Life Cycle Assessment applied to remediation technologies: methodological and practical issues

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Abstract

At the present day, remediation of polluted groundwater can be performed through various technologies; however, these technologies are often associated with relevant costs (both economic and environmental) and technical issues [1] which in some cases may affect the cost effectiveness and feasibility of remediation itself. This is why efforts in the field of research are being increasingly focused in the development of bioremediation technologies which use the degrading potential of bacteria and microorganisms to remove target pollutants. These technologies require a smaller demand for resources and technical equipment in order to achieve clean up targets compared to traditional systems.

The focus of the study was to evaluate, by a comparative Life Cycle Assessment (LCA) approach, the environmental performance of an innovative technology (a modified Permeable Reactive Barrier, PRB), within the framework of EU Minotaurus project, in comparison to a permeable reactive barrier filled with Zero Valent Iron (ZVI) and a Pump and Treat System (PTS) [3].

A few methodological issues showed up during the research. First, a full scale modified PRB had to be designed in order to allow comparison with reference technologies: the new system has been modeled introducing graphite instead of ZVI as a reactive medium. Secondly, Ecoinvent database did not provide a specific item to address the discharge of treated groundwater as surface water in the PTS, thus not allowing the evaluation of the impact resulting from the depletion of a non-renewable (in the short medium term) resource; this issue has been addressed by modeling post treatment water as if it were wastewater with a slight degree of contamination. Finally, a first run of results produced through EDIP/UMIP 97 method showed a particular emphasis on ecological and human toxicity impact categories. According toInternational reference Life Cycle Data System(ILCD [5]) suggestions tohandle with care these categories' scores, another run of results has been produced through IMPACT 2002+ method. A key to the interpretation and comparison of the results obtained by the two methods was provided by the analysis of the results produced in the Global Warming Potential category.

The results showed that, for all three systems analyzed, the critical factor is the reactive medium, to which both calculation methods associated the most relevant impacts. The modified PRB [2] showed the best performance, even if its efficiency in remediation process must be tested and backed up by field results. In passive remediation technologies the use of less impactful media turned out to be a key factor in order to improve the overall sustainability of remediation systems, with particular reference to PRB, which showed the poorest performance due to the use of ZVI. The performance of the Pump and Treat system turned out to be closely related to the amount of Granular Activated Carbon (GAC) employed: the sizing applied to this case study kept total environmental score comparable to those of the passive technologies; however, considering the relevant environmental burden of the activated carbon production process, it can be expected a high environmental cost for applications of this technology involving larger volumes of water or longer operation time.

Introduction

The comparative LCA described in this paper has been performed within the framework of the MINOTAURUS (Microorganism and enzyme Immobilization: NOvel Techniques and Approaches for Upgraded Remediation of Underground-, wastewater and Soil) project between April 2012 and March 2014. The goal of the project was to test and develop innovative techniques for bioremediation of polluted soils and groundwater.

The specific task for our team was to evaluate the overall environmental performance of a bioelectrochemical system through LCA methodology, and to compare the results with those of consolidated technologies, a Permeable reactive barrier and a Pump and treat System. In order to perform the Life Cycle Assessment for the bioelectrochemical system, which had only been tested as a lab-scale prototype, it was first necessary to define a full scale scenario for this technology. This task has been performed with the support of prof. Mauro Majone and Federico Aulenta from UNIRM.

Data for benchmark technologies were taken directly from a fully operating treatment facility in the case of the Permeable Reactive Barrier and estimated on literature references and case studies in the case of the Pump and Treat system. Conclusions provided by Bonoli et al.[1] and Bayer and Finkel [3] have been implemented in order to properly take into account specific features of active and passive remediation technologies.

Materials and methods

The three system have been modeled on the basis of case studies available in literature for thePump and Treat system, data derived from an actual working remediation facility for the Permeable Reactive Barrier and assumptions discussed with the developers of the technology for the bioelectrochemical system, since, by the time the study was carried out, it had only been tested in laboratory scale.

1. Systems layout

Bioelectrochemical system

The design of a full scale bioelectrochemical system has been modeled as a modified Permeable Reactive Barrier.

The chosen constructive layout was based on the “funnel and gate” model, which means that groundwater flow is conveyed to the reactive zone (the gate) by building a waterproof trench (the funnel).

In this case granular graphite was chosen as a reactive medium for gate filling. Graphite is supposed to work both as a substrate for bacteria and as an electrical conductor for potential difference used to optimize bacterial reductive dechlorination. The potential difference is supposed to be applied through electrodes directly driven through the soil and into the gate. The required electrical power will be produced using photovoltaic panels so no connection to national grid will be required. The modeled full-scale design is presented in Figure 1.

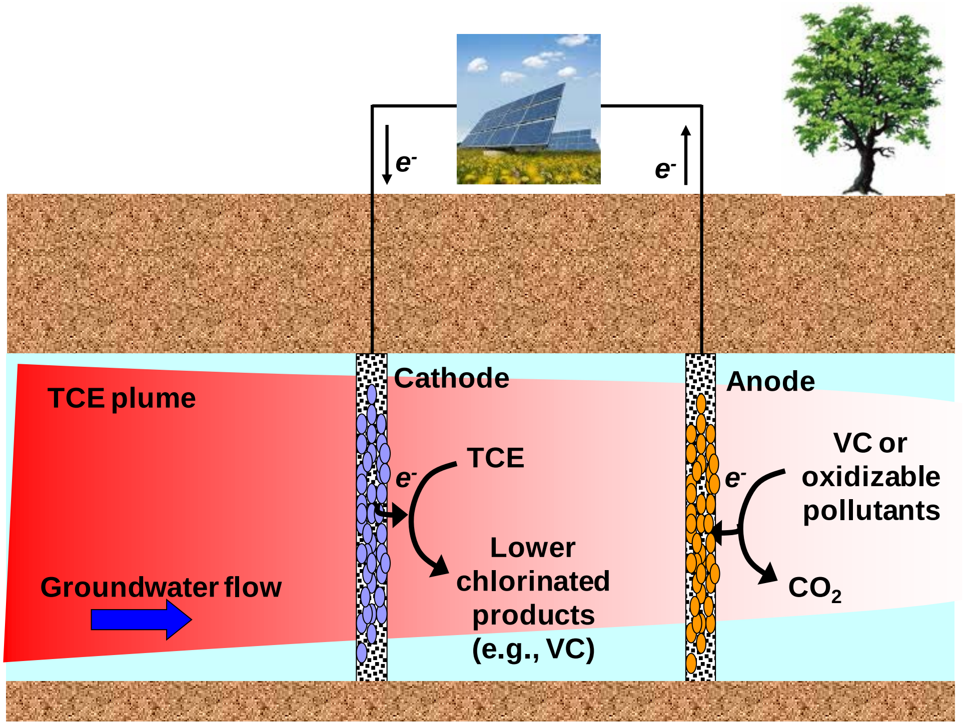

Figure1: Full scaleBioelectrochemical system [1].

The sizing of gate width is crucial in order to have the system working properly, since this parameter influences directly hydraulic residence time: also, a wider gate means a larger amount of filling medium, resulting in increasing economic and environmental costs.

Permeable Reactive Barrier

Permeable Reactive Barriers are one of the most used passive remediation technologies [6]. The remediation process is operated by placing a reactive medium in a certain zone of the aquifer so it can intercept groundwater flow (Figure 2).

As the contamination plume passes through the medium following the natural direction of the groundwater flow, contaminants react with the medium either sticking to it or being degraded to less harmful compounds.

The constructive design chosen for the permeable reactive barrier is that of the “funnel and gate”, where contaminated groundwater flow is directed to the reactive zone (the gate) by two layers of impermeable barrier (the funnel).

As a reactive medium, Zero Valent Iron (ZVI) has been identified as the most viable option for the treatment of chlorinated compounds.

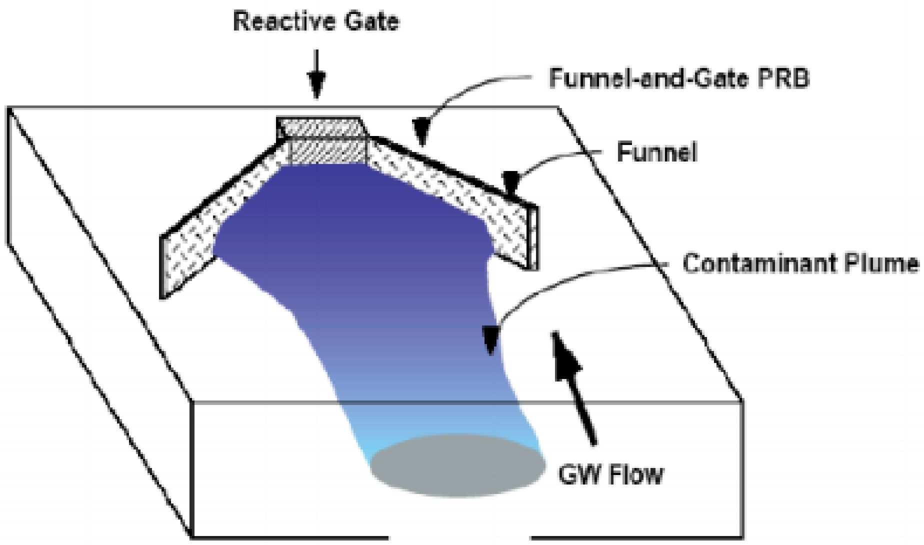

Figure2: Funnel and gate design [4].

Pump and treat

Pump and treat systems are the most established option for the treatment of contaminated groundwater. In this type of technology water is pumped out of the ground and sent to an on-site treatment facility, which can use different media to operate remediation: after treatment, treated water can be either discharged as surface water or pumped back into the aquifer.

For this case we chose Granular Activated Carbon as the reactive media (as literature points out GAC is most effective for the treatment of chlorinated compounds). Remediated groundwater is supposed to be discharged as surface water after treatment.

Due to the high environmental cost of producing activated carbons and their fast rate of consumption, it seemed reasonable to include a 40% percentage of recycled carbons in the inventory phase.

2. BioElectrochemical System and permeable reactive barrier: sizing criteria

The full scaled bioelectrochemical system modeling has been performed modifying data and constructive design of a fully functional permeable reactive barrier applied in a contaminated site near Bologna, Italy.

Its design differs from that of the PRB in these aspects:

- The use of graphite instead of ZVI as a reactive medium
- A wider gate has been implemented in order to take into account and prevent possible poor treatment efficiency.

Since the bioelectrochemical system’s full scale scenario and the pump and treat system are not backed up by field data, in order to allow comparison with the permeable reactive barrier and pump and treat system a few methodological assumptions were made.

- For all three systems a 10 years lifespan has been evaluated
- All three systems are supposed to remediate an identical volume of polluted groundwater
- For all three systems remediation performance is supposed to be equally meeting law requirements.

3. Pump and treat system: sizing criteria

The pump and treat system has been designed following examples and suggestions found in literature [3, 6, 7]. In order to allow comparison, the system is supposed to comply with the same assumptions stated in the previous paragraph for the BER and PRB systems.

In order to give a rough estimate of the impact caused by the transformation of remediated groundwater into surface water after PTS treatment, it has been decided to include in the inventory a slightly polluted water volume as output, corresponding to the total volume of treated groundwater, as suggested by Bonoli [1]. The impacts related to this inventory item basically involve those of a secondary treatment facility.

4. LCA: functional unit, system boundaries, calculation methods, software tools

The functional unit for this study was identified as 1 m^3 of treated groundwater.

The study was performed using a “cradle to grave” approach, but it has been decided to cut off end of life disposal of the materials, mainly because of the lack of information regarding passive treatment facilities’ (Bioelectrochemical system and PRB) fate once their remediation goals are accomplished and because of the different longevity of the materials involved, reactive media in particular. Life cycle Assessment boundaries thus included:

- Production and transport for all raw materials;
- Energy flows used for building facilities;
- Use phase energy demand;

While

- Reactive media disposal;
- End of life material transport;

Have been cut off.

The LCA study has been performed using Simapro 7.3.3 and EcoInvent database.

Results and discussion

All results have been first calculated through EDIP/UMIP 97, but due to the high scores attributed to human and ecological toxicity impact categories, which are not considered completely reliable by the ILCD, it has been decided to use second-run results obtained through IMPACT 2002+. The magnitude of this issue is underlined in Figure 3where normalized impacts for the biolectrochemical system are displayed. As shown in the same Figure3, EDIP/UMIP 97 attributes a heavy score to bulk waste and ecotoxicity impact categories which outweighs the relevance of other categories including Global Warming Potential (in red), which is the highest scoring category according to Impact 2002+ calculations (Figure4). Given ILCD prescriptions on LCA studies’ reliability and balance, it has been thus decided to use Impact 2002+ calculations’ output for Impact Assessment and results’ interpretation.

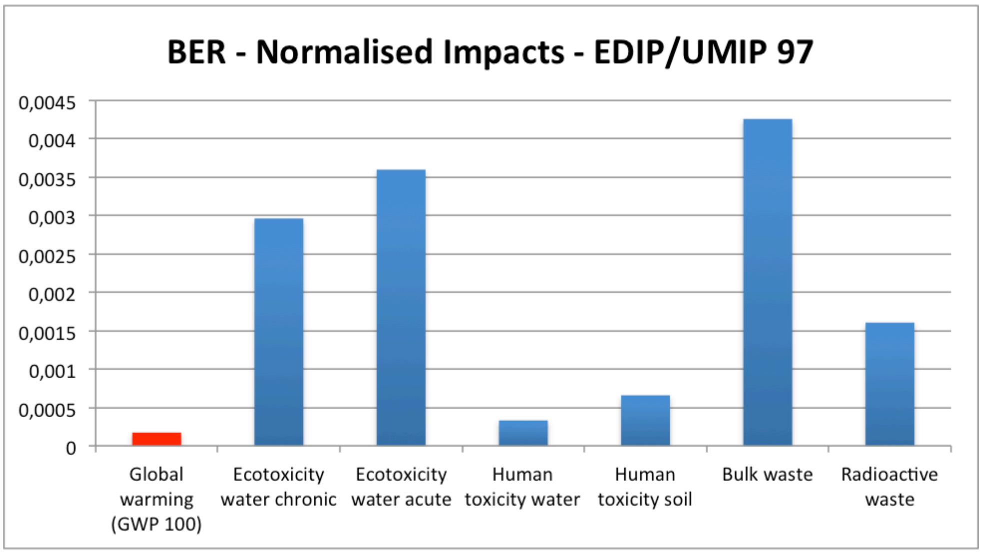

Figure3: Normalised Impacts for the bioelectrochemical system (EDIP/UMIP 97)

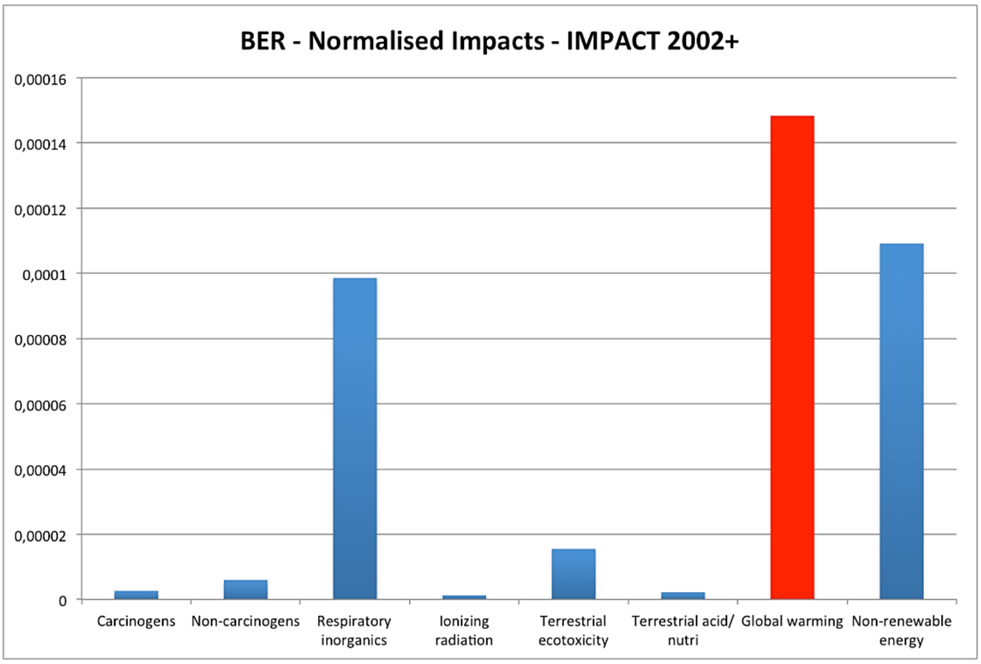

Figure4: Normalised impacts for the bioelectrochemical system (IMPACT 2002+)

LCIA –Impact assessment

Bioelectrochemical System

Figure5 shows the impact of the bioelectrochemical system's subprocesses on the overall environmental performance. The most relevant contributions to the total score (measured in Ecopoints) are related to funnel and gate building and to materials' transport, while reactive medium (graphite) production plays a minor role and energy related contribution is negligible; the most affected categories are Global Warming, Nonrenewable energy and respiratory inorganics.

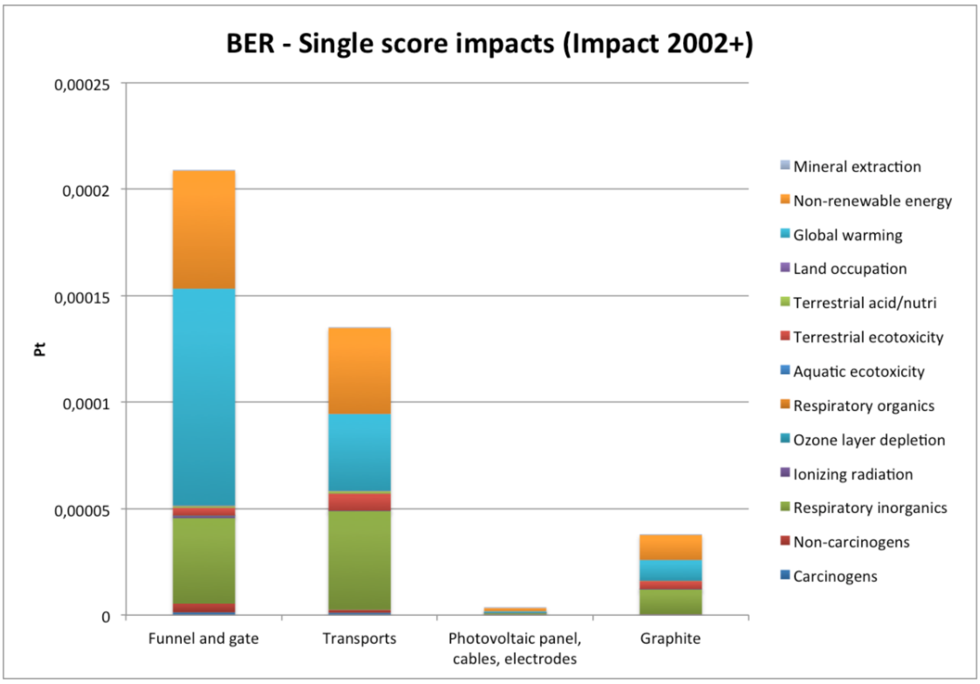

Figure5: Single score impacts (IMPACT 2002+)

PRB

Figure6 shows the huge impact of Zero valent Iron production on the permeable reactive barrier's performance. Even modeling part of this item as recycled Iron, ZVI production-related impacts are responsible for more than a half of the total score. Construction and transport related impacts are comparatively modest. This result can be explained considering the massive amount of ZVI required to fill the gate (216 tons). The most concerning impact categories are Global warming, Nonrenewable energy, respiratory inorganics and carcinogens.

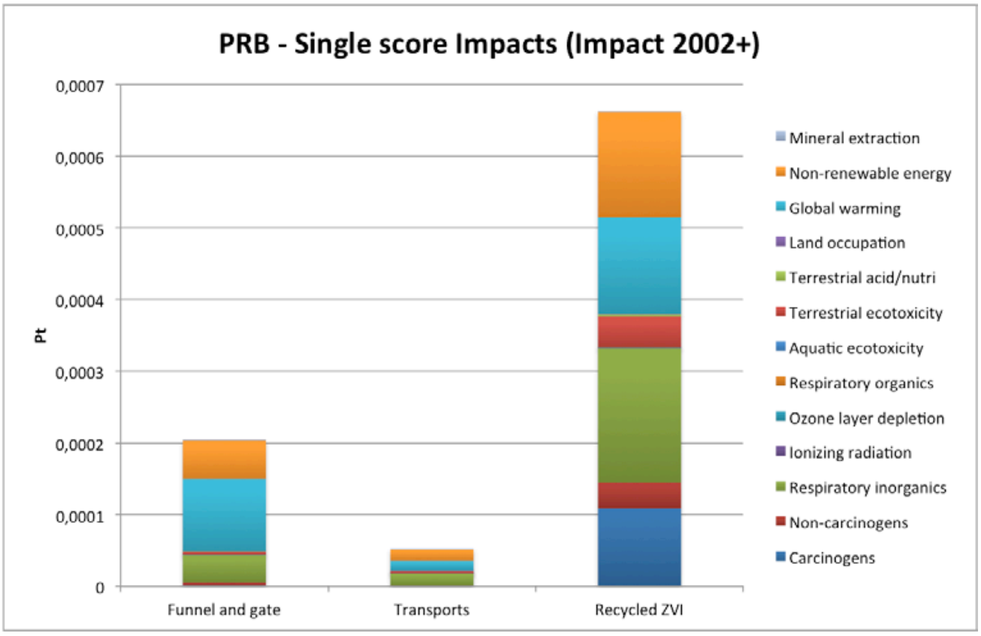

Figura 6: PRB - Single score impacts (IMPACT 2002+)

Pump and Treat System

Figure7 summarizes pump and treat system's results detailed by subprocess. The most relevant contribution is related to activated carbons production, which concurs to approximately 70% of total score: a smaller but non negligible contribution is due to the effect of post –treatment water discharge. The most affected impact categories are Nonrenewable energies, global warming and respiratory inorganics. Contrary to preliminary expectations, energy consumption related impacts had a small effect on overall environmental performance.

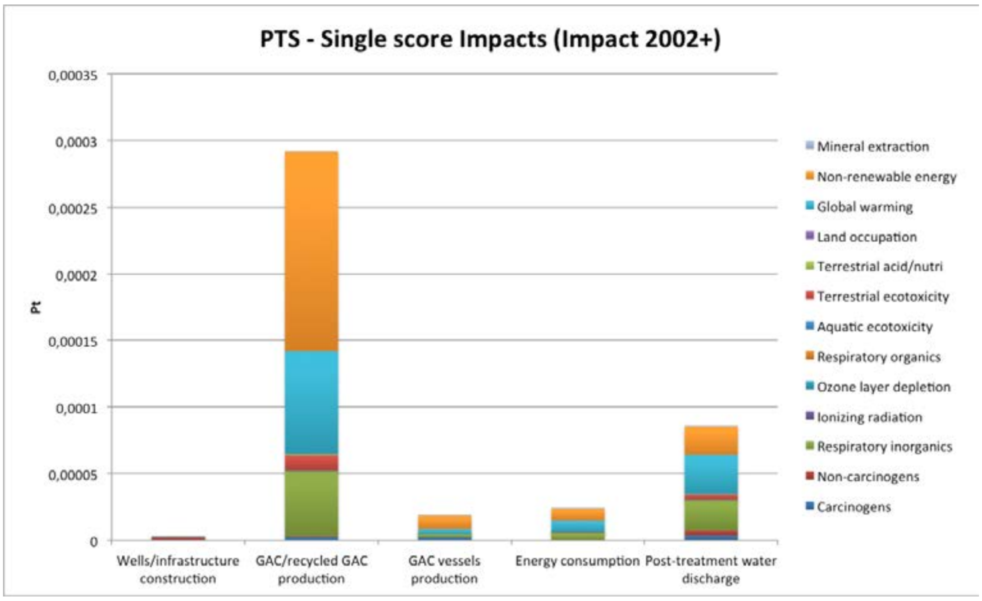

Figure7: PTS - Single score impacts (IMPACT 2002+)

Single score comparison/ reactive media

Figure8shows a quick overview of all three systems' overall performance. The highest score is attributed to the Permeable reactive barrier, while the Bioelectrochemical and Pump and Treat systems show a similar performance, resulting in a score about 50% lower than the PRB's.

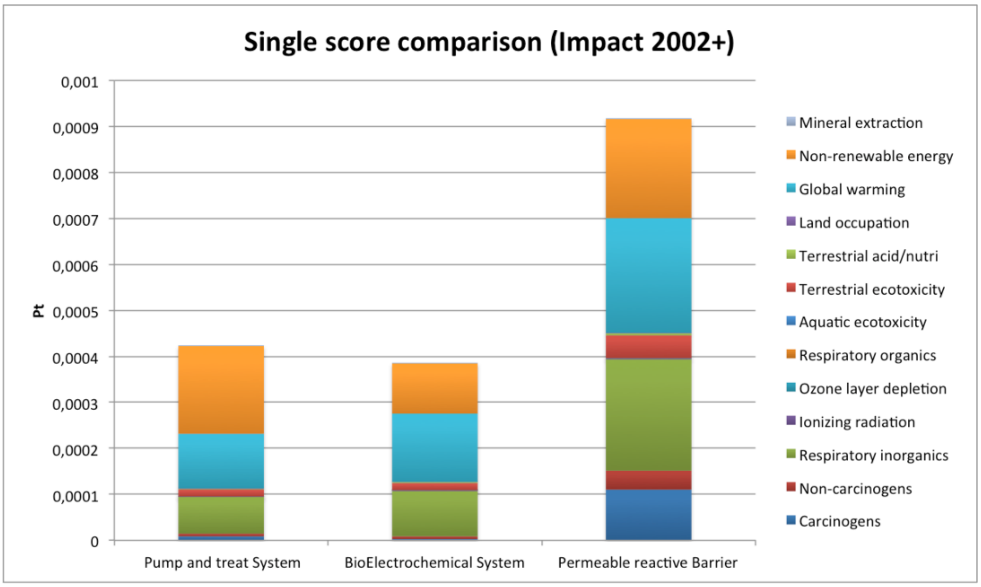

Figura 8: Single score comparison (IMPACT 2002+)

As reactive media proved to be the most impactful subprocess for each of the investigated treatment options, it has been decided to look into their standalone environmental performance. This comparison showed that granular activated carbon, even in its recycled form, has by far the most penalizing production process, because of the considerable amounts of energy and heat involved: recycled cast iron production seems comparatively much more sustainable and graphite production-related impacts appear practically negligible.

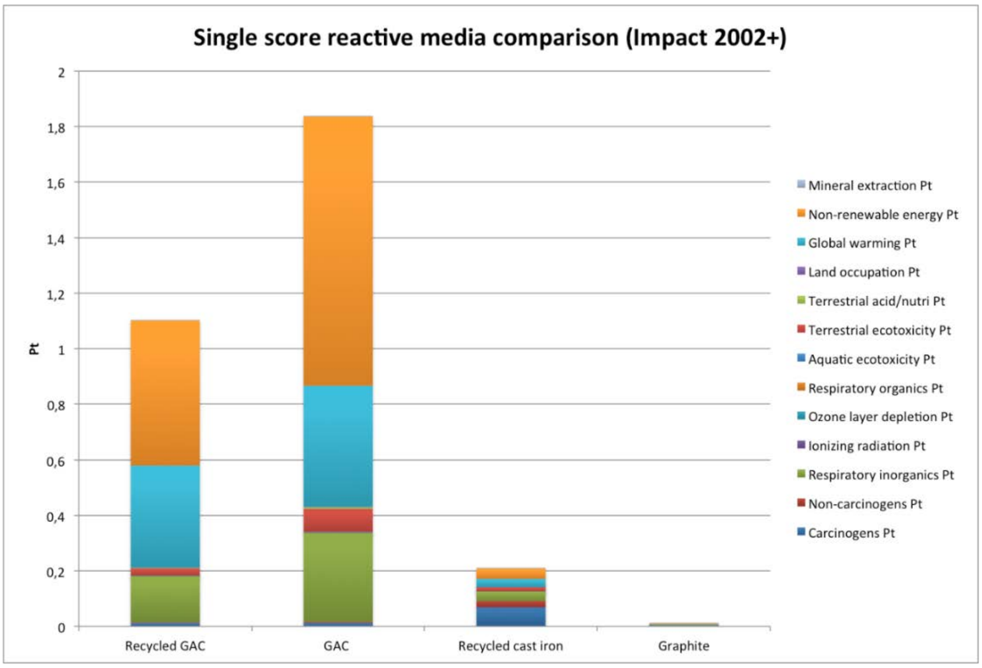

Figure9: Single score comparison (REACTIVE MEDIA) (IMPACT 2002+)

Conclusions

Reactive media production proved to be a key factor for the three systems' overall performance, with a few distinctions to be made.

The bioelectrochemical system showed a promising environmental performance, mostly because of the lighter environmental burden of graphite in respect of ZVI and granular activated carbon as a reactive medium, but these preliminary results based on a hypothetical full scaled design need to be backed up by field data.

The permeable reactive barrier showed the poorest environmental performance mainly because of the massive amount of reactive media required: even using recycled iron the associated impacts are very relevant. A possible way to optimize this technology's performance is to use a different reactive medium, as the results obtained by graphite use in bioelectrochemical system suggest.

The pump and treat system's performance was quite surprisingly close to the bioelectrochemical system's. Energy demand proved to be less impactful than expected and Granular Activated Carbon consumption, though scoring as the biggest impact-producing subprocess, did not compromise overall environmental performance. It must be noted though that being calculations based on literature case studies these considerations should be verified in the light of actual field data, as in the case of the bioelectrochemical system. Also, the need to address impacts related to groundwater discharge after PTS treatment underlined a lack of an appropriate tool in the Eco Invent database which should be developed in further studies.

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