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Environmental impacts of the Greek electricity generation sector

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Abstract

Anthropogenic activities, such as the use of fossil energy sources for electricity generation, are the main contributors to the pollution of the environment. The main energy source used in the Greek electricity generation sector is lignite as there are large reserves in the country. Petroleum is also used at a great extent mainly in the islands in the autonomous power generation systems, while the use of natural gas is also increasing. Although lignite is a “cheap” energy source, the environmental impacts associated with its use are high, something that applies also for petroleum and in a lower extent with natural gas. The total net production of electricity from thermal power plants in Greece accounts for almost 90% of the total electricity production, while only 10% derives from hydroelectric energy and other renewable energy sources (RES). A typical example of the significance of the environmental impacts associated with the electricity generation sector is the fact that almost 74% of the total CO₂ emissions in the country derive from this sector. The work presented in this paper is focused in investigating the environmental impacts associated with the atmospheric emissions and other wastes that are produced during the life cycle of the energy sources (fossil and RES) used for electricity generation in Greece. The environmental evaluation of the different energy sources is performed through the life cycle analysis methodology and the Eco-indicator 99 method and the results are used for comparison purposes.

Keywords: life cycle analysis, environmental evaluation, Eco-indicator 99, electricity generation

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1. Introduction

Energy has significant effects in the evolution of economy and technology. Electricity was the major actor during the transition from the industrial to the technological revolution, almost all the financial and economic activities depend directly on it and any development coincides with an increasing demand of electric energy. Electricity, a conversion product of other energy forms, highlights the importance of primary energy. An “energy system” can be defined as the connection, a physical way, of the facilities of energy generation/conversion, to a certain form (e.g. electricity, heat), the storage facilities, the transmission facilities and the distribution facilities, that operate as a complete system. The need for electricity is met worldwide mainly from the exploitation of fossil/conventional energy sources, i.e. coal/lignite, natural gas and petroleum in a percentage of about 80% [1]. During the last years, the use of renewable energy sources (RES), cleaner fuels and more effective technologies (e.g. cogeneration) for electricity generation is increasing, mainly due the depletion of fossil fuels reserves, geopolitical reasons and the environmental pollution [2]. It seems that the increasing demand for

electric energy is connected with previously mentioned determining factors of the future of fossil fuels. Thus, the necessity for changes in energy policy and planning and in the design of power generation systems is highlighted.

Despite the obvious benefits, the irrational exploitation and use of energy sources brings to surface many problems. The environmental pollution caused by anthropogenic activities has caused many serious environmental problems, such as the global climate change, ozone layer depletion and acidification. A typical example of the environmental impacts caused is the increase of the global mean temperature by 0,6 °C since the end of the 19th century, while there are explicit evidences of an apparent climate change in the current century (the estimated increase of the global mean temperature will be in the range of 1,4 and 5,8 °C). According to the Intergovernmental Panel on Climate Change (IPPC) this change derives from the concentration increase of the greenhouse gases in the higher atmosphere layers [3]. Greenhouse gases emissions, as well as other pollutants, have mainly anthropogenic origin. Especially, emission of CO₂ derives at its greatest extent from the exploitation, production and use of fossil fuels, e.g. for electricity generation and in the transports sector. At the same time deforestation in a global level results in the decrease of CO₂ fixation capability through the photosynthesis process and therefore in the increase of CO₂ concentration in the atmosphere [3].

In this work, the environmental pollution that derives from the use/exploitation of different energy sources, either fossil/conventional (e.g. lignite, petroleum and natural gas) or renewable (e.g. wind, hydro, etc.) in the Greek electricity generation sector, is examined. Words, such as “use/exploitation” do not refer only to the “combustion” of fossil energy sources or the “exploitation” of RES. Analysis of the energy sources is not restricted only in the operation stage of the electricity generation facilities (using fossil energy sources or RES), but a life cycle or “cradle-to-grave” approach is implemented. Therefore, the different life cycle stages of the energy sources used in electricity generation are examined. **Figure 1** presents a general diagram of the life cycle stages.

The life cycle approach for the environmental assessment of the energy sources used in electricity generation is implemented through the life cycle analysis (LCA) methodology. LCA has been used in the past mainly in studies of environmental assessment of products for the improvement of their design. It has started progressively to find application in the field of electricity generation, and it is suitable to be used for the environmental assessment of the life cycle of different energy sources and technologies used for electricity generation as well as for the environmental assessment of energy systems in general [4 - 13]. Most of research efforts related to the environmental assessment in the field of electricity generation are restricted in the operation stage of the power plants and in the creation of an inventory of inputs and outputs (mass, energy and emissions) [14, 15]. In other words, in many cases these inputs and outputs are not associated with the environmental impacts of the final product in order to create a total environmental performance score or index. However, association of inputs and outputs of the inventory phase of the total life cycle with the environmental impacts can be done through suitable factors like the ones proposed in Eco-indicator 99 method [16 – 18]. This method is a reliable and practical tool in identifying the areas where the most improvements need to be made [19]. Using the life cycle approach, i.e. examining the complete life cycle of an energy source / energy system, ensures that all inputs and outputs of all the stages of a system are examined and included in the analysis. Moreover, the results are more realistic and comprehensive and it is easier to identify which stages of the life cycle contribute more to the total environmental performance and to

the individual impacts and damage categories. A complete description of the LCA methodology can be found in SETAC's and ISO's guidelines [20, 21] and for the Eco-indicator 99 method in PRe's manual [16 – 18].

Figure 1: General diagram of the life cycles stages of the energy sources (fossil/conventional and RES) used in the Greek electricity generation sector

2. Greek electricity generation sector overview

The significant contribution of the Greek electricity generation sector in the problem of the environmental pollution is shown characteristically in **Figure 2**, where the total evolution of the greenhouse gases is presented for different Greek energy sectors. In order to enhance understanding of the burdens that are being placed on the environment from the use of fossil fuels for power production, many studies and efforts are based on environmental evaluation tools, such as LCA [20, 21]. In the context of these tools, many useful conclusions can be made concerning the use of alternative fuels or RES, in order to minimize the environmental impacts imposed by the high use of fossil energy sources.

In more detail, electricity generation, distribution and sale, has been mainly appointed to Public Power Corporation of Greece (PPC), a government owned enterprise. Only insignificant amounts of electricity are produced by others or are imported (2%, used mainly by industries that produce it and sell the excess amount to PPC). Following the energy crisis of the '70s, and after the establishment of new policies, an effort was made towards the decrease of energy dependence from oil, so efforts were

Figure 2: Evolution of greenhouse gases emissions from the Greek energy sector [23 – 25]

made towards other energy sources exploitation. Therefore, the fossil fuel that is used mainly for power production in Greece is lignite, accounting for approximately 64% [22] of the electricity generation in the country. The main reasons for this extensive use of lignite are its availability, as lignite reserves are found in abundance in the country, and the low cost of extraction and exploitation of the fuel. Greece is in the second place in the production of lignite in the EU and the sixth place worldwide. To date, a total of 1.3 billion tons of lignite have already been mined, while exploitable reserves total approximately 3.2 billion tons. Lignite is provided by the PPC's lignite mines in Ptolemaida and Megalopolis. **Table 1** presents typical data regarding the total net electricity production and installed capacity of the PPC's power plants for the period 2002 – 2004 [22].

After the Kyoto Protocol [26], the European Union issued Directives [27 – 29] and orientated its Strategies and Action Plans towards the development and increase of the share of use of RES, decrease of fossil fuels in power generation, as well as the increase of energy efficiency. The White Paper [27] has set specific objectives in increasing the share of RES (12%) for the year 2010 which would lead to the reduction of the imported fuels by 17.4% and the CO₂ emissions by 402 million tonnes/year. On the other hand, the “Kyoto Protocol” with its two mechanisms of emissions trade and clean production had set as an objective the reduction of emissions in the year 2010 by at least 5%. European Union has signed the “Kyoto Protocol” and its member states, including Greece, have been committed to deliver specific quantitative targets.

3. Life Cycle Analysis methodology overview

The environmental performance of energy systems has become a major issue, therefore many efforts are directed in investigating ways to minimize the impacts caused from the life cycle of these systems on the environment (**Table 2**). LCA considers the entire life cycle of an energy system in a “cradle-to-grave” approach. It examines all the stages of an energy system's life cycle since they are interdependent, meaning that one operation leads to the next [7]. LCA enables the assessment of the cumulative environmental impacts resulting from all the life cycle's stages [53]. In conclusion, LCA

Table 1: Installed capacity and total net electricity production of PPC power plants [22]

	Installed capacity (MW)			Total net electricity production (GWh)			
31/12	2002	2003	2004	2002	2003	2004	% (2004)
Interconnected system							
Thermal power plants							
• Lignite	4958	5288	5288	31197	31643	32388	67.39
• Petroleum	750	750	750	3394	3311	2682	5.58
• Natural gas	1581	1581	1581	6725	7632	8055	16.76
Total thermal power plants	7289	7619	7619	41316	42586	43125	89.74
Hydroelectric power plants	3060	3060	3060	3381	5211	4920	10.24
Wind & other RES	5	7	7	14	16	12	0.02
Total of interconnected system	10354	10686	10686	44711	47813	48057	100.00
Non-interconnected islands							
Thermal power plants							
• Lignite	-	-	-	-	-	-	-
• Petroleum	1352	1421	1507	4122	4327	4407	98.55
• Natural gas	-	-	-	-	-	-	-
Total thermal power plants	1352	1421	1507	4122	4327	4407	98.55
Hydroelectric power plants	1	1	1	1	1	1	0.02
Wind & other RES	32	30	30	68	73	64	1.43
Total of non-interconnected islands	1385	1452	1538	4191	4401	4472	100.00
Total of interconnected and non-interconnected islands							
Total thermal power plants	8641	9040	9126	45438	46913	47532	90.49
Total hydroelectric power plants	3061	3061	3061	3382	5212	4921	9.37
Total wind & other RES	37	37	37	82	89	76	0.14
TOTAL	11739	12138	12224	48902	52214	52529	100.00

provides a comprehensive and accurate view of the environmental aspects and the environmental trade-offs that take place in the energy system's life cycle [20, 21].

The LCA process is a systematic, phased approach and consists of four steps: (i) Goal Definition and Scoping, (ii) Inventory Analysis, (iii) Impact Assessment, and (iv) Interpretation [20].

In the Eco-indicator 99 method [16 – 18], normalization and weighting are performed at damage category level (endpoint level in ISO terminology). There are three damage categories:

- HH - Human Health: (unit: DALY= Disability adjusted life years; this means different disability caused by diseases are weighted)
- EQ - Ecosystem Quality (unit: PDF*m²yr; PDF= Potentially Disappeared Fraction of plant species)
- R - Resources (unit: MJ surplus energy - additional energy requirement to compensate lower future ore grade)

Unlike the predecessor Eco-indicator 95, the damage assessment step has been implemented in Eco-Indicator 99 (Figure 3) [16 – 18]. This means that the impact category indicator results that are calculated in the characterization step are added to form damage categories, which is preferable in most application of various research fields [10, 13, 14, 35 – 41]. Addition without weighting is justified here because all impact categories that refer to the same damage type (like human health)

Table 2: Impacts categories for global impacts within LCA context [16 – 18]

Impact Category	Scale	Relevant LCI Data	Common Characterization Factor	Description of Characterization Factor
Global Warming	Global	CO ₂ , NO ₂ , CH ₄ , CFCs, HCFCs, CH ₃ Br	Global Warming Potential	Converts LCI data to carbon dioxide (CO ₂) equivalents (global warming potentials can be 50, 100 or 500 year potentials).
Stratospheric Ozone Depletion	Global	CFCs, HCFCs, Halons, CH ₃ Br	Ozone Depleting Potential	Converts LCI data to trichlorofluoromethane (CFC-11) equivalents
Acidification	Regional Local	SO _x , NO _x , HCL, HF, NH ₄	Acidification Potential	Converts LCI data to hydrogen (H ⁺) ion equivalents
Eutrophication	Local	PO ₄ , NO, NO ₂ , Nitrates, NH ₄	Eutrophication Potential	Converts LCI data to phosphate (PO ₄) equivalents
Photochemical Smog	Local	NMHC	Photochemical Oxident Creation Potential	Converts LCI data to ethane (C ₂ H ₆) equivalents
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents	LC ₅₀	Converts LC ₅₀ data to equivalents
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish	LC ₅₀	Converts LC ₅₀ data to equivalents
Human health	Global Regional Local	Total releases to air, water, and soil	LC ₅₀	Converts LC ₅₀ data to equivalents
Resource Depletion	Global Regional Local	Quantity of minerals used Quantity of fossil fuels used	Resource Depletion Potential	Converts LCI data to a ratio of quantity of resource used versus quantity of resource left in reserve
Land Use	Global Regional Local	Quantity disposed of in a landfill	Solid Waste	Converts mass of solid waste into volume using an estimated density

have the same unit (for instance DALY). This procedure can also be interpreted as grouping. The damage categories (and not the impact categories) are normalized on a European level (damage caused by 1 European per year), mostly based on 1993 as base year, with some updates for the most important emissions.

It is very important to pay attention to the uncertainties in the methodology. Two types of uncertainties are distinguished: data uncertainties and uncertainties about the correctness of the models used. Data uncertainties are specified for most damage factors as squared geometric standard deviation in the original reports, but not in the software. It is not useful to express the uncertainties of the model as a distribution. Uncertainties about the model are related to subjective choices in the model. In order to deal with them, three different versions of the methodology were developed, using the archetypes specified in the egalitarian perspective, the hierarchist perspective and the individualist perspective, based on the “Cultural Theory” [16, 17, 18, 42, 43].

Eco-indicator 99 method, hierarchist version - adjusted for damage assessment [16 – 18]

The default Eco-indicator 99 method is the Hierarchist version with average weighting set (average of the full panel). In the hierarchist perspective the chosen time perspective is long-term, substances are included if there is consensus regarding their effect. For instance, all carcinogenic substances in IARC class 1, 2a and 2b are included, while class 3 has deliberately been excluded. In the hierarchist perspective, damages are assumed to be avoidable by good management. For instance, the danger people phase from rising water levels is not included. In the case of fossil fuels, the assumption is made that fossil fuels cannot easily be substituted. Oil and gas are to be replaced by shale, while coal is replaced by brown coal. In the DALY calculations, age weighting is not included.

Eco-indicator 99 method, individualist version - adjusted for damage assessment [16 – 18]

In the individualist perspective the chosen time perspective is short term (100 years or less), Substances are included if there is complete proof regarding their effect. For example, only proven carcinogenic substances in IARC class 1 included, while classes 2a, 2b and 3 have deliberately been excluded. In the individualist perspective, damages are assumed to be recoverable by technological and economic development. In the case of fossil fuels, the assumption is made that fossil fuels cannot really be depleted. Therefore they are left out in weighting. In the DALY calculations age weighting is included.

Eco-indicator 99 method, egalitarian version - adjusted for damage assessment [16 – 18]

In the egalitarian perspective the chosen time perspective is extremely long-term. Substances are included if there is just any indication regarding their effect. For instance, all carcinogenic substances in IARC class 1, 2a, 2b and 3 are included, based on information being available. In the egalitarian perspective, damages cannot be avoided and may lead to catastrophic events. In the case of fossil fuels, the assumption is made that fossil fuels cannot be substituted. Oil, coal and gas are to be replaced by a future mix of brown coal and shale. In the DALY calculations age weighting is not included.

4. Life cycle analysis of the energy sources used in the Greek electricity sector

4.1 General framework and assumptions made during the LCA application

Goal and scope of the LCA study – The goal of the present work is the application of the LCA methodology through the Eco-indicator 99 method in the life cycle of different energy sources used in the Greek electricity sector. The results will be used for the environmental assessment and comparison of these energy sources. The functional unit set for this work is 1 MWh of electricity production.

Data precision and completeness requirements – The results and data used in the present work for the application of LCA are used for comparison purposes of the different energy sources used in the Greek electricity sector.

System's boundary definition – The starting point for a LCA study of energy sources is the definition of the time and space boundaries of the examined system and the depth of the analysis as far as the environmental impacts are concerned. Usually, the studies concerning electricity generation are restricted in examining only the electricity generation facilities [14, 15]. Nevertheless, the boundaries

Figure 3: General representation of the Eco-Indicator 99 (hierarchist version) methodology. The white boxes below refer to procedures; the other boxes refer to intermediate results [16 – 18].

of the system examined in the present study are extended to include all the life cycle stages in order to provide more completed conclusions. A general description of these boundaries is given in **Figure 1**.

Impact assessment phase – In the present study, the LCA methodology is performed through the Eco-Indicator 99 method and the factors used for the classification, characterization, normalization and valuation correspond to the Dutch and European zone as they are the only available and reliable data that can be used in LCA studies in Greece [16 – 21, 30 – 34].

Impacts and damage categories – In every LCA study, the environmental impacts that will be addressed have to be identified. The sum of the environmental impacts (impacts and damage categories) that are addressed in the present study, refer to pollutants that are known and can be quantified easily, and include:

Impacts categories

- Respiratory Inorganics
- Climate Change
- Acidification / Eutrophication
- Carcinogens
- Respiratory Organics
- Ozone Layer
- Ecotoxicity
- Fossil Fuels

Damage categories

- Human Health
- Ecosystem Quality
- Resources

Other remarks – assumptions

- Priority and more attention is given to the emissions that are produced from the electricity

generation and extraction/acquisition stages of the life cycle of the energy source because (a) the highest percentage of the total emissions is attributed to these stages [44] and, (b) there are more analytical and reliable data for the emissions of these stages.

- Pollutants emitted and listed during the transportation stage of the energy sources' life cycle are attributed to the emissions produced due to the fuel consumption of the means of transport [45].
- Emissions attributed to the energy sources' life cycle stage of construction materials transport and construction and dismantling of generation facilities are based on data of the EXTERNE research project [46 – 50].
- Data concerning emissions of power production cycle, derive from the Greek Public Corporation's and the Hellenic Ministry for the Environment, Physical Planning & Public Works' official reports [22, 51]

4.2 Life cycle analysis results

A typical LCI of the different energy sources used in the Greek electricity sector is presented in **Tables 3, 4** and **5**. More information on the analytical data (concerning the power plants, lignite mines, wind parks, energy sources properties, e.t.c.) used to provide the life cycle inventory, are presented in **Tables 3, 4** and **5** can be found in Theodosiou [52]. **Table 6** presents the results of the application of the LCA methodology obtained with the Eco-indicator 99 method applied through the SimaPro 5.0 software tool [16 – 18]. The values correspond to environmental performance indexes, overall, and for every impacts and damage category. A high index means that the contribution of the life cycle of an energy source in an impact or damage category is high, and the environmental performance of the energy source is low. **Figures 4 –6** present the results of the valuation step of the impact assessment phase of the LCA. The results are presented for every impacts and damage category for every energy source as well as overall for all energy sources.

Table 3: LCI – Air emissions of the life cycle of energy sources used in the Greek electricity sector

Energy source / Life cycle stage	Air emissions – Type of pollutant (kg/MWh)						
	CO ₂	NO _x	SO ₂	PM ₁₀ (air)	CO	HC	CH ₄
LIGNITE (TOTAL)	2364.78	1.1187	1,886	1.484	n/a	n/a	n/a
Electricity generation	2310	1.02	1.84	0.078	n/a	n/a	n/a
Lignite loading – unloading	--	--	--	0,680	n/a	n/a	n/a
Transportation by conveyor belts and trucks	54.7	0.097	0.046	0.726	n/a	n/a	n/a
Transport of construction materials / electricity generation facilities construction / dismantling	0.097476	0.001681	0.000087	0.000122	n/a	n/a	n/a
PETROLEUM (TOTAL)	778.95	1.451	3.644	0.3135	0.01285	0.049	n/a
Electricity generation	738	1.357	3.148	0.302	n/a	n/a	n/a
Transportation and distillation of crude oil	38.875	0.0898	0.479	0.0106	0.0126	0.0488	n/a
Heavy oil transportation	2.013	0.00464	0.0364	0.000832	0.000238	0.000238	n/a
Electricity generation facilities construction / dismantling	0.057	0.000131	0.00102	0.0000226	0.0000071	n/a	n/a
NATURAL GAS (TOTAL)	768.13	0.557	0.0249	0.00023	0.00013	n/a	1.767

Electricity generation	767	0.555	0.0148	n/a	n/a	n/a	1.767
Natural gas transportation	1.13	0.0023	0.01	0.00022	0.00013	n/a	n/a
Electricity generation facilities construction / dismantling	0.0012	$7.8 \cdot 10^{-6}$	$1.6 \cdot 10^{-5}$	$7.3 \cdot 10^{-6}$	n/a	n/a	n/a
HYDROELECTRIC ENERGY (TOTAL)	0.91	0.016	0.0008	0.0012	n/a	n/a	n/a
WIND ENERGY (TOTAL)	9.65	0.0376	0.093	n/a	n/a	n/a	n/a

Table 4: LCI – Other emissions of the life cycle of energy sources used in the Greek electricity sector

Energy source	Emissions - Type of pollutant (kg/MWh)			
	Liquid wastes	Solid wastes	PM dissolved (water)	PM suspended (water)
Lignite	682.13	161.44	$5.7 \cdot 10^{-5}$	$9.25 \cdot 10^{-7}$

Table 5: LCI – Emissions in the water of the life cycle of energy sources used in the Greek electricity sector

Energy source	Emissions in the water – Type of pollutant (kg/MWh)							
	BOD ₅	COD	PM	VOC	S	NH ₃	N	Zn
Petroleum	0.00165	0.0086	0.0019	0.00022	0.000037	0.000298	0.0008	0.000037

The energy sources examined are three fossil fuels, lignite, petroleum (diesel and heavy oil), and three RES, wind and hydroelectric energy and geothermal energy. **Figure 4** presents the contribution of the emissions of the life cycle of every energy source in the impacts categories as a single score environmental index. **Figure 5** presents the significance and extent of every impacts category for every life cycle stage of the energy sources examined as a single score environmental index. Therefore, the main conclusions that can be drawn are:

- Pollutants emitted from the life cycle of petroleum when used for electricity generation, contribute mainly in the impacts categories of respiratory inorganics, climate change, ecotoxicity and acidification/eutrophication.
- Pollutants emitted from the life cycle of natural gas when used for electricity generation, contribute mainly to the impacts categories of climate change, respiratory inorganics and acidification/eutrophication.
- Pollutants emitted from the life cycle of lignite when used for electricity generation, contribute mainly to the impacts categories of respiratory inorganics, climate change, acidification/eutrophication and ecotoxicity.
- Pollutants emitted from the life cycle of geothermal energy systems when used for electricity generation, contribute mainly to the impacts categories of respiratory inorganics, climate change, and acidification/eutrophication.

- Pollutants emitted from the life cycle of wind energy, contribute mainly in the impacts categories of respiratory inorganics, ecotoxicity, climate change and acidification/eutrophication, in a much lower extent than in the case of fossil energy sources.
- Pollutants emitted from the life cycle of hydroelectric energy, contribute mainly in the impacts categories of respiratory inorganics, climate change and acidification/eutrophication, in a much lower extent than in the case of fossil energy sources.

The pollutants that contribute in every impacts category are shown in **Figure 3**.

Figure 6 presents the contribution of the emissions of the life cycle of every energy source in the damage categories. It is obvious that the use of fossil energy sources, mainly lignite and petroleum, for electricity generation is main source of causing problems both to human health and ecosystem quality. In **Table 7** the impacts and damage categories are presented aggregated, as well as the contribution of the energy sources in these categories. A rating system has been created with star symbols, ranging from «*» to «*****», that symbolizes which energy source contributes more to a specific category. More stars means higher contribution.

Table 6: Environmental evaluation indexes of the valuation step of the impact assessment phase of the LCA of energy sources used in the Greek electricity generation sector)

Impacts category / Energy source	Lignite	Natural Gas	Petroleum	Wind energy	Hydroelectric energy	Geothermy
Respiratory Inorganics	0.0148	0.000993	0.0087	0.000164	0.0000374	0.000741
Climate Change	0.0097	0.0033	0.00319	0.0000396	0.00000373	0.000328
Acidification/Eutrophication	0.000652	0.00025	0.000942	0.0000243	0.00000719	0.000126
Carcinogens	--	--	--	--	--	--
Respiratory Organics /	--	0.000000442	--	--	--	--
Ozone Layer	--	--	0.000000047	--	--	--
Ecotoxicity	--	--	--	--	--	--
Fossil Fuels	--	--	--	--	--	--
TOTAL	0.0252	0.00454	0.0128	0.000228	0.0000483	0.0012
Damage category	Lignite	Natural Gas	Petroleum	Wind energy	Hydroelectric energy	Geothermy
Human Health	0.0245	0.00429	0.0119	0.000204	0.0000411	0.00107
Ecosystem Quality	0.000652	0.00025	0.000943	0.0000243	0.00000719	0.000126
Resources	--	--	--	--	--	--
OVERALL ENVIRONMENTAL EVALUATION INDEX	0.0252	0.00454	0.0128	0.000228	0.0000483	0.0012

5. Conclusions – Discussion

The application of the LCA methodology in the Greek electricity generation sector presented in the present work has resulted in useful conclusions:

- For the fossil energy sources, the life cycle stage that is responsible for the higher quantities of pollutants emitted and thus with the higher environmental impacts is the facilities operation and electricity generation stage (combustion process), while for RES the life cycle stages of materials processing and components, equipment and facilities manufacturing.

Figure 4: Valuation step / Life cycle impacts categories of the energy sources used in the Greek electricity generation sector (Eco-indicator 99, Hierarchist H/A version)

Figure 5: Valuation step / Life cycle impacts categories of the energy sources used in the Greek electricity generation sector (Eco-indicator 99, Hierarchist H/A version)

Figure 6: Valuation step / Life cycle damage categories of the energy sources used in the Greek electricity generation sector (Eco-indicator 99, Hierarchist H/A version)

- The energy source with the worse environmental performance is lignite followed by petroleum and natural gas which is the most environmentally “friendly” from the three. The use of RES is associated with much lower environmental impacts.
- The significance and weight of every impact and damage category or of every pollutant in an impact or damage category is not the same. For example, the emission of CO₂ may be greater in quantity than the emission of CH₄. According to the characterization, classification, normalization and valuation factors of the Eco-indicator 99 method, the contribution of CO₂ in an impact or damage category may be lower than the contribution of CH₄. Thus, in many cases, any improvements need to be made should be focussed also in the reduction of the most hazardous pollutants on a significance and damage aspect and not quantity.
- The impact category with the higher environmental evaluation index is the respiratory inorganics. In this category, the main contributors are the SO₂ and NO_x emissions. The emitted quantity of these two pollutants is much lower than the emitted quantity of CO₂ but the environmental impacts caused from their release in the atmosphere are far greater.

The results of a LCA study can be used in many ways. They can be used to compare two or more energy sources that constitute the alternatives of an energy system design, to identify the areas where improvements must be made in order to improve the environmental performance of an energy system, etc. The intended use set in the present work is to demonstrate the environmental performance of the different energy sources used in the Greek electricity sector. In this scope, the reliability and completeness of the data used is satisfactory, and the final results are considered to be representative of the real picture of the Greek electricity sector. Therefore, it is obvious that the use of fossil fuels adds a heavy burden on the environment and new energy policies, planning and strategies need to be established in order to lighten that burden. For example, the increase of RES use is a feasible goal that can be set and reached since the availability of RES in Greece is high but up to date the RES exploitation percentage is not what it should really be.

Table 7: Contribution of the life cycle of the energy sources used in the Greek electricity sector in the impacts and damage categories

Impacts category	Lignite	Natural gas	Petroleum	Wind energy	Geothermy
Respiratory Inorganics	*****	***	****	*	**
Climate Change	*****	***	****	*	**
Acidification / Eutrophication	****	***	*****	*	**
Carcinogens	****	***	*****	*	**
Respiratory Organics	***	****	*****	**	*
Ozone Layer	*****	***	*****	*	**
Ecotoxicity	*****	**	*****	***	*
Fossil Fuels	***	*****	****	*	*
Damage Category					
Human Health	*****	***	****	*	**
Ecosystem Quality	****	***	*****	*	**
Resources	***	*****	****	*	*

References

1. Omer A. M., 2007. *Renewable energy resources for electricity generation in Sudan*. Renewable and Sustainable Energy Reviews, 11(7), 1481-1497.
2. Asif, M., & Muneer, T. 2007. *Energy supply, its demand and security issues for developed and emerging economies*. Renewable and Sustainable Energy Reviews, 11(7), 1388-1413.
3. IPPCa, Intergovernmental Panel on Climate Change, <http://www.ipcc.ch/>
4. Clift R., 1998. *Life cycle assessment — how to slim down your ecoprofile*. Institution of Chemical Engineers Environmental Protection Bulletin, 9-13.
5. Pessó C., 1993. *Life cycle methods and applications: Issues and perspectives*. Journal of Cleaner Production, 7(3-4), 139-142.
6. Lee J., O'Callaghan P., and Allen D., 1995. *Critical review of life cycle analysis and assessment techniques and their application to commercial activities*. Resources, Conservation & Recycling, 13, 37-56.
7. Azapagic A., 1999. *Life cycle assessment and its application to process selection, design and optimization*. Chemical Engineering Journal, 73, 1-21.
8. Benetto E, Rousseaux P., and Blondin J., 2004. *Life cycle assessment of coal by-products based electric power production scenarios*. Fuel 83, Pages 957–970.
9. Lombardi L., 2002. *Life cycle assessment comparison of technical solutions for CO₂ emissions reduction in power generation*. Energy Conversion and Management, Volume 44, Issue 1, Pages 93-108.
10. Furuhoft E., 1995. *Life cycle assessment of gasoline and diesel*. Resources, Conservation and Recycling, 14, 251-263.
11. Theodosiou G., Koroneos C., and Moussiopoulos N., 2005a. *Alternative scenarios analysis concerning different types of fuels used for the coverage of the energy requirements of a typical apartment building in Thessaloniki, Greece. Part I: Fuel consumption and emissions*. Building and Environment, Volume 42, Issue 3, March 2005, Pages 1522-1530.
12. Theodosiou G., Koroneos C., and Moussiopoulos N., 2005b. *Alternative scenarios analysis concerning different types of fuels used for the coverage of the energy requirements of a typical apartment building in Thessaloniki, Greece. Part II: life cycle analysis*. Building and Environment, Volume 40, Issue 12, December 2005, Pages 1602-1610.
13. Sheehan J.J., Duffield J.A., Coulon R.B., and Cambreco V.J., 1996. *Life-cycle assessment of biodiesel versus petroleum diesel fuel*. Proceedings of the 31st intersociety energy conversion conference, vol. 3, August (pp. 2140-2143).
14. Schreiber, A., Zapp, P., & Kuckshinrichs, W. 2009. *Environmental assessment of German electricity generation from coal-fired power plants with amine-based carbon capture*. The International Journal of Life Cycle Assessment, 14(6), 547-559.
15. Gagnon, L., Belanger, C., & Uchiyama, Y. 2002. *Life-cycle assessment of electricity generation options: The status of research in year 2001*. Energy policy, 30(14), 1267-1278.

16. PRé Consultants, 2000. *The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment*. Manual for Designers, Second edition, <http://www.pre.nl>
17. PRé Consultants, 2001a. *The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment*. Methodology Annex, Third edition, <http://www.pre.nl>
18. PRé Consultants, 2001b. *The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment*. Methodology Report, Third edition, <http://www.pre.nl>
19. Gurauskienė, I., & Varžinskas, V. 2006. *Eco-design methodology for electrical and electronic equipment industry*. Environmental research, engineering and management, 37(3), 43-51.
20. ISO International Standard 14040, 1997E. *Environmental management – Life cycle assessment – Principles and framework*. International Organisation for Standardisation (ISO), Geneva.
21. SETAC, Society of Environmental Toxicology and Chemistry, 1993. *Guidelines for Life Cycle Assessment: A code of practice*. Washington DC
22. PPC, Greek Public Power Corporation, www.dei.gr
23. Hellenic Ministry for the Environment, Physical Planning & Public Works / National Observatory of Athens, 2002. National inventory of greenhouse gases and other gases emissions for the years 1990 – 2000. Athens.
24. Hellenic Ministry for the Environment, Physical Planning & Public Works, 2004. National Allocation Plan for the period 2005 – 2007. Athens.
25. Hellenic Ministry for the Environment, Physical Planning & Public Works, 2006. National Allocation Plan for the period 2008 – 2012. Athens.
26. European Commission, 1998. Climate Change - Towards an EU Post-Kyoto Strategy (COM(98) 353)
27. European Commission, 1997. White Paper: Energy for the future - renewable sources of energy (COM(97) 599 final)
28. European Commission, 1996. Communication from the Commission - Energy for the Future: Renewable Sources of Energy - Green Paper for a Community Strategy (COM(96) 576)
29. European Commission, 2005. Green Paper on Energy Efficiency or Doing More With Less (COM(2005) 265)
30. ISO International Standard 14041, 1998E. *Environmental management - Life cycle assessment - Goal and scope definition and Inventory analysis*. International Organisation for Standardisation (ISO), Geneva.
31. ISO International Standard 14042, 2000Ea. *Environmental management - Life cycle assessment - Life cycle Impact assessment*. International Organisation for Standardisation (ISO), Geneva.
32. ISO International Standard 14043, 2000Eb. *Environmental management - Life cycle assessment - Life cycle Interpretation*. International Organisation for Standardisation (ISO), Geneva.
33. SETAC, 1991. *A technical framework for life cycle assessments*.
34. SETAC, Society of Environmental Toxicology and Chemistry, 1994. *Life Cycle Assessment Data Quality: A conceptual framework*. Washington DC.
35. Goedkoop M., Hofstetter P., Müller-Wenk R., and Spriensma R., 1998. *The Eco-Indicator 98 Explained*. In: International Journal of LCA, Volume 3, Issue 6, Pages 352-360.
36. Jungbluth N., and Frischknecht R., 2000. *Eco-indicator 99 - Implementation: Assignment of Damage Factors to the Swiss LCI database "Ökoinventare von Energiesystemen"*. ESU-services, Uster, retrieved from: www.esu-services.ch
37. Kyriakis N., Tsilingiridis G., and Martinopoulos G., 2004. *Life cycle environmental impact of a thermosyphonic domestic solar hot water system in comparison with electrical and gas water heating*. Renewable Energy, Volume 29, Issue 8, Pages 1277-1288.
38. Carpentieri M., Corti A., and Lombardi L., 2005. *Life cycle assessment (LCA) of an integrated biomass gasification combined cycle (IBGCC) with CO2 removal*. Energy Conversion and Management, Volume 46, Issues 11-12, Pages 1790-1808.
39. Prek M., 2002. *Life-Cycle Analysis and Environmental Impact Assessment of Heating and Air-Conditioning Systems*. Advances in Building Technology, Pages 1485-1492.
40. Meier M.A., and Hungerbühler K., 2000. *Uncertainty Analysis and Toxicity Classification in Life-Cycle Assessment Using the Case-study of Gas Purification Systems*. International Journal of LCA, Volume 5, Issue 2, Pages 75-77.
41. Flake M., and Heilmann J., 2001. *Assessment of Agricultural and Industrial Material Flows: Production Line Analysis of a Varnish Based on Linseed Oil: Comparison of Different Assessment Methods (Review Series)*. UWSF, Volume 13, Issue 5, Pages 301-309.
42. Hofstetter P., 1998. *Perspectives in Life Cycle Impact Assessment; A Structured Approach to Combine Models of the Technosphere, Ecosphere and Valuesphere*. Kluwers Academic Publishers, 1998, Info: www.wkap.nl/book.htm/07923-8377-X.
43. Thompson M., Ellis R., and Wildavsky A., 1990. *Cultural Theory*. Westview Print Boulder

44. European Commission, 2006. *Reference Document on Best Available Techniques for Large Combustion Plants*. Integrated Pollution Prevention and Control.
45. NTUA, Natural Technical University of Athens, Laboratory of Industrial and Energy Economics, 1997. *External costs of Electricity generation in Greece*. Research funded by the European Commission in the framework of the Non Nuclear Energy Programme JOULE II.
46. European Commission, DGXII, Science, Research and Development, JOULE, 1995a. *Externalities of Fuel Cycles, 'ExternE' Project*. Report 3, Coal and Lignite Fuel Cycles.
47. European Commission, DGXII, Science, Research and Development, JOULE, 1995b. *Externalities of Fuel Cycles, 'ExternE' Project*. Report 4, Oil and Gas Fuel Cycles.
48. European Commission, DGXII, Science, Research and Development, JOULE, 1995c. *Externalities of Fuel Cycles, 'ExternE' Project*. Report 1, Summary.
49. European Commission, DGXII, Science, Research and Development, JOULE, 1995d. *Externalities of Fuel Cycles, 'ExternE' Project*. Report 2, Methodology.
50. European Commission, DGXII, Science, Research and Development, JOULE, 1995e. *Externalities of Fuel Cycles, 'ExternE' Project*. Report 6, Wind and Hydro Fuel Cycles.
51. Hellenic Ministry for the Environment, Physical Planning & Public Works, <http://www.minenv.gr/>
52. Theodosiou G., 2007. *Eco-design and optimization of the design of energy systems*. PhD Thesis, Aristotle University of Thessaloniki, School of Engineering, Department of Mechanical Engineering, Thessaloniki, Greece. In Greek.
53. Berger, M., & Finkbeiner, M. (2010). *Water footprinting: How to address water use in life cycle assessment?*. Sustainability, 2(4), 919-944.