LIFE CYCLE ASSESSMENT (LCA) OF A GAS TURBINE POWER PLANT

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Abstract. *This article presents the environmental life cycle impact assessment (LCA) of gas turbine power plant-based electricity generation. The process studied in this LCA can be divided into main subsystems, namely transportation, fabrication of equipment and structural materials, plant construction, operation, decommissioning, electricity generation. For these subsystems materials and energy flows were quantified for each process block; otherwise, resourses, emissions, and energy use of upstream process were taken form SimaPro database. The results show an effective influence of power plant operation phase on all the damage assessment parameters, during the entire life cycle. This means that its construction, maintenance and dismantling, does not affect significantly the total impact.*

Keywords: *life cycle assessment (LCA), greenhouse effect, environment impact, thermo power plant..*

1. Introduction

Life cycle assessment (LCA) is a systematic procedure for identifying and assessing all upstream and downstream environmental impacts of manufactured products. Moreover, LCA framework provides a system-wide basis for accounting for all effects of a specific technological choice, functioning as a decision making guide for managing technological innovation over time.

LCA framework can identify various risks in the product manufacturing stream and, although in a less precise way, capable of offering managerial guidance about how to sequence technological improvements in order to provide improved environmental performance, and therefore acting as a static measure of a technical system. In view of the growing need for decision makers to design feasible strategies by which a technological transformation to sustainability can proceed, LCA can be expected to become more important to the identification and evaluation of alternative technological development paths.

This paper reports the preliminary results of an analysis of a single case study of technological approach in gas turbine power systems over a period of several decades with an analysis of innovative applications of the turbine technologies to test the adequacy of an LCA framework to measure environmental burdens associated with thermal power plant electricity generation accurately.

This paper proceeds with a brief description of the LCA methodology, and a short description of the major environmental factors related with gas turbine to generate electricity. The results of life cycle assessment of natural gas (NG) power plants are then reported. Finally, a few preliminary topics regarding the role of LCA in the management of thermal power plant are discussed.

2. Life cycle assessment

Life-cycle assessment (LCA) is a technique that can be used to evaluate the environmental performance of a product, process or activity from "cradle to grave" as it follows it from extraction of raw materials to final disposal. Originating from "net energy analysis" studies first published in the 1970's (e.g. Boustead, 1972; Sundstrom, 1973) LCA use and importance has been increasing in the last twenty years. Most of the early LCA studies considered only packaging and only in the beginning of the 1990's LCA started to be applied to different consumer products like chemicals and agricultural products or activities like transports. Conceptual guidance was developed as a result of the need of a more standard approach of conducting LCA studies. In 1990 the Society for Environmental Toxicology and Chemistry (SETAC) initiated activities to define LCA and developed a general methodology for LCA. Soon afterwards the International Organization for Standardization (ISO) started similar work on developing principles and guidelines for the LCA methodology. These two organizations reached a general consensus on the methodological framework and final documents on the international standardized LCA methodology are expected by the end of this year.

Life-cycle assessment, as defined by SETAC, is "a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to effect environmental improvements" (Assies, 1991, Consoli, 1993, Curran, 1996).

The methodology used in this LCA is based according to ISO 14040 standards that determines the cycle life product as being: the consecutive and interlinked states of a product, from the extraction of raw materials or transformation of natural resources, to the final deposition of the product in the Nature.

There are four ISO standards specifically designed for LCA application:

- **ISO 14040: Principles and framework**
- **ISO 14041: Goal and Scope definition and inventory analysis**: Goal and Scope definition means definition of system boundaries, details accuracy and data quality, functional units and impact models to be used for the analysis; Inventory Analysis addresses that all necessary data must first be available from literature surveys or direct measurements and classified according to the type of environmental impact (for instance, distinguishing between air, water and soil emissions, solid wastes, energy and materials consumption). The collected data must be allocated according to each considered process output unit.
- **ISO 14042: Life Cycle Impact assessment**: All data need to be first characterized in terms of the considered environmental effects. This is followed by normalization of the results to obtain nondimensional values which allow measuring the impact. According to the used impact model, it is possible to evaluate a global environmental score through appropriate weighting factors.
- **ISO 14043: Interpretation**: Improvement Analysis. In order to propose improvements in the environmental performance, the most significant impact sources must be determined and possible alternatives and/or modifications considered for the process.

2.1 Environmental considerations on Thermal Electricity Generation

Figure 1 shows the boundaries for the system, depicting actual material and energy flows (solid lines) and indicating logical connections between process blocks (dotted lines).

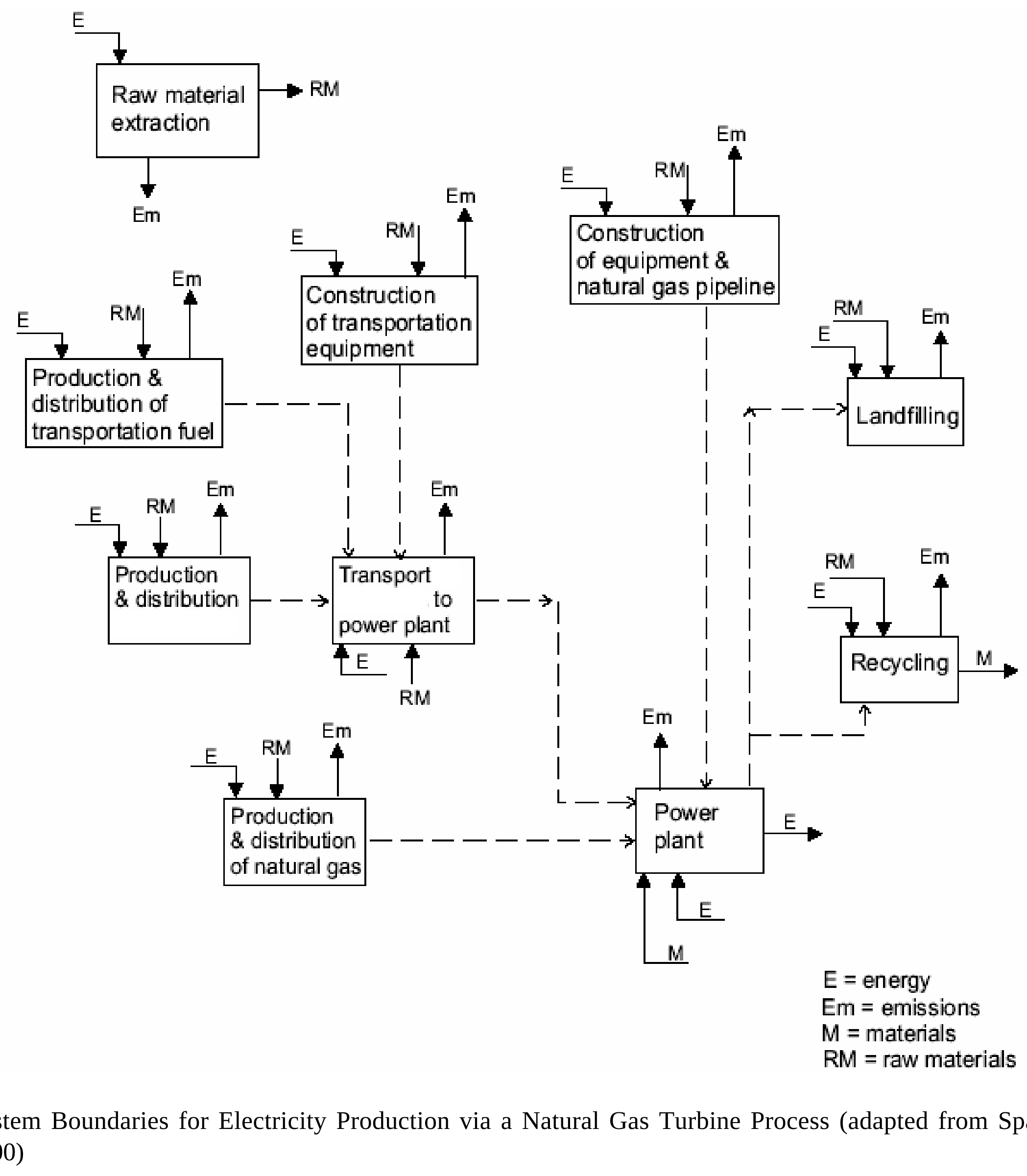

Figure 1. System Boundaries for Electricity Production via a Natural Gas Turbine Process (adapted from Spath and Mann, 2000)

The impact of any power plant has upon its environmental must be minimized as much as possible. Legislation in different countries establishes rules and laws that have to be fulfilled. Quite often emission limits are based upon the best available emission-control technology. Exhaust emissions to the environment are mainly controlled in the gas turbine.

2.1.1. Gas Turbine concepts

The gas turbine is the key component of the Turbine Power Plant, and the following emissions from a power station affect directly the environment:

- Combustion products (exhausts and ash)
- Waste heat
- Waste-water
- Noise

Exhausts can include the following components: H_2O, N_2, O_2, NO, NO_2, CO_2, CO, C_nH_n (unburned hydrocarbons - UHC), SO_2, SO_3, dust, fly ash, and heavy metals.

The first three of these are harmless; the others can negatively affect the environment. Concentration levels of these substances in the exhaust gas depend on the fuel composition and the type of installation. However, the greater the efficiency of installation, the greater the drop-off in the proportion of emissions per unit of electrical energy produced.

For turbine power plant (gas or diesel), the most relevant emissions in the exhaust are NO and NO_2. NO_x (NO and NO_2) emissions generate nitric acid (H_2NO_3) in the atmosphere which together with sulfuric and sulfurous acids (H_2SO_4, H_2SO_3) are factors responsible for acid rain. CO_2 is created by burning fossil fuels and is held responsible for global warming.

Table 1. Main Characteristic Data of Modern Gas Turbines for power Generation

Main Characteristic Data of Modern Gas Turbines for power Generation	
Net power from gas turbines	336 MW
Natural gas feed rate (100% operating capacity)	1,673 Mg/day
Net heat rate	7,378 KJ/KWh
Average operating capacity factor	80%

The gas turbine process is simple: ambient air is filtered, compressed to a pressure of 14 to 30 bar, and used to burn the fuel producing a hot gas with a temperature generally higher than 1000 ºC (1832 ºF). This expands in a turbine driving the compressor and generator. The expanded hot gas leaves the turbine at ambient pressure and at a temperature between 450 to 650 ºC depending on the gas turbines efficiency, pressure ratio, and turbine inlet temperature. Figure 2 presents a schematic diagram of a typical gas turbine, as well as photography of a current installation of thermal power plant based on gas turbine units.

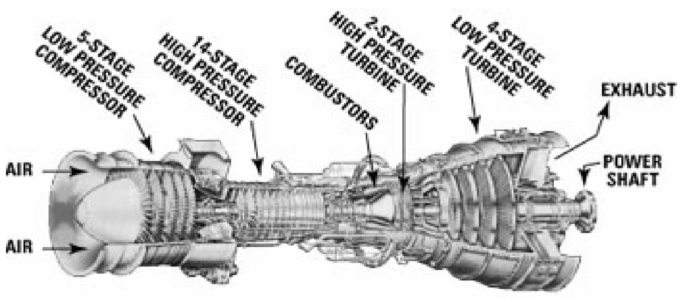

Figure 2. Turbine schematic diagram / gas turbine power plant photography (from Thermal Power Plant of Eletronorte at Santana/AP)

3. LCA methodology

Life cycle assessment is a means of analyzing and interpreting the inventory data from an environmental perspective. There are several options for analyzing the system's impact on the environment and human health. To meet the needs of this study, categorization and damage assessment approaches as described by SimaPro5.1 software have been taken (SimaPro5.1, 2003). Assies (1991), Consoli (1993) and Curran (1996), describe additional details about the different methods available for conducting impact assessments. A discussion of the stressor categories as well as information about the known effects of these stressors from the power plant system can be found in Spath and Mann (2000).

3.1. Functional unit

The functional unit corresponds to the main parameter that will quantify the system action when executing the associated function, serving as data of reference for possible comparison objects. The correct definition of the functional unit constitutes a decisive step for the evaluation of the life cycle.

The functional unit is defined as "kWh of net electricity produced by the power plant", as averages over the life of the system so that the relative percent of emissions from each subsystem could be examined. The following sections contain the results for the base case analysis, including air emissions, energy requirements, resource consumption, water emissions, and solid wastes.

The size of the gas turbine power plant is assumed to be of 336 MW.

3.2. System boundary and input/out put identification

The subsystems included in this life cycle assessment are power plant construction, gas turbine operation, plant operation, electricity use and some transportation at the plant decommissioning phase. Figure 3 presents how these subsystems are connected within the LCA, as they are integrated with each other by SIMAPRO software.

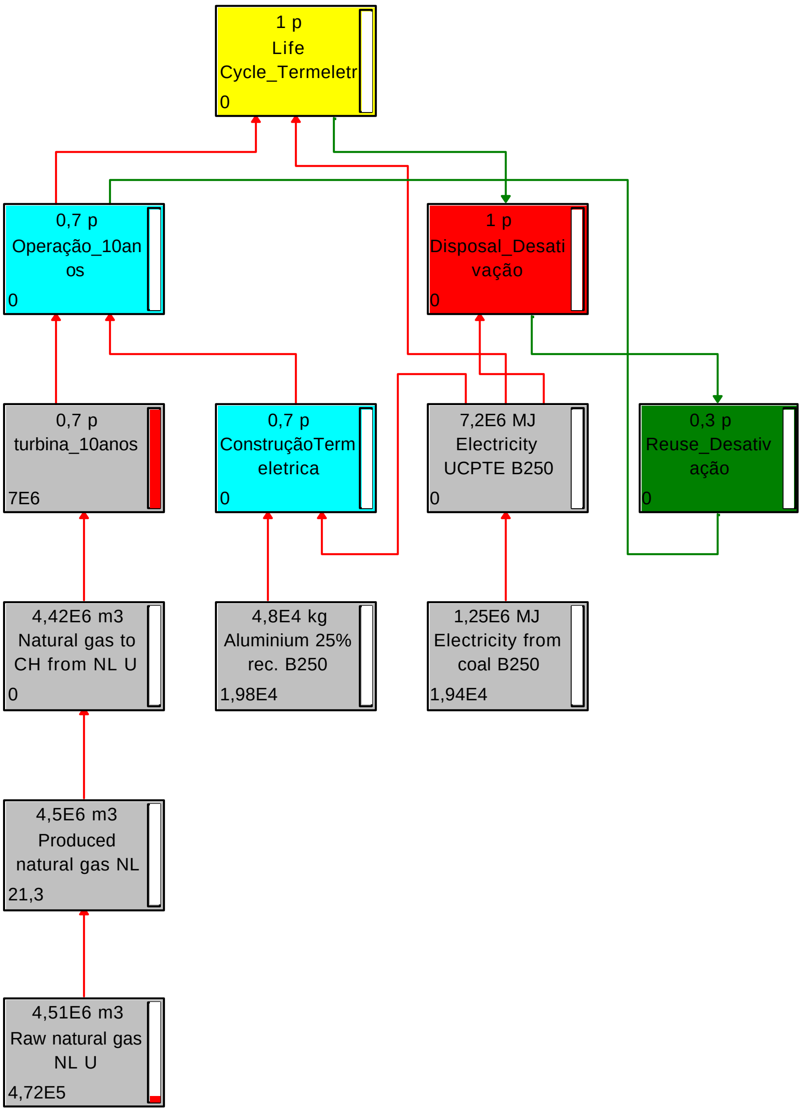

Figure 3. Diagram of the Power Plant Subsystems in the LCA

3.3. Inventory

If performed properly, an LCA can provide a wide range of useful results. The emissions and resource use can be examined for the entire system or subsystems. Similarly, emissions can be segregated by the medium into which they are released and can be inventoried for the full system or any subsystem.

In this case, a meaningful comparison is the overall system description. Namely, the description of the power plant life cycle includes three specific periods of time, the plant construction, the use of the power plant, and it's decommissioning.

For this study, the plant life was set at 30 years with 2 years of construction, as follows:

Year -2 through -1 - plant construction takes place;
Year 1 - the power plant begins to operate 40% of the time;
Year 2 through 29 - normal plant operation occurs with the plant operating at a capacity factor of 80%;
Year 30 - the plant is decommissioned during the last quarter of that year, operating 60% of the last year.

3.3.1. Plant construction

The inventory of the construction phase includes the data acquisition of the main building materials streams used, qualitatively as well as quantitatively. Table 2 lists the power plant construction material requirements used in this study. These values were based on a study by Spath and Mann (2000).

It is also considered material transportation from production site to the plant site, as well as the main equipment transportation requirements. In general, the main material flows to the plant site encompass steel, iron, aluminum and concrete.

Table 2. Power Plant Material Requirements

Material	Amount required (Kg/MW of plant capacity)
Concrete	97,749
Steel	31,030
Iron	408
Aluminum	204

3.3.2. Plant operation

Plant operation stands for more than 90% of gas turbine power plant life cycle. During this period, the main material streams are related with turbine operation (fuel production, transportation and storage) and maintenance (spare parts and theirs packaging subsystems), and with plant operation itself (mainly electricity).

Since this information is precisely provided for, SimaPro will supply all the emissions associated with these materials life cycle as they are available at its several data base.

3.3.3. Plant decommissioning

In fact, the construction and decommissioning subsystem includes power plant construction and decommissioning as well as construction of the fuel supply route.

Among the others phases, decommissioning has the lowest environmental impact, which are mainly related to usual end-of-life processes, disassembling, reuse and land filling, as well as to transportation.

The total results, for each impact, of the dismantling phase depend on the balance between real emissions and avoided emissions.

4. Using SimaPro

The model for the investigated gas turbine power plant was built in SimaPro. The results of the analysis of SimaPro for the construction, operation and decommissioning phases are presented in the following figures. Resources, emissions, and energy use of upstream process were taken from SimaPro database.

Figure 4 displays the life cycle diagram for the studied case, representing the main processes associated with the construction, power plant operation and end-of-life subsystems after a 30 year period of use. The tree shows all processes that influences more than 0.05% on the final environmental impact quantifier (in SimaPro it is used the normalized parameter *Point* to quantify and sum the environmental impact of the different systems).

Figure 6 shows the environmental impact characterization chart of the main analyzed systems. Negative values represent the decommissioning phase, whereas reutilization contributes for minimizing global life cycle impact.

The same cut-off limit of 0.05% is used to prepare the inventory table, presented at Fig. 6. This table highlights the main stressor for each studied subsystem within the studied life cycle.

Figure 7 presents the life cycle global damage assessment, making clear the impact associated with the operation phase of the power plant in all the three damage aspects, namely human health, ecosystems, and natural resource depletion. It also depicts the small influence of electricity use on the ecosystem damage analysis, mainly due to the necessary electricity supply during the power plant operation.

Figures 8 to 10 show some of the process/assemblies data entry forms used by SimaPro to collect data. Namely are presented power plant operation phase data entry, Fig. 8, construction phase, Fig. 9, and gas turbine characteristics of materials utilization, fuel and emissions, Fig. 10.

5. Sensitivity Analysis

At this point it is worthy to assess the effect of the total plant operational life time. On this regard, a sensitivity analysis was performed on this variable, considering its variation from a minimum of 10 years life time to the maximum 30 years.

Therefore, the total mass flux was recalculated using the same formers figures estimating different life times.

Figure 11 to 13 depict that almost all of the impact is associated with use phase, and that even decreasing the power plant life time to 1/3 of its original value (namely to 10 years), the relative impact of construction phase keeps its low strength.

6. Conclusions

A Life Cycle Assessment for 336 MW gas turbine thermal power plant, operating during a 30-year period, has been performed. The results show an effective influence of power plant operation phase on all the damage assessment parameters, during the entire life cycle. This means that its construction, maintenance and dismantling, does not affect significantly the total impact.

This study allows the development of a LCA model to analyze thermal power plant-based electricity generation processes. Further developments will include the characterization of an actual Brazilian thermo power plant, and a sensitivity analysis of material requirement for different fuels supply, for operating capacity factor, for power plant efficiency and for power plant NOx emissions.

7. Acknowledgement

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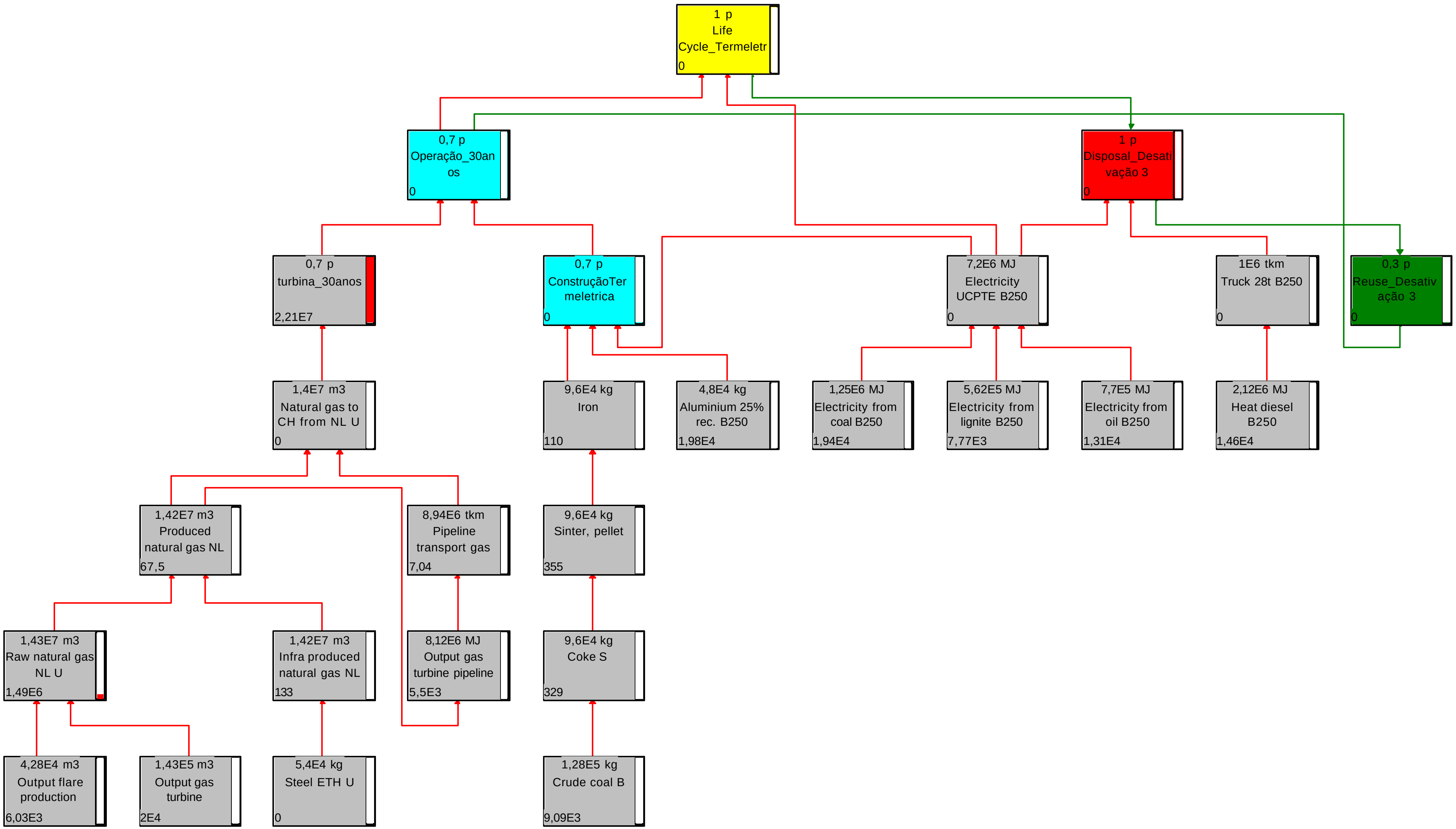

Figure 4. Life cycle diagram for the 30-year operation of the gas turbine power plant

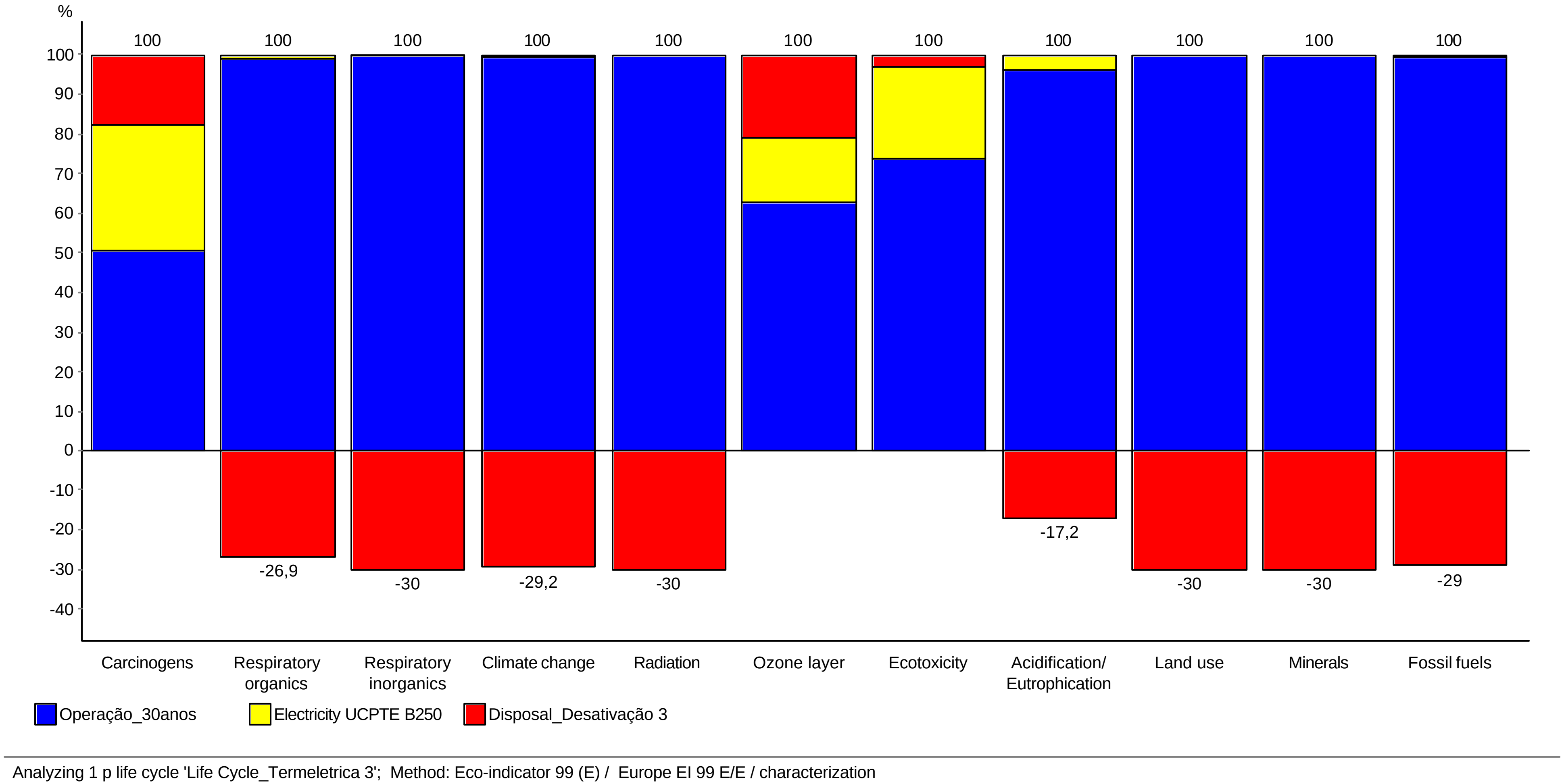

Figure 5. Environmental impact characterization

Process	DQI	Unit	Total	Operação_30anos	Electricity UCPTE B250	Disposal_Desativação
Total of all processes		Pt	2,38E7	3,39E7	2,29E4	-1,01E7
Remaining processes		Pt	7,83E3	1,06E4	166	-2,97E3
turbina_30anos		Pt	2,21E7	3,16E7	x	-9,49E6
Raw natural gas NL U		Pt	1,49E6	2,13E6	x	-6,4E5
Output gas turbine production sweet g		Pt	2E4	2,85E4	x	-8,56E3
Aluminium 25% rec. B250		Pt	1,98E4	2,83E4	x	-8,48E3
Electricity from coal B250		Pt	1,94E4	0,00969	9,69E3	9,69E3
Heat diesel B250		Pt	1,46E4	2,01E3	x	1,26E4
Electricity from oil B250		Pt	1,31E4	0,00653	6,53E3	6,53E3
Crude coal B		Pt	9,09E3	1,3E4	x	-3,9E3
Electricity from lignite B250		Pt	7,77E3	0,00389	3,89E3	3,89E3
Output flare production sweet gas U		Pt	6,03E3	8,62E3	x	-2,58E3
Output gas turbine pipeline NL U		Pt	5,5E3	7,85E3	x	-2,36E3
Electricity from gas B250		Pt	5,28E3	0,00264	2,64E3	2,64E3
Crude coal bj		Pt	4,04E3	5,77E3	x	-1,73E3
Coal from underground mine UCPTE U		Pt	2,4E3	3,44E3	x	-1,03E3
Natural gas B		Pt	1,85E3	2,64E3	x	-792
Diesel in diesel generator onshore U		Pt	1,55E3	2,21E3	x	-663
Crude oil production onshore U		Pt	1,39E3	1,98E3	x	-594
Leakage production natural gas NL U		Pt	1,19E3	1,7E3	x	-509
Crude oil production offshore U		Pt	1,11E3	1,59E3	x	-478
Drilling waste to land farming U		Pt	857	1,22E3	x	-367
Coal tailings in landfill U		Pt	610	872	x	-262
Sinter ETH U		Pt	594	848	x	-254
Leakage raw natural gas NL U		Pt	534	763	x	-229
Diesel in building equipment U		Pt	505	722	x	-217
Concrete (reinforced) I		Pt	504	720	x	-216

Analyzing 1 p life cycle 'Life Cycle_Termeletrica 3'; Method: Eco-indicator 99 (E) / Europe EI 99 E/E / single score

Figure 6. Inventory of main stressors for the gas turbine life cycle

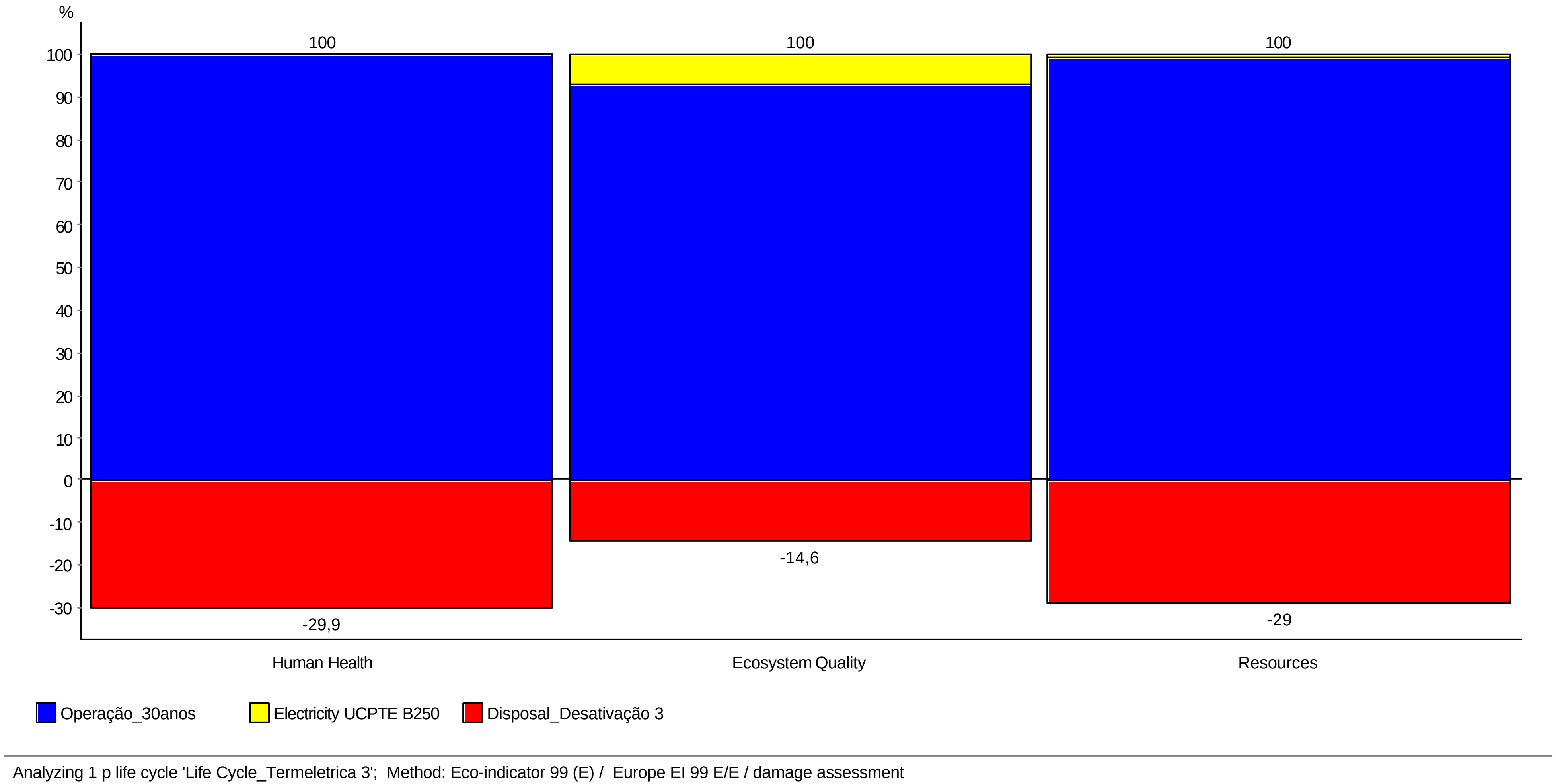

Figure 7. Life cycle global damage evaluation

Name			Comment
Operação_30anos			

Materials/Assemblies	Amount	Unit	Comment
turbina_30anos	1	p	
ConstruçãoTermeletrica	1	p	

Processes	Amount	Unit	Comment

Figure 8. Table for process/assemblies data entry – Thermo power plant operation phase

Name			Comment
ConstruçãoTermeletrica			Refere-se ao material, energia e transporte dos materiais necessários à construção da termelétrica.Plant capacity 336MW

Materials/Assemblies	Amount	Unit	Comment
Concrete (reinforced) I	32842,664	kg	97,749 por MW of plant capacity (caso base NGCC-NREL)
Steel I	10426,08	kg	31,030 por MW of plant capacity
Iron	137088	kg	408 por MW of plant capacity
Aluminium 25% rec. B250	68544	kg	204 por MW of plant capacity

Processes	Amount	Unit	Comment
Electricity UCPTE B250	1	kWh	
Truck 40t B250	248900	tkm	248900 Kg (total), por uma distância média de 1000Km

Figure 9. Table for process/assemblies data entry – Thermo power plant construction phase

Name	Amount	Unit	Quantity	Low value	High value	Allocation %	Waste type	Category
turbina_30anos	1	p	Amount	0	0	100 %	Others	Outros

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Low value	High value	Comment

Inputs

Known inputs from nature (resources)

Name	Amount	Unit	Low value	High value	Comment

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Low value	High value	Comment
Natural gas to CH from NL U	19956833,80	m3	0	0	Quantidade total de gas natural requerida para o funcionamente de 20 anos da termelétrica. Sendo que no primeiro e no ultimo ano de funcionamento o fator de capacidade de produção foi respectivamente de 40% e 60%.Para os demais anos foi utilizado um fator de funcionamento da unidade de 80%.

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Low value	High value	Comment

Outputs

Emissions to air

Name	Amount	Unit	Low value	High value	Comment
CO2 (fossil)	25569,5	ton	0	0	371,247 kg por GWh de energia produzida(dados retirados daNational Renewable Energy Laboratory-NREL). Energia total produzida durante os 30 anos de operação da unidade Termelétrica: 68.874,62 GWh
CO	1859,62	ton	0	0	27 kg por GWh de energia produzida (NREL)
methane	3030,5	ton	0	0	44 kg por GWh de energia produzida (NREL)
particulates (PM10)	4270,22	ton	0	0	62 kg por GWh de energia produzida (NREL)
SOx	137,75	ton	0	0	2 kg por GWh de energia produzida (NREL)

Figure 10. Table for process/assemblies data entry – gas turbine specifications of use of materials, fuel and of emissions

Impact category	turbina_10anos	Construção	turbina_20anos	Construção	turbina_30anos	Construção
Total	99,5	0,519	99,7	0,25	99,8	0,165
Carcinogens	0,00405	0,0115	0,00406	0,00554	0,00406	0,00365
Respiratory organics	0,00265	0,00126	0,00266	0,000608	0,00266	0,0004
Respiratory inorganics	91,9	0,0927	92,2	0,0447	92,3	0,0294
Climate change	1,09	0,0284	1,1	0,0137	1,1	0,009
Radiation	1,14E-5	x	1,14E-5	x	1,14E-5	x
Ozone layer	8,71E-6	3,92E-5	8,74E-6	1,89E-5	8,75E-6	1,24E-5
Ecotoxicity	0,00782	0,00687	0,00784	0,00331	0,00785	0,00218
Acidification/ Eutrophication	0,0518	0,0119	0,0519	0,00571	0,052	0,00376
Land use	0,00487	0,00143	0,00489	0,00069	0,00489	0,000455
Minerals	0,00059	0,0317	0,000591	0,0153	0,000592	0,0101
Fossil fuels	6,38	0,334	6,4	0,161	6,4	0,106
	a)		b)		c)	

Figure 11. Results of sensititvity analysis of the effect of power plant operational life time on the relative influence of Construction phase-related environmental impacts
a) 10 years;
b) 20 years;
c) 30 years.

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