AN ENVIRONMENTAL LIFE CYCLE STUDY OF THE LARNACA WASTEWATER TREATMENT PLANT

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Abstract

Life Cycle Assessment (LCA) is routinely applied for the environmental impact assessment of municipal wastewater treatment plants (WWTPs), aiming at the improvement of the environmental performance of the plants.

The scope of this manuscript is the presentation of the results of LCA applied on the wastewater treatment plant in Larnaca, Cyprus. The scope of the study includes the operation of the WWTP during 2005-2007 and the examination of two alternative schemes, namely conventional anaerobic digestion and MBR, examined for the extension of the WWTP. The LCA was carried out using the CML2 Baseline 2000 as the impact assessment method.

The main conclusions are that: (a) the use of oil for electricity generation in Cyprus generates the main environmental impacts, and (b) MBR technology, being selected as the preferred extension scheme for the WWTP, has higher environmental impacts in global warming and abiotic resource depletion but also higher environmental credits in terms of eutrophication and water reuse.

Keywords: Life cycle assessment, wastewater, Cyprus

1 Introduction

Wastewater treatment systems have been designed to minimize the environmental impacts of discharging untreated wastewater to natural water bodies. Wastewater treatment plants (WWTPs) are *a priori* considered as environmentally friendly systems [1]. However, for their operation they require natural resources in the form of raw materials and energy, which impose negative environmental impacts [2]. Different systems for wastewater treatment have different performance characteristics and generate different direct impacts on the environment [3].

Life cycle assessment (LCA) is a method for assessing the environmental impacts of a product, service or process over its entire life cycle [2]. More specifically, the International Standards Organization has defined LCA as: "A technique for assessing the environmental aspects and potential impacts associated with a product by:

- Compiling an inventory of relevant inputs and outputs of a product system,
- Evaluating the potential environmental impacts associated with those inputs and outputs,
- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study" [4].

LCA has been used to explore the sustainability of wastewater systems since the mid 1990s [2]. Among the first applications, Tillman et al. examined via means of LCA the changing from the existing centralized municipal WWTPs to more localized systems with an increased extent of recycling plant nutrients [5]. Just to name a few more, Hospido et al. examined the environmental performance of a municipal WWTP in Spain [1]. LCA has been also utilised for the environmental assessment of wastewater sludge alternatives [6-8].

The aim of this manuscript is the environmental assessment of the operation of the Larnaca municipal WWTP in Cyprus during 2005-2007. In addition, two proposed extension schemes for the WWTP will be compared in terms of LCA.

2 Description of the WWTP

The Larnaca's sewage system has been in operation since 1995. It covers the area stretching from Dekhelia to the Larnaca International Airport serving mainly the tourist zone and the city's commercial centre. Today works are for the extension of the sewer network to cover the whole city of Larnaca under way [9].

The incoming wastewater, via the inlet chamber, enters the screening unit. Then, it exits the screening channel and flows into the grit removal tank. In the secondary stage, wastewater along with returned activated sludge flows to the two oxidation ditches and finally to the final secondary settlement tanks. Secondary effluent is stored in large storage lagoons. Tertiary treatment consists of sand filters and chlorination for disinfection. The reclaimed water is utilized for the irrigation of the municipal, hotel gardens and local football fields. In addition, reclaimed water is utilised for the irrigation of fodder crops, such as silage and corn plantations, situated at the neighbouring communities.

Regarding sludge treatment, excess sludge is fed to the sludge thickener and from there to the aerobic digestion units. Digested sludge is fed to the sludge drying beds or to the dewatering unit. Dried biological sludge, a waste water treatment by-product, is applied free of charge on local fields for soil improvement [9].

3 LCA of the Larnaca WWTP

3.1 Goal and scope definition

The goal of the study is the environmental life cycle assessment of the WWTP in Larnaca, Cyprus. The scope of the study includes: (1) LCA of the operation of the WWTP based on the operational data from 2005-2007, and (2) LCA of two scenarios examined for the expansion of the WWTP (termed as MBR and Conventional).

3.2 System boundary

System boundary includes all unit operations for wastewater treatment in addition to the unit operations required for sludge treatment during 2005-2007. The WWTP is modeled as an integrated system (black box), due to the lack of operational data for its specific unit operations.

3.3 Functional Unit

The functional unit is defined as the annual input of wastewater in the WWTP. For the operation during 2005-2007 this value corresponds to 6,762 m^3/day while for the extension of the plant, it corresponds to 18,000 m^3/day.

3.4 Data sources

Operational data for 2005-2007 as well as design data for the extension of the Larnaca WWTP were taken from the upgrading design report [10]. In addition, data from the SimaPro 5 database and peer-reviewed literature sources were also utilized.

4 Results

For each one of the scenarios included in the scope of the study, the life cycle inventory table and the life cycle impact assessment results are presented.

4.1 Life cycle inventory of the present operation of the WWTP

The inventory data for the operation of the existing WWTP in Larnaca are presented in Table 1. The input and output data for the WWTP are the average values for 2004-2007. The construction and demolition phase of the infrastructure of the WWTP, and the electrical-mechanical equipment are not taken into account in the LCA.

Table 1 around here

4.2 Life cycle impact assessment of the present operation of the WWTP

The impact assessment method used was CML 2000 developed by the Centre of Environmental Science of Leiden University [11]. The impact category indicators, included in the CML 2000 ready-made method, considered in our assessment, were: abiotic depletion factor (ADF), stratospheric ozone depletion potential (ODP), global warming potential for time horizon 100 years (GWP100), Marine aquatic ecotoxicity potential (MAETP), fresh water aquatic ecotoxicity potential (FAETP), terrestrial ecotoxicity potential (TEP), human toxicity potential (HTP), photochemical ozone creation potential (POCP), acidification potential (AP), and eutrophication potential (EP). The CML 2000 ready-made impact assessment method has been used previously by other authors focusing on LCA of wastewater treatment plants [4, 12-14].

Characterisation results are presented in Table 2. These results indicate that the main contributor to all of the impact categories is electricity. Note that since Cyprus is an island, its electricity generation during 2005-2007 depended exclusively on the use of crude oil [15]. The use of chlorine for disinfection is the second most important contributor (see Table 2). This finding is in agreement with what is reported in the review by Corominas et al., i.e., that the majority of environmental burdens associated with wastewater treatment are due to a limited number of key system inputs and outputs, such as energy use in operation [2].

Table 2 around here

Regarding the carbon footprint of the present operation of the WWTP, our calculations indicated a value of approx. 1 kg CO_2 eq. per m^3 of wastewater treated.

In order to assess the most important impact categories, normalisation of the impact assessment results is performed based on the 1995 values for Western Europe [11]. Normalised results show that the operation of the WWTP contributes mainly to marine aquatic ecotoxicity, acidification, abiotic depletion, terrestrial ecotoxicity, and global warming. On the other hand, it has a positive overall environmental impact, indicated by the negative green bar in Figure 1, in terms of eutrophication.

Figure 1 around here

5 LCA of the WWTP extension

The WWTP in Larnaca needed to be upgraded because of: (a) the extension of the sewerage system of Larnaca which results in increased flows in the WWTP, (b) lack of nitrogen removal in the existing WWTP, and (c) lack of proper sludge stabilization in the existing WWTP [10].

Two following two alternative treatment technologies, which are economically equivalent, were examined and compared [10]:

- Activated sludge treatment with primary sedimentation, conventional aeration and anaerobic sludge digestion, and
- Membrane bioreactor (MBR) system operating as extended aeration.

5.1 Life cycle inventory of the extension of the WWTP

The life cycle inventory of the two proposed extension wastewater treatment schemes is presented in Table 3. In both cases the design daily flow is 18,000 m^3/d, the inlet BOD and SS concentrations are 333 mg/L, while the inlet TN and TP concentrations are 72 and 19.4 mg/L respectively.

Table 3 around here

Note that data on the preparation of the infrastructure for the two extension schemes are also included, expressed as m^3 of reinforced concrete required for the various treatment tanks and as m^3 of excavation earthworks performed by a hydraulic digger. Note also that the infrastructure inputs for the conventional anaerobic digestion system are higher compared to the respective inputs required for the MBR system. In both cases, the lifetime of the infrastructure is assumed to be 20 years. The electrical equipment and new buildings required for the extension are not taken into account in the LCA due to the lack of data. The demolition phase of the WWTP is also not taken into account.

5.2 Life cycle impact assessment of the extension of the WWTP

Again, the impact assessment method used was CML 2000 [11]. The impact characterization results for the proposed conventional anaerobic digestion and MBR systems are presented in Table 4 and Table 5 respectively. The environmental impacts of the MBR system are higher in each and every impact category compared to the respective values for the conventional anaerobic digestion wastewater treatment system. In both systems, the major contributor to the environmental impacts is the consumption of electricity. The overall electricity consumption is higher for the MBR system, therefore its environmental impacts are higher compared to the conventional system.

Tables 4 and 5 around here

However, note that the environmental credit, as expressed by the negative eutrophication values, is also higher for the MBR system. Based on the data presented in Tables 4 and 5, our findings indicate that the environmental impact of the MBR system is approximately 12% higher per kg PO_4^{---} eq. avoided as eutrophication, in every one of the remaining impact categories, compared to the conventional anaerobic digestion system. The aforementioned comparison between the impact categories values is also depicted graphically in Figure 2. The blue bars correspond to the conventional anaerobic digestion system while the yellow bars correspond to the MBR system. However, note that the MBR alternative has certain technical advantages, such as the higher effluent quality and ease of future extensions, making treated water reuse more feasible. Our findings are in agreement with the conclusion by Rodriguez-Garcia et al. that "obtaining an effluent of higher quality, meaning disinfected and with lower eutrophication potential, increases both with GWP and overall expense" [16].

Figure 2 around here

Our finding that the MBR system generates higher environmental impacts is in agreement with the statement by Corominas et al., i.e., that in the case of MBRs, energy use is the key element that needs to be optimized in order to improve the environmental performance [2].

In the case of Cyprus, the current generation mix consists entirely of oil [15]. Therefore, an alteration of the electricity mix towards an environmentally favourable one, would improve the environmental performance of the WWTP. Moreover, the same author estimated that if 60% of the oil in the generation mix is replaced with natural gas, the cost of electricity generation will be reduced by 30%, in addition to reducing the environmental impacts [15].

Conclusions

An LCA of the WWTP is Larnaca has been performed. Based on the presented results, the assumptions, and limitations of the current study, the following conclusions are drawn: the operation of the WWTP in Larnaca has a positive impact on the alleviation of the eutrophication resulting from the release of untreated wastewater in the water bodies. Regarding the operation of the WWTP, based on the data for years 2005-2007, it impacts adversely mainly the following impact categories: marine aquatic ecotoxicity, acidification, abiotic depletion, terrestrial ecotoxicity and global warming. The main contributor in all of these environmental impacts is electricity, which in the case of Cyprus is generated via the consumption of crude oil.

Regarding the extension of the WWTP, the MBR system is anticipated to generate more environmental impacts compared to the conventional anaerobic digestion system. On the other hand, the positive environmental impact in term of reduced eutrophication is also greater for the MBR system. Our results also showed that the WWTP infrastructure has a negligible effect on the environmental impacts.

Acknowledgement

Access to the content of the "Larnaca WWTP extension and upgrading design report" is greatly acknowledged.

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Table 1. Life cycle inventory for the operation of the WWTP (2005-2007).

	Unit	Input	Output
Wastewater	m^3/day	6,762	
Chlorine	kg	55,000	
Polyelectrolyte	kg	5,404	
Electricity consumption	KWh	2,755,665	
Space requirement	m^2	21,000	
BOD	mg/L	311.5	19.7
COD	mg/L	703.8	69.0
SS	mg/L	194.8	34.1
N-NH3	mg/L	68.3	19.5
TP	mg/L	60.2	6.6

Table 2. Characterisation results of the annual operation of the WWTP in Larnaca during 2005-2007.

Impact category	Unit	Total	Chlorination	Electricity	Flocculants	Wastewater treated
abiotic depletion	kg Sb eq.	15,700	349	15,300	4.55	-
global warming (GWP100)	kg CO_2 eq.	2,540,000	58,400	2,480,000	638	-
ozone layer depletion (ODP)	kg CFC-11 eq.	2.14	x	2.14	0.000266	-
human toxicity	kg 1,4-DB eq.	1,140,000	1,360	1,140,000	217	-
fresh water aquatic ecotox.	kg 1,4-DB eq.	126,000	82.5	126,000	33.8	-
marine aquatic ecotoxicity	kg 1,4-DB eq.	8.16E+08	11,400,000	8.04E+08	710,000	-
terrestrial ecotoxicity	kg 1,4-DB eq.	34,200	1,550	32,600	2.47	-
photochemical oxidation	kg C_2H_2	1,380	18.7	1,360	0.196	-
acidification	kg SO_2 eq.	30,700	430	30,300	4.91	-
eutrophication	kg PO_4^{---} eq.	-29,600	0.17	5.79	0.154	-29,600

Table 3. Life cycle inventory table of the two extension scenarios.

	Units	AD	MBR
Inputs (Infrastructure)			
Concrete (reinforced)	m^3	10,110	9,130
Earthworks	m^3	47,500	40,500
Space requirement	m^2	85,000	65,000
Inputs (operation)			
Electricity	KWh/y	9,093,194	9,905,879
Polymer consumption	Kg/y	13,689	12,726
Chlorine consumption	kg	52,560	6,570
Land requirement	m^2	85,000	65,000
Outputs			
Energy generation	KWh/y	1,366,694	-
BOD	mg/L	12.5	3
COD	mg/L	26.2	6.3
SS	mg/L	17.5	0
N-NH3	mg/L	0	0
TP	mg/L	0.9	0.09

Table 4. Characterisation results for the extension based on conventional anaerobic digestion technology.

Impact category	Unit	Total	Chlorination Conventional	Electricity Conventional	Flocculants Conventional	Infrastructure Conventional	Treated Wastewater Conventional
abiotic depletion	kg Sb eq.	44,300	334	42,900	11.5	1,090	-
global warming (GWP100)	kg CO_2 eq.	7,150,000	55,800	6,960,000	1,620	130,000	-
ozone layer depletion (ODP)	kg CFC-11 eq.	5.99	-	5.99	0.000673	0.00276	-
human toxicity	kg 1,4-DB eq.	3,220,000	1300	3,200,000	550	18,900	-
fresh water aquatic ecotox.	kg 1,4-DB eq.	355,000	78.8	353,000	85.7	1,190	-
marine aquatic ecotoxicity	kg 1,4-DB eq.	2.28E+09	10,900,000	2.25E+09	1,800,000	14,100,000	-
terrestrial ecotoxicity	kg 1,4-DB eq.	93,100	1,480	91,500	6.26	145	-
photochemical oxidation	kg C_2H_2	3,900	17.9	3,810	0.498	68.6	-
acidification	kg SO_2 eq.	85,900	411	84,900	12.4	586	-
eutrophication	kg PO_4^{---} eq.	-89,200	0.162	16.2	0.391	26	-89,300

Table 5. Characterisation results for the extension based on MBR technology

Impact category	Unit	Total	Chlorination MBR	Electricity MBR	Flocculants MBR	Infrastructure MBR	Treated Wastewater MBR
abiotic depletion	kg Sb eq.	56,000	41.7	55,000	10.7	982	-
global warming (GWP100)	kg CO_2 eq.	9,050,000	6,970	8,930,000	1,500	118,000	-
ozone layer depletion (ODP)	kg CFC-11 eq.	7.68	-	7.68	0.000625	0.00242	-
human toxicity	kg 1,4-DB eq.	4,120,000	162	4,100,000	511	17,000	-
fresh water aquatic ecotox.	kg 1,4-DB eq.	454,000	9.85	453,000	79.6	1,070	-
marine aquatic ecotoxicity	kg 1,4-DB eq.	2.91E+09	1,360,000	2.89E+09	1,670,000	12,700,000	-
terrestrial ecotoxicity	kg 1,4-DB eq.	118,000	185	117,000	5.82	130	-
photochemical oxidation	kg C_2H_2	4,950	2.24	4,880	0.463	62	-
acidification	kg SO_2 eq.	109,000	51.3	109,000	11.6	529	-
eutrophication	kg PO_4^{---} eq.	-99,300	0.0203	20.8	0.363	23.4	-99,400

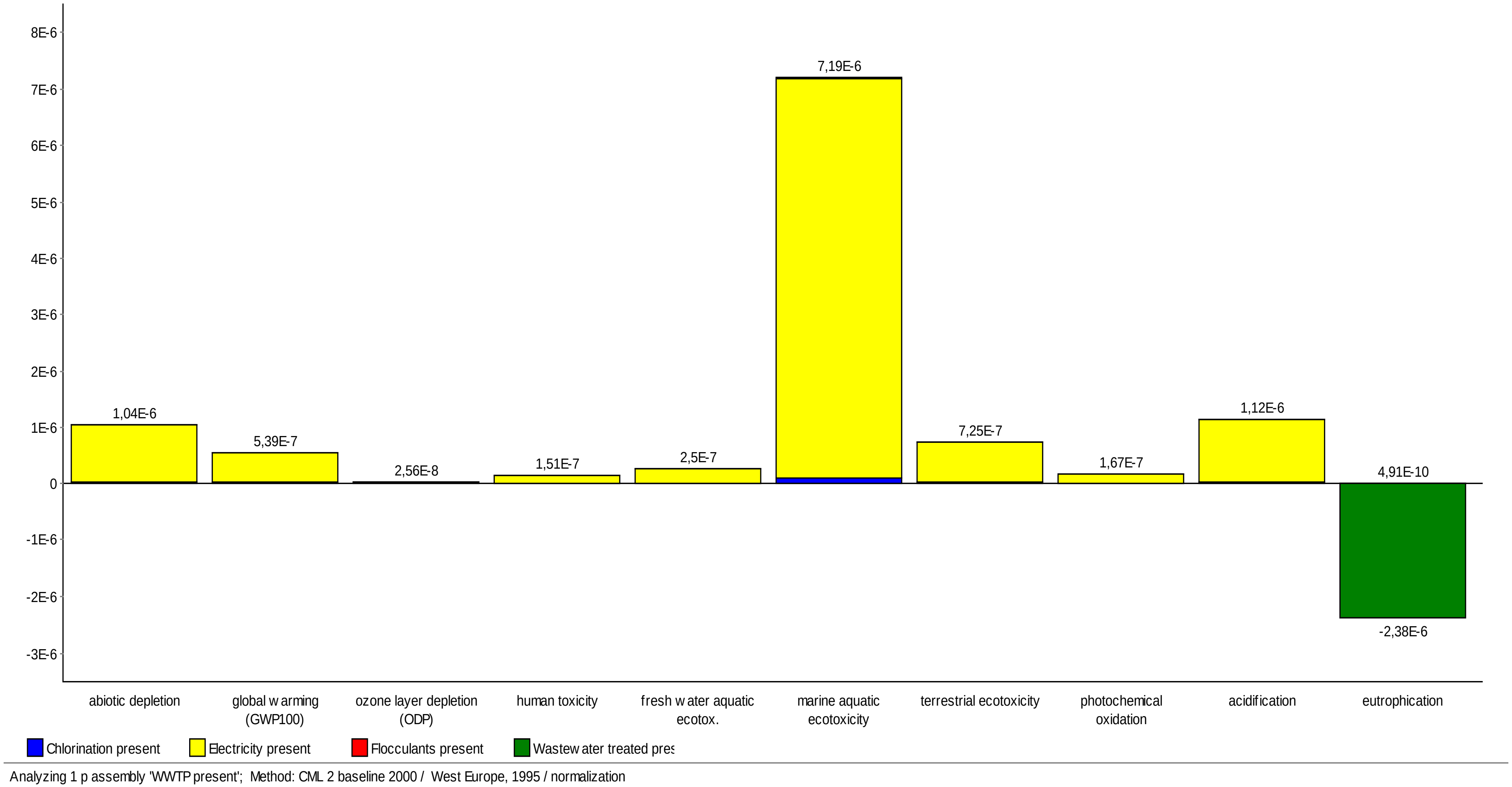

Fig. 1. Normalisation results per impact category for the operation of the WWTP during 2005-2007.

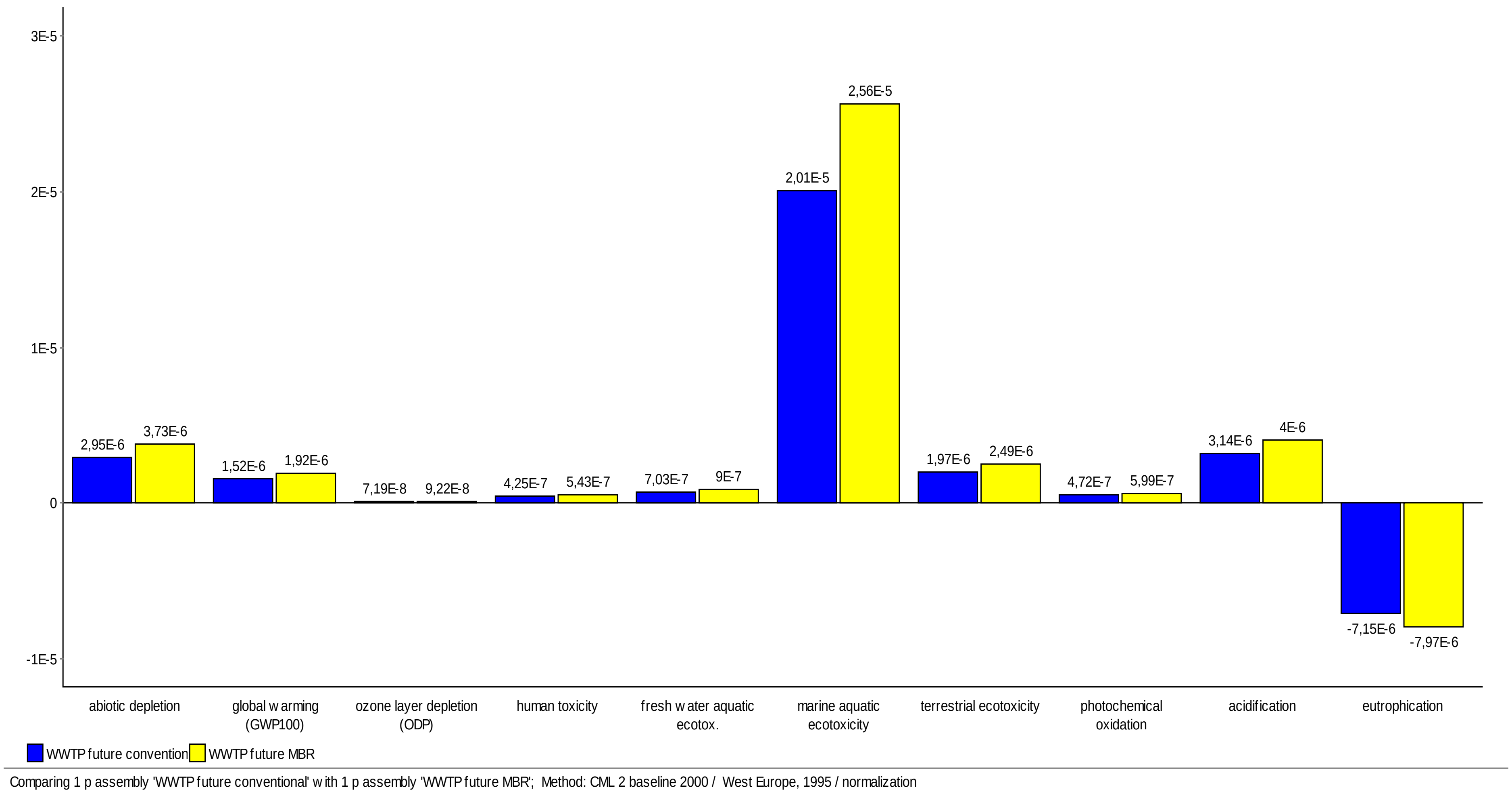

Fig. 2. Normalised results for the comparison of the two alternatives for the extension of WWTP