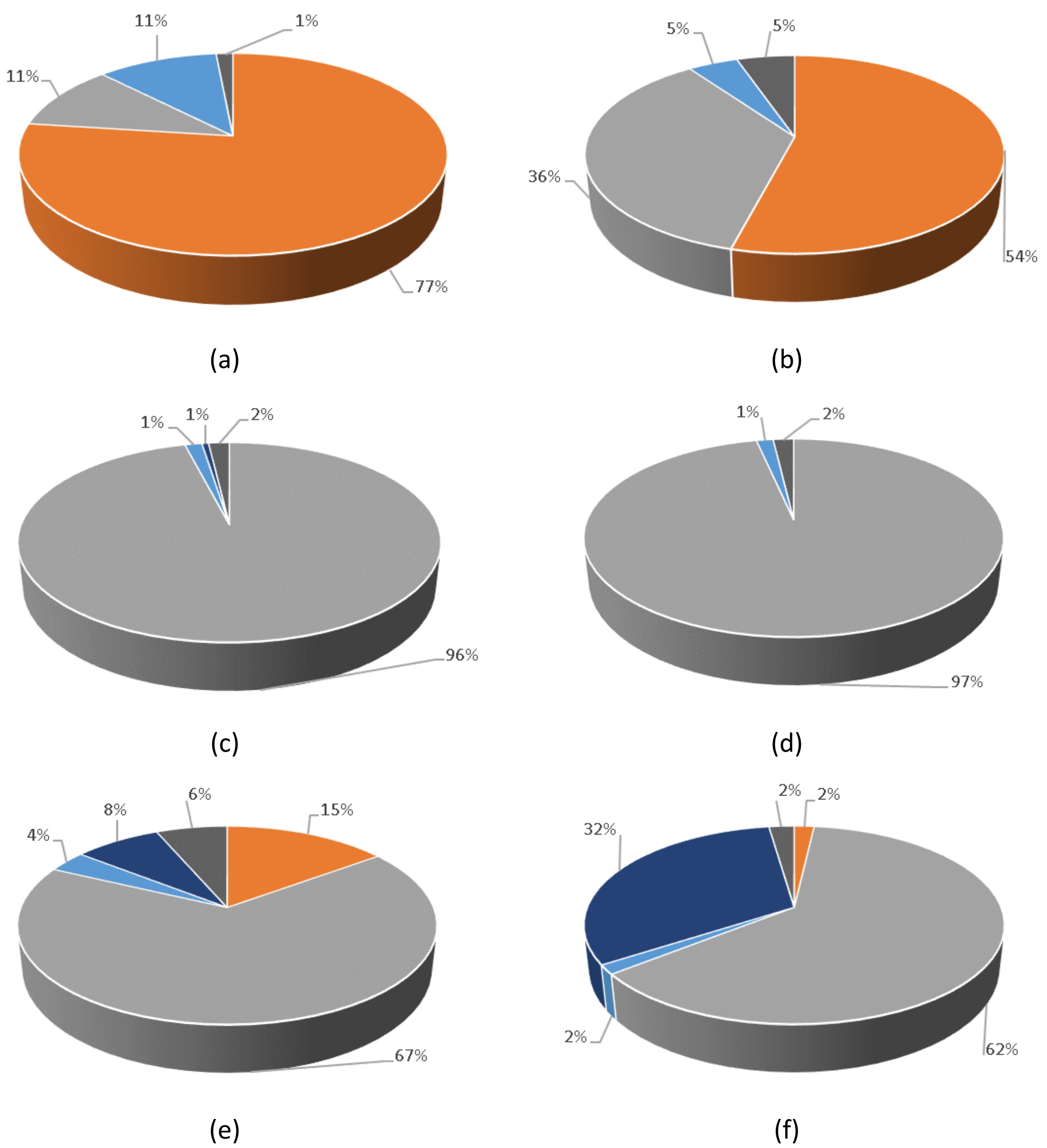


Figure 6. Relative contributions of processes and emissions to the process of thermal regeneration of activated carbon for (a) global warming, (b) terrestrial acidification, (c) freshwater eutrophication, (d) marine eutrophication, (e) damage to human health and (f) ecosystem diversity loss. Colors code: electricity (■), direct emissions (■), natural gas - heat (■), hard coal ash management (■) and others (■).

The outcomes obtained in the analysis of the current process of thermal regeneration are relevant for PORTABLECRAC development. The identification of the main hotspots under an environmental perspective will allow to underline the benefits of the PORTABLECRAC system vs. the current technology. First, no thermal processes will be applied with the novel system and consequently most of direct emissions will be avoided. And second, one of the main characteristics of thermal regeneration is the large demand of energy during the process which is expected to be reduced with the PORTABLECRAC technology. Even so, it should be considered that the current process is based on bibliographic processes and any input received throughout the development of the project will be considered for the environmental assessment update and improvement.

In the environmental assessment of thermal regeneration special attention needs to be paid to energy use because this input shows the largest shares in freshwater eutrophication, marine eutrophication, human toxicity and freshwater ecotoxicity ranging from 62% to 97%. The process used in the analysis for electricity is based on a European average for medium voltage which includes different energy sources typically used in Europe. The analysis of substances emitted during the processes revealed that $2.58{\cdot}10^{-4}$ kg P por kg of spent activated carbon are a consequence of Phosphate emitted to water while $1.81{\cdot}10^{-5}$ kg N por kg of spent activated carbon are due to Nitrate release.

3.3.3 Use of activated carbon in drinking water facilities

The assessment of the use of activated carbon in large and small facilities allows covering the whole life cycle of the material under an environmental perspective. It means that not only production and regeneration are considered, but also transport, material losses during thermal processes or final spent material management are evaluated.

The main difference between scenarios is that spent activated carbon is regenerated in large facilities or directly removed to be incinerated in the smallest ones. It needs to be underlined that the objective of this evaluation is not to compare both scenarios carried out at different scales but to show the real potential impacts of large and small units operation to be in a further stage compared with the system developed in the PORTABLECRAC project. Therefore, potential burdens related to the operation with large amounts of activated carbon (Table 7) and related to small units (Table 8) will be discussed again when the PORTABLECRAC system evaluated.

Table 7. Potential impacts related to the use of 1 filter of 100 m^3 of activated carbon in a medium-large size drinking water facility for 20 years

Impact categories	Value	Units
Global warming	$1.36{\cdot}10^{6}$	kg CO_2 eq
Terrestrial acidification	3,995.25	kg SO_2 eq
Freshwater eutrophication	131.38	kg P eq
Marine eutrophication	8.34	kg N eq
Human toxicity	0.23	cases
Freshwater ecotoxicity	$2.94{\cdot}10^{10}$	PAF·m^3·day

Table 8. Potential impacts related to the use of 1 filter of 20 m^3 of activated carbon in a small size drinking water facility for 20 years

Impact categories	Value	Units
Global warming	$6.30 \cdot 10^5$	kg CO_2 eq
Terrestrial acidification	2,107.06	kg SO_2 eq
Freshwater eutrophication	56.88	kg P eq
Marine eutrophication	3.43	kg N eq
Human toxicity	0.15	Cases
Freshwater ecotoxicity	$2.25 \cdot 10^{10}$	PAF·m^3·day

The relative contributions to the global impacts for both scenarios include the production and transport of virgin activated carbon and final incineration while for larger units also regeneration and transportation of spent and regenerated carbon are evaluated.

Looking at the shares obtained for the use of units of 100 m^3 of activated carbon it is highlighted the relevance of the processes of production of activated carbon for global warming, terrestrial acidification, freshwater eutrophication and marine eutrophication (Figure 7a-d) and incineration for human toxicity and freshwater ecotoxicity (Figure 7e and 7f). On the other hand, regeneration (process and transport) represents a maximum of 33% for marine eutrophication and lower percentages in the rest of categories. This percentage is expected to be reduced with the PORTABLECRAC system. Moreover, virgin activated carbon production includes not only 100 m^3 of new material but also the quantity used for losses replacement (10% of material lost during thermal regeneration). In case the PORTABLECRAC technology allows to perform regeneration without losses, this percentage will be also reduced. Transportation does not lead to significant shares when compared to energy demanding processes such as production and thermal regeneration.

The relevance of production and regeneration in the impact categories evaluated can be verified with data shown in Figure 3 (58.5 Ton of virgin activated carbon and 135 Ton of carbon regenerated) and the impacts depicted in Table 5 and Table 6.

On the one hand, the breakdown of potential impacts related to new activated carbon to analyze global warming, terrestrial acidification, freshwater eutrophication and marine eutrophication (Figure 7a-d) is depicted in Figure 5. Accordingly, direct emissions and hard coal management are the main responsible for the related impacts. On the other hand, toxicity and ecotoxicity are mainly caused by the process of incineration of spent activated carbon. As mentioned in the LCI section, the process was modeled as "hard coal ash incineration" because of the impossibility of collecting data for the real process. Therefore, in the next steps to perform the LCA of the PORTABLECRAC system, the process of incineration needs to be accordingly described and modified in order to show a more reliable profile of both impact categories.

Regarding the smallest unit evaluated, 20 m^3 of activated carbon, relative contributions include virgin activated carbon use and transport and final incineration (Figure 8). As discussed for the largest unit, emissions caused during incineration are significant for toxicity and ecotoxicity and virgin activated carbon production is the main responsible for the rest of categories evaluated. The fact of using new activated carbon every 5 years is significant specially for eutrophication related categories with shares around 97% (Figure 8c and 8d). Therefore, the reduction of environmental impacts thanks to the PORTABLECRAC technology is expected in case in-situ regeneration leads to lower impacts than those related to theproductionof new activated carbon. Finally, as discussed for Figure 7, the LCI of the real process of incineration is necessary to have more reliable results.

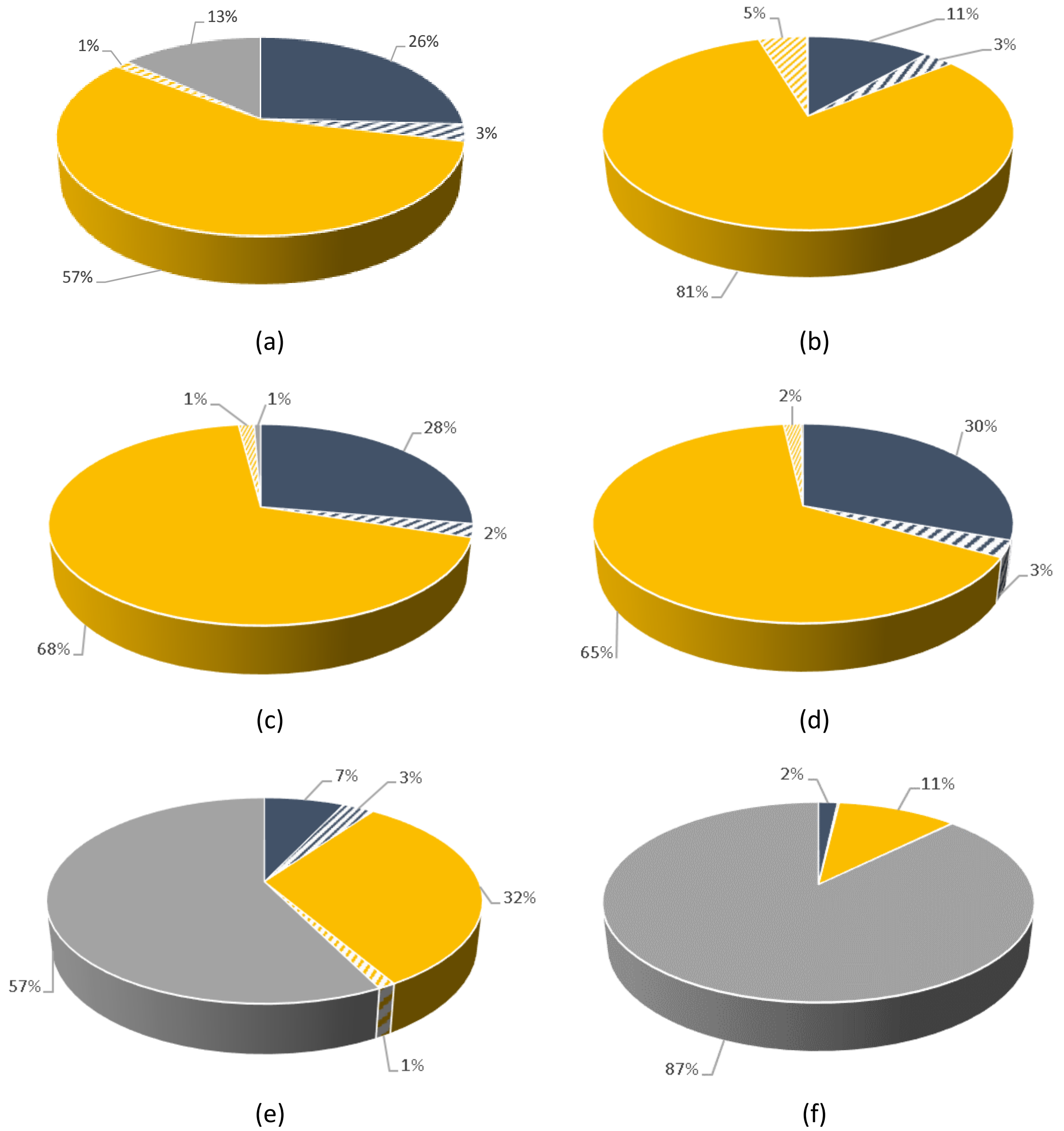


Figure 7. Relative contributions of processes and emissions to the potential impacts related toa filter of 100 m^3 of activated carbon. Impact categories: (a) global warming, (b) terrestrial acidification, (c) freshwater eutrophication, (d) marine eutrophication, (e) damage to human health and (f) ecosystem diversity loss. Colors code: production of virgin activated carbon (■), transportation of virgin activated carbon (◪), activated carbon regeneration (■), transport for regeneration (◪) and final incineration (■).

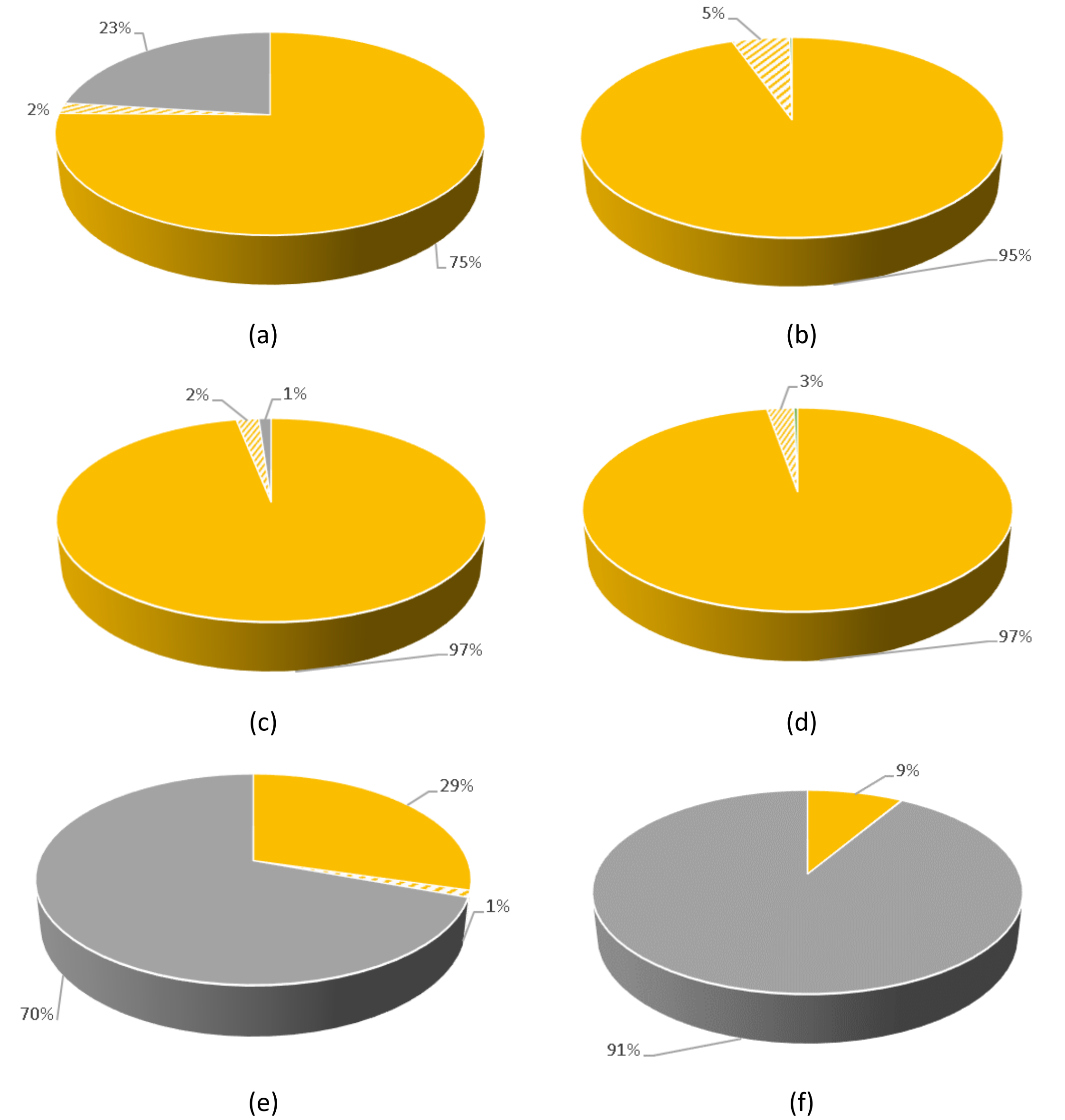


Figure 8. Relative contributions of processes and emissions to the potential impacts related to a filter of 20 m^3 of activated carbon. Impact categories: (a) global warming, (b) terrestrial acidification, (c) freshwater eutrophication, (d) marine eutrophication, (e) damage to human health and (f) ecosystem diversity loss. Colors code: production of virgin activated carbon (■), transportation of virgin activated carbon (▨) and final incineration (■).

4 LIFE CYCLE COST (LCC) ANALYSIS

LCC analysis is a valuable technique used to predict and assess the cost performance of goods and products. This method considers initial costs which include capital investment costs, purchase, and installation costs; future costs which refer to energy costs, operating costs, maintenance costs, capital replacement costs and financing costs and finally any resale, salvage, or disposal cost, over the lifetime of the project or product (Figure 9). LCC analysis is a useful tool used for the evaluation of different project options from the perspective of economic efficiency. This method is based on obtaining the present value of future costs and benefits linked with decisions of the processes in the production chain. LCC analysis is interesting because it covers another pillar of sustainability, together with LCA and social life cycle assessment (S-LCA), the latter out of the scope of the present study. LCC analysis is based on monetary values for most of inputs included in the LCI and additional parameters.

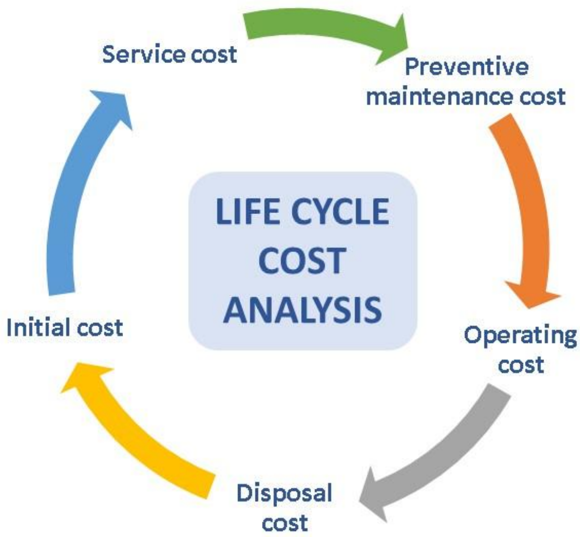


Figure 9. Steps included in the life cycle cost (LCC) analysis.

LCC analysis is applied to assess process from diverse sectors, including wastewater treatment plants (Ciroth et al., 2011; Hunkeler et al., 2008, Lorenzo et al., 2016). Although the FU can be selected depending on the purpose of the study, in this case 20 years covering the whole cycle of activated carbon will be assessed to be consistent with the LCA. By this way, the FU agrees with the time horizon of this analysis.

The objective of this deliverable is to be compared with LCC analysis of the PORTABLECRAC solution. For this reason, a conventional life cycle costing or financial life cycle costing is carried out. It is only focused on private investments from consumer perspective, which is enough for a comparative purpose of conventional regeneration and PORTABLECRAC project.

The LCC basic calculation formulas are presented below, eq. (1) - (3). The present value of LCC, named PVLCC, can be calculated as follows:

$$PVLCC = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \tag{1}$$

Where:

- C_t is the sum of all relevant costs occurring in year t.
- n is the length of the study period in years.
- i is the nominal discount rate.

The main PVLCC components are:

$$PVLCC = IC + PV(OM\&R + R + F - S) \tag{2}$$

Where:

- IC are investment costs.
- PV is the present value obtained through nominal discount rate (i).
- OM&R are operating, maintenance and repair costs.
- R are replacement costs
- F are fuel costs.
- S is the residual value (such as resale).

The nominal discount rate takes into account the inflation rate and can be calculated as follow:

$$i = (1 + r)(1 + I) - 1 \tag{3}$$

Where:

- r is the real discount rate.
- i is the nominal discount rate.
- I is the general price inflation.

The discount rate refers to the rate that reflects the time value of money and it is used to find the current value of future amounts of money. In conducting an LCC analysis to compare different investment alternativesit is essential to determine a discount rate to find the equivalent value for each alternative in a common base date(Kirk et al., 1995).

The International Standard ISO 15686-5:2017 recommends that the determined discount rate, for private sector projects, should cover the opportunity cost of the invested capital which can be:

- the interest cost of a loan for investment,
- the interest lost from cash reductions from deposits,
- the lost return from other possible investment,
- the actual return from capital investments,
- the anticipated rate of return from thenew business.

Taking those into account, a real discount rate of 4 % will be assessed.

The inflation/deflation refers to the continuous increase/decrease in the general price levels of goods and services. In conducting a life cycle cost analysis for economic appraisal purposes, nominal or real costs can be used in the analysis. The nominal costs refer to the costs which are estimated taking into account the effect of price inflation/deflation; the nominal costs represent the amount of money that will be paid when the costs are due to be paid. The real costs, on the other hand, reflect the current value of goods or services; the effect of inflation/deflation on the costs is disregarded in the real terms. In using LCC analysis to compare various alternatives, it is recommended to estimate the LCC in the real terms to reduce the uncertainty associated with forecasting future inflation/deflation rates(Kirk et al., 1995).So regarding equation (3), it will be for this study:

$$i = r = 4\,\%$$

4.1 COSTS QUANTIFICATION

As abovementioned, the target water drinking plant uses 100 m^3 of activated carbon per filter and considering losses around 10% during regeneration, 10 m^3 of new activated carbon are replaced after the process. Moreover, the saturation period ranges between 4-6 years, a mean of 5 years will be considered in the analysis, and the material accepts up to 3 regenerations. After that, spent activated carbon is incinerated and virgin activated carbon is used for drinking water treatment.

However, this scenario considers that the water drinking plant has enough capacity to afford regeneration. Nowadays, small plants do not regenerate their spent activated carbon because the cost difference between it and to get new does not justify it. So for the purpose of this deliverable, to analyze one of thesealternatives is mandatory. A plant which uses 20 m^3 of activated carbon per filter was selected.

Being based on equation (2) for this study, investment costs are zero, OM&R and replacement costs were provided by the target drinking water facility and they are as follow:

- New activated carbon including transport for a large filter = 650 €/m^3
- New activated carbon including transport for a small filter = 900 €/m^3
- Regenerated activated carbon including transport for a large filter = 410 €/m^3
- Filter extraction cost for open filters = 40 €/m^3
- Filter extraction cost for close filters = 200 €/m^3

Fuel costs are none and residual value is zero, but a new term could be added to the equation for this study. It is the end of life costs (ELC), which includes waste management through incineration and its value is 17.10 €/m^3. It is also provided by the target drinking plant.

The difference in the new activated carbon price is because of large plants buy a higher amount of activated carbon, so they can negotiate a better unitary price. Also, the filters in these facilities are bigger, open and the replacement is easier than in small ones where the filters are closed doing more difficult this task.

4.2 LCC RESULTS

4.2.1 Scenario 1: EMIVASA plant with 100 m^3 of activated carbon per filter.

LCC results are summarized in Table 9 and Figure 9. The main cost contribution is OM&R category, which includes in this study the cost of new or regenerated activated carbon when the filters are saturated. The remaining categories, extraction cost (R) and waste management (ELC) have a minimal impact.

Table 9. Potential costs related to the use of activated carbon in a filter of a medium-large size drinking water facility for 20 years

	0	5	10	15	20
OM&R	65,000.00 €	47,500.00 €	47,500.00 €	47,500.00 €	0.00 €
New activatedcarbon	65,000.00 €	6,500.00 €	6,500.00 €	6,500.00 €	0.00 €
Regeneratedactivatedcarbon	0.00 €	41,000.00 €	41,000.00 €	41,000.00 €	0.00 €
Replacement	0.00 €	4,000.00 €	4,000.00 €	4,000.00 €	4,000.00 €
Wastemanagement	0.00 €	0.00 €	0.00 €	0.00 €	1,710.00 €
COSTS	65,000.00 €	51,500.00 €	51,500.00 €	51,500.00 €	5,710.00 €
ACUMULATIVE COSTS	65,000.00 €	116,500.00 €	168,000.00 €	219,500.00 €	225,210.00 €

PORTABLECRAC solution will affect to OM&R category, decreasing regeneration cost. As abovementioned, this category is the principal life cycle costing actor. So it is expected a remarkable reduction in relation to the present analysis.

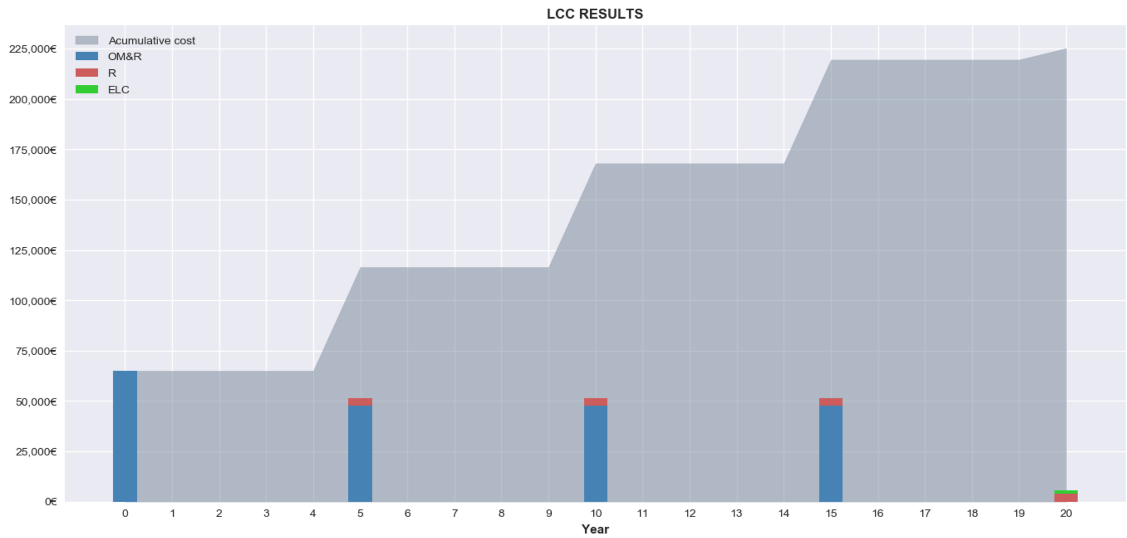


Figure 9.LCC contributions to the scenario using 100 m^3 of activated carbon per filter in medium-large size drinking water treatment facilities.

Finally, applying equation (1) the present value of the whole cycle costs is calculated:

$$PVLCC = \sum_{t=0}^{20} \frac{OM\&R(t) + R(t) + ELC(t)}{(1+0.04)^t} = \mathbf{173,322.89}\ €$$

$$PVLCC\ \left(€/_{m^3}\right) = \mathbf{1,733.23}\ €/_{m^3}$$

4.2.2 Scenario 2: EMIVASA plant with 20 m^3 of activated carbon per filter.

Likewise, calculations are analogous to previous scenario.

Table 10. Potential costs related to the use of activated carbon in a filter of asmall size drinking water facility for 20 years

	0	5	10	15	20
OM&R	20,000.00 €	20,000.00 €	20,000.00 €	20,000.00 €	0.00 €
New activatedcarbon	20,000.00 €	20,000.00 €	20,000.00 €	20,000.00 €	0.00 €
Replacement	0.00 €	4,000.00 €	4,000.00 €	4,000.00 €	4,000.00 €
Wastemanagement	0.00 €	342.00 €	342.00 €	342.00 €	342.00 €
COSTS	20,000.00 €	24,342.00 €	24,342.00 €	24,342.00 €	4,342.00 €
ACUMULATIVE COSTS	20,000.00 €	44,342.00 €	68,684.00 €	93,026.00 €	97,368.00 €

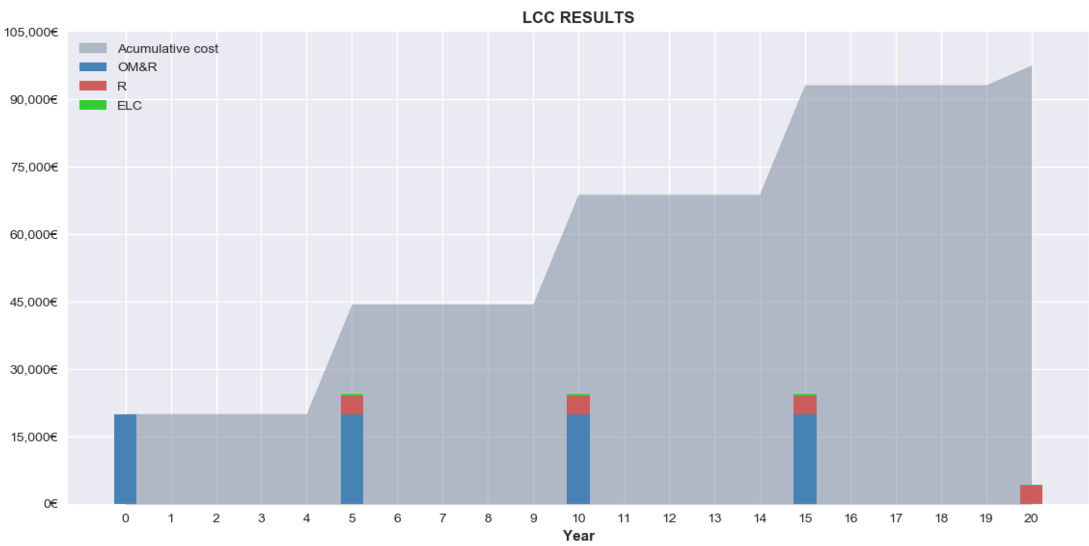


Figure 10.LCC contributions to the scenario using 20 m^3 of activated carbon per filter in small size drinking water treatment facilities

$$PVLCC = \mathbf{71,949.81}\ €$$

$$PVLCC\ \left(€/_{m^3}\right) = \mathbf{3,597.49}\ €/_{\mathbf{m^3}}$$

PVLCC in €/m^3 is more than the double for this scenario in comparison with the previous one, because small size drinking water facilities do not regenerate their spent activated carbon and they have a weaker position to negotiate their costs. PORTABLECRAC solution will make affordable the regeneration on a small scale, so the impact will be even greater for these drinking water facilities.

5 CONCLUSIONS AND FURTHER DEVELOPMENTS

On the one hand, the LCA of activated carbon production from hard coal concludes that direct emissions are the main hotspot, representing more than half of global warming. Also, they have an important weight in human toxicity. Electricity leads to shares between 15% and 34% in the impact categories evaluated and treatment of ashes become relevant when it comes to ecotoxicity analysis. On the other hand, the LCA of activated carbon thermal regeneration concludes that the potential impacts obtained are much lower than those related to the process of activated carbon production, but they have a similar behaviour. Special attention needs to be paid to energy use. To conclude with LCA studies, the assessment of the use of activated carbon in large and small facilities allows to cover the whole life cycle of the material under an environmental perspective. It is highlighted the relevance of the processes of production of activated carbon for global warming, terrestrial acidification, freshwater eutrophication and marine eutrophication and incineration for human toxicity and freshwater ecotoxicity. On the other hand, regeneration (process and transport) represents a maximum of 33% for marine eutrophication and lower percentages in the rest of categories. Transportation does not lead to significant shares when compared to energy demanding processes such as production and thermal regeneration. The outcomes obtained in this analysis are relevant for PORTABLECRAC. First, no thermal processes will be applied with the novel system and consequently most of direct emissions will be avoided. Moreover, one of the main characteristics of thermal regeneration is the large demand of energy during the process which is expected to be reduced with the PORTABLECRAC technology. And finally, the losses of regeneration are expected to be lower, so less novel activated carbon, which has greater impacts, will be needed.

Finally, the LCC was carried out of the use of activated carbon in EMIVASA large and small facilities with the objective to stablish an initial point for the future comparison with the economical assessment of PORTABLECRAC technology. For both cases, the main cost contribution is OM&R category, which includes in this study the cost of new or regenerated activated carbon when the filters are saturated. The remaining categories, extraction cost and waste management, have a minimal impact. PORTABLECRAC solution will mainly affect to OM&R category, decreasing regeneration cost, so it is expected a remarkable reduction in relation to the present analysis. PVLCC for a drinking water facility filter with 100 m^3 of activated carbon is 173,322.89 € and per used volume, 1,733.23€/m^3. PVLCC for a small plant filter with 20 m^3 of activated is 71,949.81€. PVLCC in €/m^3 is 3,597.49€/m^3, more than the double for this scenario in comparison with the previous one, because small size drinking water facilities do not regenerate their spent activated carbon and they have a weaker position to negotiate their costs. PORTABLECRAC solution will make affordable the regeneration on a small scale, so the technology impact will be even greater for these drinking water facilities.

Further developments must be focused on the fact that the present environmental analysis is mainly based on a bibliographic process. In case real scenarios are analyzed throughout the development of the project, LCI will be accordingly modified and alternative scenarios will be proposed to improve the environmental profile. In fact, an activated carbon manufacturer of EMIVASA reported that they use 6.7 kg of hard coal to produce 1 kg of activated carbon. This amount differs a lot with bibliographic data, so further investigation should be done to validate this quantity and include it in the analysis. Also, in next steps to perform the LCA of the PORTABLECRAC system, the process of incineration should be accordingly described and modified in order to show a more reliable profile of both impact categories. Moreover, 10% of losses in regeneration process were taken into account, but this value could reach to 20% in some cases. So further analysis of the process should be done. Finally, according to bibliographic inventories, natural gas was assumed as thermal energy precursor; but further investigation may be done in Chinese production; due to it is a country were primary energy is mainly based on coal. Stablishing coal as thermal energy precursor would increase potential impacts such as global warming and terrestrial acidification. On the other hand, LCC studies were based on real data provided by EMIVASA, but in some drinking water facilities the production of fresh water is stopped when the filters need to be replaced during activated carbon regeneration. This could be assessed not only as a cost, but also as an environmental impact due to direct emissions of polluted water, which is not considered in the present analysis due to lack of information.

To conclude, regarding both life cycle analysis, the saturation period of activated carbon was assessed in 5 years as the average value of the data provided by EMIVASA, but this time gap is variable and depends on the pollutants of the treated water. It could vary from 1 to 7 years, so future work will consider it and a sensitivity analysis in LCA and LCC results will be developed.

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