Air pollutants externalities associated with the life cycle of renewable energy sources power plants: A comparative appraisal

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***Abstract*—** Preventing dangerous climate change is a strategic priority for almost countries. The aim of the present work is to estimate and compare the air pollutants externalities associated with the life cycle of renewable energy sources power plants. This is being realized by applying the NEEDS framework to quantify the external cost, as well as the basic principles of the Life Cycle Assessment (LCA) methodology. The examined external cost has been calculated for five types of power plants (biomass-fired, hydro, photovoltaic, wind and geothermal ones). The results are given per impact type (human health, loss of biodiversity, crop yield, material damage and climate change) and show that this cost seems to be considerable for the biomass-fired and geothermal power plants, much lower for photovoltaic installations and practically insignificant for hydro and wind power plants. Regarding the impact categories, the biodiversity, the crop yield and the health of people are affected mostly by the biomass-fired and the geothermal power plants while the hydro, wind and photovoltaic installations have an effect on the climate. The general limitation of the external cost methodology applies to this work. Similarly, the data limitations as well as the assumptions related to the LCA framework may affect the results.

***Keywords*—**Air pollution, external cost, life cycle assessment, renewable energy sources

I. INTRODUCTION

ENERGY production and consumption generates pollutants (air, water, soil), whose impact needs to be reduced as far as possible. As tackling climate change is one of the five headline themes of the wide-ranging Europe 2020 policy, European legislation is forcing European Union member states, towards a secure, sustainable and competitive energy market by stimulating innovation in clean technologies such as renewable energy and energy efficiency [1]-[2]. Energy supply sector in 2011 was responsible for some 33% of greenhouse gas emissions of total greenhouse gas emissions in the 28 EU countries [3]. Considering that carbon dioxide concentrations globally have increased by 40% since pre-industrial times, primarily from fossil fuel emissions [4], an appropriate understanding of greenhouse gases (GHG) emission characteristics of various power generation systems from an environmental perspective is required [5]. Alongside, the external cost estimations due to environmental impacts of airborne emissions from conventional electricity generation systems can be an important policy tool [6]. Moreover, since climate change is a global issue, and does not respect national boundaries serious, consideration is currently being given to a range of international and local policy actions to reduce carbon dioxide emissions and their potentially damaging effects on the climate [7]-[8].

Energy services and resources will be increasingly affected by climate change which has direct effects on energy endowment, infrastructure, and transportation and indirect effects through other economic sectors [9]. In conclusion a high penetration of renewable energy beyond 2020 is a pre-requisite for a secure, zero-carbon energy system, thus many policies are supporting the transition to renewable energy sources [10]-[11]. The use of renewable electricity in European Union in 2010 was 641.7 TWh of which 333.7 TWh from hydro power, 155.1 TWh from wind power followed by biomass (123.6 TWh), solar (23.2 TWh), geothermal (5.6 TWh) and marine (0.5 TWh) [12].

On the other hand, achieving a low-carbon energy system requires further measures in addition to a carbon price, including the removal of potentially environmentally harmful subsidies, setting targets for renewables, and energy efficiency and increases in research and development and awareness-raising. A low carbon energy system is expected to result in additional benefits, including ancillary environmental benefits, enhanced security of supply, and potential beneficial effects for employment [13]. As for the role of renewable energy resources in sustainable energy systems, it has to be pointed out that the necessary contribution of the renewable electricity sector will not come by itself. Without increased political support, especially in the field of fair grid access and regulatory measures to ensure that the current electricity system is transformed to be capable to absorb these amounts of renewable electricity, the expected growth is questionable [14]. However, the cost of renewable electricity supporting measures should also be appraised in comparison to the climate change external cost avoided as a result of them.

In this context, the present work attempts to investigate the air pollutants externalities associated with the energy

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generation from renewable energy sources (RES), making a comparison among them. However, when comparing environmental issues of different options fulfilling a similar function, it is important to consider the complete life cycle and not only one phase, e.g. production or use. This is because environmental impacts and benefits may occur at different phases of the life cycle. The most important phases may not be the same when two options are compared [15]. Thus, a life cycle approach is needed and, more precisely, the Life Cycle Assessment (LCA) methodology should be used. LCA is the scientific approach behind modern environmental policies and business decision support related to sustainable consumption and production [16]-[17]. Specifically, LCA is a method for evaluating the environmental impact associated with a product, process or activity during its life cycle by identifying and describing, both quantitatively and qualitatively, its requirement for energy and materials, as well as the emissions and waste released to the environment [18]-[19].

II. LIFE CYCLE ASSESSMENT OF POWER GENERATION SYSTEMS

Life Cycle Assessment was originally developed to create a decision-making tool, which is aimed at a systematic assessment of the environmental performance of products systems due to the increasingly interested of general public in the environmental quality of products and production processes [20]-[21]-[22]-[23]. The prime purpose of LCA, is to support the choice of different (technological) options for fulfilling a certain function by compiling and evaluating the environmental consequences of these options [24].

During the evolution of LCA, a number of related applications emerged, such as decision-making support, choice of environmental performance indicators, product design and market claims etc and this variation is also reflected in the level of sophistication and to some extent also in the choice of methodology [25]-[26]. LCA provides a consistent basis for comparisons between alternatives based on the environmental consequences associated with them, however it is fundamental to apply the life cycle vision and take into account both the economic and environmental costs when identifying the most eco-efficient technology [27]-[28]-[29]. However, results from an LCA can mainly be used for identification of parts and aspects of a life cycle where improvements in the environmental performance are important [30]-[31].

The philosophy adopted by LCA is that the true extent of the environmental burden can only be understood if all steps in the delivery, use, and eventual disposal of the product or service are accounted for in the final analysis. As a consequence ISO has sponsored the development of a series of international standards to describe a consistent methodology. The ISO 14040 series of standards, which is part of the ISO 14000 series on environmental management, is the result. The umbrella standard is ISO 14040 *Life Cycle Assessment-Principles and Framework*. It summarizes the aim of LCA in the following way: LCA is 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 and interpreting the results [32].

In this context, the LCA methodology is described by four phases: (1) goal and scope definitions; (2) inventory analysis; (3) impact assessment; and (4) interpretation [33]-[34]. The foundation of a product LCA is the inventory component, where energy, raw materials and environmental releases are measured [35]-[36]. Specifically, the task in the Inventory stage is to trace (ideally) all inputs to and outputs from every stage in the life cycle back to the associated terminal inputs from and outputs to nature (the environment). The flows may usefully be segregated into inputs of materials and outputs of wastes to air, land and water. In practice, it may not be possible to follow all of the input flows all the way back to the extraction of resources from the environment, but where this is so it must be acknowledged in the study report and the consequences (for the use of the report) should be assessed [37].

The use of LCA in environmental management and sustainability has grown in recent years as seen in the steadily increasing number of published papers on LCA methodology and on case studies that have been performed to use LCA [38]. As a result, life cycle management is quickly becoming a well-known and often used approach for environmental management in the energy sector as well and, thus, LCA studies of different energy products [39], fuels [40]-[41], power generation systems [27]-[42]-[43] and relevant technologies' appraisals [44]-[45] are very common.

In the present work, the life cycle inventory concept is being used in order to quantify the atmospheric emissions associated with each RES power generation technology under examination (biomass-fired, hydro, photovoltaic, wind and geothermal). It is process-oriented, involving consideration of the individual technologies of interest. All energy systems are described on a “cradle to grave” basis, from the stage of extracting raw materials from the environment through downstream processes, with each stage in the chain being decomposed into construction, operation and dismantling phases [46]. In the power sector, the assessment should include extraction, processing and transportation of fuels, building of power plants, production of electricity and waste disposal [47]. The life cycle stages considered in this analysis for the RES power plants under examination are presented in Fig. 1 to 3.

III. EXTERNAL COST OF POWER GENERATION SYSTEMS

The external costs of energy are the costs not reflected in the market price, well over 100% for some energy sources [48], [49]. Comparative information on health and environmental impacts of various energy systems can assist in the evaluation of energy options [50]. In order to appraise the environmental power plants impacts of various electricity production technologies, one of the most widely accepted approach today relies on external costs i.e. monetary value of damages caused by electricity production. External costs are imposed on society (e.g. human health) and the environment (e.g. built environment, crops, forests and ecosystems) and are not accounted for by the producers or the consumers of electricity [51]. Generally, monetary estimates of both market and non-market damages are ideally expressed in the form of willingness to pay, or willingness to accept compensation. Willingness to pay measures the amount of income a person is willing to forgo in exchange for an improved state of the world, and willingness to accept compensation is an estimate of the compensation required in order to accept deterioration [52] Estimates of future economic damages resulting from atmospheric pollution have an important impact on policy decisions being made today. Reducing airborne emissions and protecting ourselves from those impacts will be costly, but a failure to act to address these impacts would be even more expensive [53] and will affect the quality of life (QLF) as environmental aspects are one of the most important aspects for improving human life quality [54].

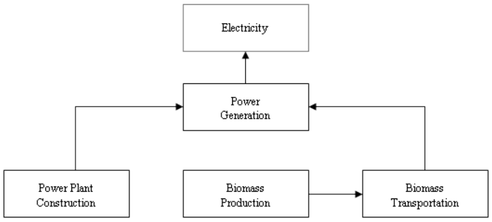

Fig. 1 The process stages of electricity generation in biomass-fired

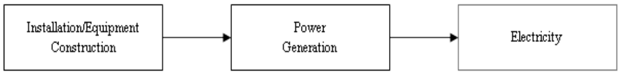

Fig. 2 The process stages of electricity generation in hydro, photovoltaic and wind installations

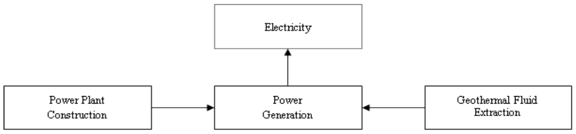

Fig. 3 The process stages of electricity generation in geothermal power plants

Several authors have attempted to publish estimates of annual climate change damages. Most of the estimates are comprehensive because they address market and non-market impacts. They based their estimates on different assumptions about the rates of climate change and sea level rise, rates of return on investment, and changes in population and income. Such a comprehensive estimate concerning the United States estimates that in 2012, the federal government spent $96 billion to clean up the disastrous effects of climate disruption [53]. Moreover, the Intergovernmental Panel on Climate Change (IPCC) has concluded that the costs of reducing emissions to stabilise atmospheric greenhouse concentrations rise with successively lower levels of stabilisation [55]. On the other hand, emissions seem to increase much faster in developing countries than in developed countries [56]. Regarding Europe existing socio−economic vulnerabilities may be exacerbated by the impacts of climate change. Significant reductions in damage costs can be achieved by global and European mitigation policies, consistent with the UNFCCC 2 °C objective, in combination with adaptation actions [57].

Regarding the biomass-fired power plants, one should note the following: power production from biomass is often said to be carbon neutral [58]. In other words, the biomass fuel cycle is considered as CO_2-free. Since the CO_2 absorbed during the growth of biomass equals the CO_2 released during its conversion. The only amounts of CO_2 from the cycle that are contributing to the global warming phenomenon are that released from the combustion of fossil fuels used for biomass production and transportation [59]-[60]. In some instances it is claimed that carbon sequestration to plant and soil, along with non-invasive farming methods make biomass electricity carbon negative, that is, less carbon is emitted than is removed from the atmosphere overall. Many authors assert carbon neutrality, with emissions from combustion balanced by carbon capture of the next crop. There is inevitably some fossil fuel usage not balanced by this equation, resulting from fertiliser, cultivation, collection and transportation. According to some authors, harvest methods that remove vegetation at or above soil level, leaving roots in the soil, leave sufficient carbon to balance all other emissions and maintain carbon neutrality [58]. Concerning the release of methane (anaerobic decomposition of residues), it was found out that even a 1% methane production rate has important impacts on the GHG balance since removing forest residues to produce electricity would avoid the release of methane and a GHG credit should be included in the assessment [61].

IV. ESTIMATION OF LCA EXTERNAL COST OF RES POWER PLANTS

Electricity is a key factor for economic and social development, but all energy systems emit greenhouse gases (GHGs) and contribute to anthropogenic climate change [62]. It is now widely recognized that GHG emissions resulting from the use of a particular energy technology need to be quantified over all stages of the technology and its fuel life cycle as the power generation has significant environmental impacts. The most important being human health impact (both, increased mortality in term of reduction of life expectancy as well as increased morbidity, i.e. cardiovascular and pulmonary problems, due to long or short-term exposure) caused by air pollutants (particulate matter, nitrogen oxides, sulphur dioxide, etc) formed during the normal plant operation [63]. However, impacts from the whole life cycle of electricity supply and not only the operation of a power plant should also be adequately taken into account [64]. A practice for evaluating the environmental impacts of the energy sector is the impact pathway methodology developed in the ExternE project funded by the European Commission. The impact pathway analysis aims at modelling the causal chain of interactions from the emission of a pollutant through transport and chemical conversion in the atmosphere to the impacts on various receptors, such as human beings, crops, building materials or ecosystems. Welfare losses resulting from these impacts are transferred into monetary values based on the concepts of welfare economics [65]-[66]. Impact pathway assessment is a bottom-up-approach in which environmental benefits and costs are estimated by following the pathway from source emissions via quality changes of air, soil and water to physical impacts, before being expressed in monetary benefits and costs. Generally, depending on the analytical framework and the target, different methods may be used for making estimates of external costs. These include: impact pathway approach, standard price approach and top-down approach. On the other hand, the ExternE project uses the bottom-up methodology to assess the external costs related with electricity generation [67]-[68]-[69].

The calculation of the external cost in our study is based on the ‘impact pathway’ methodology which has been developed in the series of ExternE projects, and is further improved within NEEDS and other related ongoing projects. The impacts covered by the methods used for external cost assessment within NEEDS are Human Health, Loss of Biodiversity, Crop Yield and Material Damage. Regarding Climate Change, estimates of the damage costs of greenhouse gas emissions differ not only because the underlying integrated assessment models represent key climate and socio-economic relations differently, but also because there are a number of assumptions to be made to which these estimates are highly sensitive, which cannot easily be resolved. The unit damage costs used for quantifying externalities from airborne pollutants and GHG are summarised in Table I [66].

Table I contains the various pollutants and CO_2 life cycle emission factors, of the five power generation technologies examined here (biomass-fired, hydro, photovoltaic, wind and geothermal). The construction and operation in each stage were examined, while the decommissioning in each stage was excluded. Subsequently Table II includes LCA atmospheric emission factors concerning the best currently available technology of various electricity generation plants, reported in the literature [27]-[66]-[70]-[71]. However, regarding the hydro power plant these data refer to the present-day technology of actual plants in Greece because these technologies are strongly site-specific. Particularly, the LCA airborne pollutants of the hydro power plant have been estimated based on direct relevant information given by PPC Renewables SA (the subsidiary for renewables of Public Power Corporation - PPC, the major electricity producer in Greece). The information concerns a local hydropower plant (2x85MW) with dam. Specifically, during its construction it has been used:

- 153,200 m^3 of concrete,
- 8,800,000 m^3 of clay, sand and gravel, aggregates etc,
- 1,775,000 kg of steel,
- 11,892,568.2 litres of diesel.

The average annual production of energy is about 320 GWh/y, while its lifespan is 100 years approximately. For the calculation of the emission factors it has been considered the following: the LCA NMVOC (non-methane volatile organic compounds), NOx, and PM emission factors of concrete for Greece are 0.0028, 0.0105, 0.0009 kg/m^3 respectively [72]; the LCA NMVOC, NOx, PM and SO_2 emission factors of steel (hot rolled coil) are 0.00072, 0.0078, 0.00372 and 0.0052 kg/kg respectively [71]-[73]; the combustion of 1 litre of diesel fuel produces around 0.003, 0.0623, 0.0003 and 0.0015 kg of NMVOC, NOx, PM and SO_2 respectively [74]; the LCA SO_2 emission factor of aggregates is 1.48×10^{-5} kg/kg, which has been calculated considering that the bulk density of sand and gravel is 1300-2000 kg/m^3 and of clay at mine is 2000 kg/m^3 [71]-[73]. Regarding the CO_2 LCA emission factor of the hydro power plant, it refers to the same plant, as it has been reported in the literature [27].

Finally, external costs are calculated by multiplying the relevant life cycle inventory data presented in Table II with the unit damage costs derived from the Table I. The results are shown in Table III, given per impact type (human health, loss of biodiversity, crop yield, material damage and climate change). It should be noted, however, that taking into account the overall uncertainties related to both the quantification of external costs as well as to the life cycle specification of different electricity generation technology configurations, the data of Table III provides rather external cost estimates for typical average configurations than detailed external cost information, and thus they indicate the order of magnitude of externalities from the electricity generation technologies examined here.

V. DISCUSSION AND CONCLUSIONS

In order to better understand the outcome of our analysis, a radar presentation is used in Fig. 4 to 8. This makes the appraisal easier since the comparison can be realized simultaneously in two levels: the first level is the polygon area and the second level is the impact categories (i.e. the polygon axes), if there is particular interest. However, as one could mention, in this chart type, each impact category (health, biodiversity, crop yield, material damage and climate change) has its own value axis radiating from centre point. The problem is that each of these axes should have different scale.

To overcome this problem, normalized impact categories are used. The latter ones are calculated by dividing each of them by the larger one of the same kind (i.e. the impact categories of health for every RES type are divided by this of geothermal power plants, which is the largest one among them). Thus, each impact category (e.g. health, biodiversity etc.) has its own axis scaled from 0 to 1 (for better displaying the results, in hydro and wind figures, the scale of the diagram has been adapted from 0 to 0.1). Lines connect all the values

Table I. Unit damage costs for air pollutants per impact category

Pollutant	Unit	Impact				
		health	biodiversity	crop yield	material damage	climate change
NMVOC	€/t	941	-70	189	0	0
NOx	€/t	5,722	942	328	71	0
PPM (2.5-10 μm)	€/t	1,327	0	0	0	0
PPM (< 2.5 μm)	€/t	24,570	0	0	0	0
SO_2	€/t	6,348	184	-38	259	0
CO_2	€/t	0	0	0	0	7

Table II Life cycle air pollutants emission factors of various RES power plants

Pollutant	Unit	RES Type				
		Biomass [a]	Hydro [b]	PV [a]	Wind [c]	Geothermal [d]
NMVOC	kg/kWh	2.22E-04	1.17E-06	7.09E-05	8.05E-06	0.00E+00
NOx	kg/kWh	1.76E-03	2.36E-05	1.36E-04	3.86E-05	2.00E-05
PPM (2.5-10 μm)	kg/kWh	4.86E-05	3.22E-07	4.73E-05	1.17E-05	1.00E-05
PPM (< 2.5 μm)	kg/kWh	4.25E-05	0.00E+00	2.37E-05	0.00E+00	0.00E+00
SO_2	kg/kWh	5.31E-04	8.99E-06	2.33E-04	3.83E-05	2.71E-03
CO_2	kg/kWh	1.80E-02	2.51E-03	5.52E-02	9.56E-03	1.31E-01

Table III LCA external costs of various RES power plants

RES Type	Unit	Impact type					Total
		Health	Biodiversity	Crop Yield	Material Damage	Climate Change	
Biomass	€/kWh	1.48E-02	1.74E-03	5.99E-04	2.62E-04	1.26E-04	**1.75E-02**
Hydro	€/kWh	1.94E-04	2.38E-05	7.62E-06	4.00E-06	1.76E-05	**2.47E-04**
PV	€/kWh	2.97E-03	1.66E-04	4.92E-05	7.00E-05	3.86E-04	**3.64E-03**
Wind	€/kWh	4.87E-04	4.28E-05	1.27E-05	1.27E-05	6.69E-05	**6.22E-04**
Geothermal	€/kWh	1.73E-02	5.17E-04	-9.64E-05	7.03E-04	9.14E-04	**1.94E-02**

forming a polygon (the LCA polygon). In general, a radar diagram compares the aggregate value of a number of data series. Therefore, it is evident that the RES type that covers the most area represents the worst environmental performance.

Consequently, a first remark that could be done is that, in spite that the analysis concern RES technologies, it does exist external cost (even if it is almost negligible in some cases) associated with their life cycle. Specifically, this cost seems to be higher for biomass-fired and geothermal power plants, much lower for photovoltaic installations (a considerable source of alternative energy [77]) and practically insignificant for hydro and wind power plants. Regarding the impact categories, the biomass-fired power plants affect mainly the biodiversity, the crop yield and the health of people, while the geothermal power plants have damages on health, climate and materials. The impacts of hydro, wind and photovoltaic installations are less important and concern principally the climate change issue.

On the other hand, regarding the reliability of the above findings, one should mention the followings: As regards the LCA concept, in recent years, many workers have examined the implications of various sources of uncertainty for the reliability of Life Cycle Assessment. More precisely, even though LCA is a powerful tool to assess the environmental impacts of products/services, some important limitations have been identified in recent year. The main limitations are related to the LCA methodological approach, especially data quality and collection, definition of the system, time boundaries, and process modelling. The time aspect is often critical in including or excluding some effects of the systems under analysis. Regarding the issue of the estimation procedure, many experts have questioned the usefulness of damage costs estimates since they are well known for their large uncertainties. However, the estimation of external costs is important for decision makers in the electricity sector to develop strategies for emission reduction and to develop environmental and energy policies.

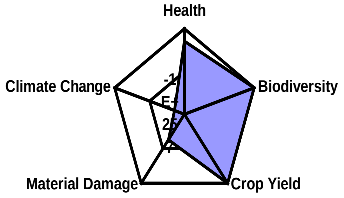

Fig. 4 LCA polygon of a biomass-fired power plant

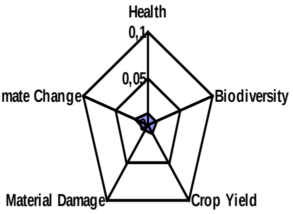

Fig. 5 LCA polygon of a hydro power plant

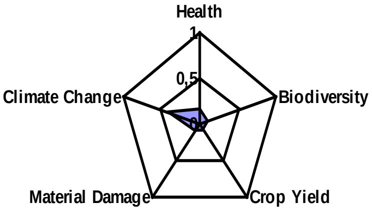

Fig. 6 LCA polygon of a photovoltaic installation

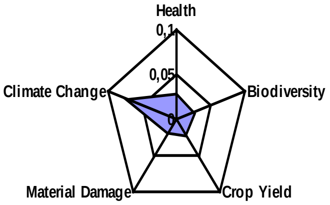

Fig. 7 LCA polygon of a wind power plant

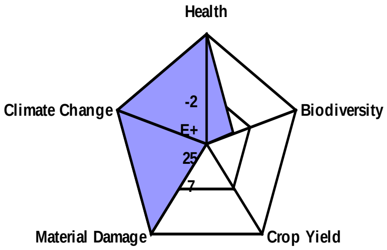

Fig. 8 LCA polygon of a geothermal power plant

REFERENCES

[1] *The European Union explained: Energy*, EU, 2013. Available: http://bookshop.europa.eu/en/energy-pbNA7012005/?CatalogCategoryID=sciep2OwkgkAAAE.xjhtLxJz

[2] *The European Union explained: Climate action*, EU, 2013. Available: http://bookshop.europa.eu/en/climate-action-pbNA7012016/?CatalogCategoryID=sciep2OwkgkAAAE.xjhtLxJz

[3] *EC COM (2013) 698 final : Progress towards achieving the Kyoto and EU 2020 objectives*, European Commission, 2013. Available : http://ec.europa.eu/clima/policies/g-gas/docs/com_2013_698_en.pdf

[4] *Climate Change 2013: The Physical Science Basis*, IPCC, 2013. Available: https://www.ipcc.ch/report/ar5/wg1/docs/WGIAR5_SPM_brochure_en.pdf

[5] H. Hondo, "Life cycle GHG emission analysis of power generation systems: Japanese case," *Energy*, vol. 30, no. 11-12, pp. 2042-2056, August–September 2005.

[6] *Study on External Environmental Effects Related To The Life Cycle of Products and Services*, BIO Intelligence Service-O2 France, EC, DG Environment, 2003. Available: http://ec.europa.eu/environment/ipp/pdf/ext_effects_finalreport.pdf

[7] P. Hardisty, M. Sivapalan, and P. Brooks, "The Environmental and Economic Sustainability of Carbon Capture and Storage," *International Journal of Environmental Research and Public Health*, vol. 8, no. 5, pp. 1460-1477, May 2011.

[8] *Climate and air quality impacts of combined climate change and air pollution policy scenarios*, EUR 24572, EU, 2010. Available: http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/15085/1/lbna24572enc.pdf

[9] *Climate impacts on energy systems*, The World Bank, 2011. Available: https://openknowledge.worldbank.org/handle/10986/2271

[10] *Hat-trick 2030*, European Renewable Energy Council, 2013. Available: http://www.erec.org/fileadmin/erec_docs/Documents/Publications/EREC_Hat-trick2030_April2013.pdf

[11] L. Ruieneanu, "Avoided CO_2 Cost. Case Study for a Conventional Power Plant," *International Journal of Energy*, vol. 8, pp. 24-28, 2014

[12] *Snapshots of renewable energy developments in the European Union*, EUR 26338, EU, 2013. Available: http://iet.jrc.ec.europa.eu/remea/sites/remea/files/reqno_jrc85377_snapshots_res_final_print.pdf

[13] *Climate Change and a European Low-Carbon Energy System - EEA Report No 1/2005*, EEA, 2005. Available: http://www.eea.europa.eu/publications/eea_report_2005_1

[14] Renewable Energy Snapshots 2010, EUR 24440, EU, 2010. Available: http://iet.jrc.ec.europa.eu/sites/default/files/documents/scientific_publications/2010/final_snapshots_eur_2010.pdf

[15] Å. Moberg, G. Finnveden, J. Johansson, and P. Lind, "Life cycle assessment of energy from solid waste - Part 2: landfilling compared to other treatment methods," *Journal of Cleaner Production*, vol. *13*, no. 3, pp. 231-240, February 2005.

[16] *International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Provisions and Action Steps*, EUR 24378, EU 2010. Available: http://www.eurosfaire.prd.fr/7pc/doc/1286804198_lbna24378enc_002.pdf

[17] M. Poeschl, S. Ward, and P. Owende, "Environmental impacts of biogas deployment - Part I: life cycle inventory for evaluation of production process emissions to air," *Journal of Cleaner Production*, vol. 24, pp. 168-183, March 2012.

[18] S. Madival, R. Auras, S.P Singh, S.P and R. Narayan, "Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology," *Journal of Cleaner Production*, vol. 17, no. 13, pp. 1183-1194, September 2009.

[19] Y. Liu, V. Langer, H-J Henning and H. Egelyng, "Life Cycle Assessment of fossil energy use and greenhouse gas emissions in Chinese pear production," *Journal of Cleaner Production*, vol.18, no. 14, pp. 1423-1430, September 2010.

[20] H. Jeswani, A. Azapagic, P. Schepelmann and M.Ritthoff, "Options for broadening and deepening the LCA approaches," Journal of Cleaner Production, vol. 18, no. 2, pp. 120-127, January 2010.

[21] G. Rebitzera, T. Ekvallb, R. Frischknechtc, D. Hunkelerd, G. Norrise, T. Rydbergf,, W.-P. Schmidtg, S. Suhh, B.P. Weidemai and D.W.

Penningtonf, "Life cycle assessment. Part 1: Framework, goal and scope definition, inventory analysis, and applications," *Environment International,* vol. 30, no. 5, pp. 701– 720, July 2004.

[22] D. Huybrechts, R. Berloznik, G. Wouters, J.-Y. Marion, G. Valenduc and P. Vendramin, "The role of ecobalances in environmental decision-making," *Journal of Cleaner Production*, vol. 4, no. 2, pp 111-119, 1996.

[23] B. Steen, "Environmental costs and benefits in life cycle costing," *Management of Environmental Quality: An International Journal,* vol. 16, no. 2, pp. 107-118, 2005.

[24] J. Guinée, G. Huppes and R. Heijungs, "Developing an LCA guide for decision support," *Environmental Management and Health,* vol. 10, no. 3, pp. 301-311, 2001.

[25] S. Vinodh and G. Rathod, "Integration of ECQFD and LCA for sustainable product design," *Journal of Cleaner Production*, vol. 18, no. 8, pp. 833-842, May 2010.

[26] *Life Cycle Assessment (LCA): A guide to approaches, experiences and information sources*, European Environmental Agency, Environmental Issues Series, no 6, 1997, Available: http://www.eea.europa.eu/publications/GH-07-97-595-EN-C/Issue-report-No-6.pdf/view

[27] D. Georgakellos, "Climate change external cost appraisal of electricity generation systems from a life cycle perspective: The case of Greece," *Journal of Cleaner Production,* vol. 32, pp. 124-140, September 2012.

[28] I. Bribián, A. Capilla and A. Usón, "Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential," *Building and Environment*, vol. 46, no. 5, pp. 1133-1140, May 2011.

[29] L. Gao and Z. Winfield, "Life Cycle Assessment of Environmental and Economic Impacts of Advanced Vehicles," *Energies*, vol. *5*, no.3, pp. 605-620, March 2012.

[30] T. Graedel, B. Allenby, *Industrial Ecology and Sustainable Engineering*, Pearson: Upper Saddle River, NJ, USA, 2010.

[31] M. Höjer, S. Ahlroth, K.-H. Dreborg, T. Ekvall, G. Finnveden, O. Hjelm, E. Hochschorner, M. Nilsson and V. Palm, "Scenarios in selected tools for environmental systems analysis," *Journal of Cleaner Production*, vol. *16*, no. 18, pp. 1958-1970, December 2008.

[32] S. Ross and D. Evans, "Use of Life Cycle Assessment in environmental management," *Environmental Management,* vol. 29, no. 1, pp. 132-142 January 2002.

[33] D. Georgakellos, "The use of the LCA polygon framework in, waste management," *Management of Environmental Quality: An International Journal*, vol. 17, no. 4, pp 490-507, 2006

[34] *Life cycle assessment: principles and practice*, EPA/600/R-06/060, U.S. Environmental Protection Agency: Cincinnati, USA, 2006. Available: http://www.epa.gov/nrmrl/std/lca/lca.html

[35] O. Hassan, "A value-focused thinking approach for environmental management of buildings construction," *Journal of Environmental Assessment Policy and Management*, vol. 5, no. 3, pp. 247-261, June 2003.

[36] E, Ison and A. Miller, "The use of LCA to introduce life-cycle thinking into decision-making for the purchase of medical devices in the NHS," *Journal of Environmental Assessment Policy and Management*, vol. 2, no.4, pp. 453-476, December 2000.

[37] D. Georgakellos, "Evaluation of life cycle inventory results using critical volume aggregation and polygon-based interpretation," *Journal of Cleaner Production*, vol. 13, no. 6, pp. 567-582, May 2005.

[38] B. Notarnicola, K. Hayashi, M-A Curran and D. Huisingh, "Progress in working towards a more sustainable agri-food industry," *Journal of Cleaner Production*, vol. 28, pp. 1-8, June 2012.

[39] H. von Blottnitz, and M-A Curran, "A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective," *Journal of Cleaner Production*, vol. *15*, no. 7, pp. 607-619, 2007.

[40] C. Dinca, P. Rousseaux and A. Badea, "A life cycle impact of the natural gas used in energy sector in Romania," *Journal of Cleaner Production,* vol. *15*, no. 15, pp. 1451-1462, October 2007.

[41] T. Tsoutsos, V. Kouloumpis, T. Zafiris and S. Foteinis, "Life Cycle Assessment for biodiesel production under Greek climate conditions," *Journal of Cleaner Production,* vol. 18, no. 4, pp. 328-335, March 2010.

[42] C. Babbitt and A. Lindner, "A life cycle inventory of coal used for electricity production in Florida," *Journal of Cleaner Production,*, vol. 13, no. 9, pp. 903-912, July 2005.

[43] P. Hardisty, T. Clark and R. Hynes, "Life cycle greenhouse gas emissions from electricity generation: A comparative analysis of Australian energy sources," *Energies*, vol. 5, no. 4, pp. 872-897, 2012.

[44] T-L. Nguyen and S. Gheewala, "Fossil energy, environmental and cost performance of ethanol in Thailand," *Journal of Cleaner Production*, vol. 16, no.16, pp. 1814-1821, November 2008.

[45] C. Wang, L. Zhang, S. Yang and M. Pang, "A hybrid Life-Cycle Assessment of nonrenewable energy and greenhouse-gas emissions of a village-level biomass gasification project in China," *Energies*, vol. 5, no. 8., pp. 2708-2723, 2012.

[46] R. Dones, U. Gantner and S. Hirschberg, "Greenhouse gas total emissions from current and future electricity and heat supply systems," in *Proceedings of 4th International Conference on Greenhouse Gas Control, Technologies (GHGT-4),* B. Eliasson, P. Riemer, and A. Wokaun, Ed. Amsterdam: Pergamon, 1999, pp. 891-896.

[47] L. Gagnon, C. Belanger and Y. Uchiyama, "Life-cycle assessment of electricity generation options: The status of research in the year 2001," *Energy Policy*, vol. 30, no. 14, pp. 1267-127, November 2002.

[48] *Health and Environmental Impacts of Electricity Generation Systems: Procedures for Comparative Assessment*, Technical reports series no. 394, International Atomic Energy Agency, Vienna, 1999.

[49] D. Hall, "External Costs of Energy," in *Encyclopedia of Energy*, vol. 2, C. Cleveland, Ed. Elsevier , 2004, pp. 651-667.

[50] R., Montanari, "Environmental efficiency analysis for enel thermo-power plants," *Journal of Cleaner Production,* vol. 12, no. 4, pp. 403-414, May 2004 .

[51] F. Ackerman and A. Stanton, "The Cost of Climate Change," *Natural Resources Defence Council*, New York, USA, 2008. Available: http://www.nrdc.org/globalwarming/cost/cost.pdf

[52] S. Fankhauser, "Climate change costs - Recent advancements in the economic assessment," *Energy Policy*, vol. 24, no. 7, pp. 665-673, July 1996.

[53] D. Lashof, A. Stevenson, "Who Pays for Climate Change?,", NRDC Issue paper, May 2013. Available: http://www.nrdc.org/globalwarming/files/taxpayer-climate-costs-IP.pdf

[54] R. Mousa, "The effect of Landscape Elements on the Satisfaction of the Low Income People in Egypt, " in *Proc. of the 2014 International Conference on Environmental Science and Geoscience,* Venice, Italy, 2014, pp. 62-68.

[55] S. Hitz, and J. Smith, "Estimating global impacts from climate change," *Global Environmental Change,* vol. 14, no. 3, pp. 201-218, October 2004.

[56] *Economic Assessment of Post-2012 Global Climate Policies: Analysis of Greenhouse Greenhouse Gas Emission Reduction Scenarios with the POLES and GEM-E3 models*, EUR 23768, EC 2009. Available: http://ftp.jrc.es/EURdoc/JRC50307.pdf

[57] *Climate change, impacts and vulnerability in Europe 2012,* EEA Report No 12, Nov 2012. Available: http://www.eea.europa.eu/publications/climate-impacts-and-vulnerability-2012

[58] A. Evans, V. Strezov, and T. Evans, "Sustainability considerations for electricity generation from biomass," *Renewable and Sustainable Energy Reviews,*vol. 14, no. 5, pp. 1419-1427, June 2010.

[59] *Extern E: Externalities of Energy - National Implementation, Vol XX,* EC, DG XII: Science, Research and Development. Available: http://www.externe.info/externe_d7/sites/default/files/vol10.pdf

[60] F. Sebastián, J. Royo, and M Gómez, "Cofiring versus biomass-fired power plants: GHG (Greenhouse Gases) emissions savings comparison by means of LCA (Life Cycle Assessment) methodology," Energy 2011, vol. 36, no. 4, pp. 2029-2037, April 2011.

[61] J. Nunes and F. Freire, "Life cycle energy and GHG emissions of biomass-to-electricity systems in Portugal: gasification vs direct combustion," *Life Cycle Assessment IX, Toward the Global Life Cycle Economy*, Boston, USA, 2009. Available: http://www.lcacenter.org/LCA9/presentations/86.pdf

[62] A. Behfar, M. M. Riyahi Alam, R. Shahmoradi, M. Tadi and S. Vahabzadeh, "Optimizing energy performance of a neighborhood via IMM® methodology: Case Study of Barcelona, vol. 7, no. 2, pp. 74-85, 2013.

[63] A. Hainoun, A. Almoustafa, M. Seif Aldin, "Estimating the health damage costs of syrian electricity generation system using impact pathway approach," Energy, vol. 35, no. 2, pp. 628–638, February 2010.

[64] *CASES: Cost Assessment of Sustainable Energy Systems*, Project co-funded by the EC within the Sixth Framework Programme, Deliverable No D.13.5, November 2008. Available: http://www.feem-project.net/cases/documents/deliverables/D_13_5%20participation%20report.pdf

[65] *ExternE, Externalities of Energy*, A research project of the European Commission. Available: http://www.externe.info/externe_2006/

[66] *External costs from emerging electricity generation technologies*, Deliverable n° 6.1 – RS1a NEEDS Project, March 2009. Available: http://www.needs-project.org/docs/RS1a%20D6_1%20External%20costs%20of%20reference%20technologies%2024032009.pdf

[67] *Handbook on estimation of external costs in the transport sector*, European Commission DG TREN, February 2008. Available: http://ec.europa.eu/transport/themes/sustainable/doc/2008_costs_handbook.pdf

[68] *Information on methods and tools for impact, vulnerability and adaptation assessments*, United Nations Framework Convention on Climate Change, September 2007. Available: http://unfccc.int/resource/docs/2007/sbsta/eng/misc13.pdf

[69] *Economic valuation of environmental damage; methodological convention for estimates of environmental externalities*, Federal Environment Agency, Germany, April 2007

[70] *Life cycle inventories of energy systems: Results for current systems in Switzerland and other UCTE countries*, Data v2.0 Ecoinvent report No. 5, Ecoinvent centre, Swiss Centre for Life Cycle Inventories, Dec 2007.

[71] *Life Cycle Analysis of GHG and Air Pollutant Emissions from Renewable and Conventional Electricity, Heating, and Transport Fuel Options in the EU until 2030*, ETC/ACC Technical Paper 2009/18, Available: http://acm.eionet.europa.eu/reports/docs//ETCACC_TP_2009_18_LCA_GHG_AE_2013-2030.pdf

[72] A. Biska, N. Oikonomou, "Environmental Consideration of Ready-Mixed Concrete Production," *Tech. Chron. Sci. J.* TCG , I, vol. 26, no. 3, pp. 35-48, September-October 2006.

[73] *Methodology report: Life cycle inventory study for steel products* World Steel Association 2011. Available: http://www.worldsteel.org/dms/internetDocumentList/bookshop/LCA-Methodology-Report/document/LCA%20Methodology%20Report.pdf

[74] *The Environmental Footprint of Surface Freight Transportation*, Transportation Research Board Special Report 291, Lawson Economics Research, Inc Ottawa, Canada, June 2007. Available: http://onlinepubs.trb.org/onlinepubs/sr/sr291_lawson.pdf

[75] D. Kellenberger, H.-J.Althaus, N. Jungbluth N. and T.Künniger, "Life Cycle Inventories of Building Products," *Final report ecoinvent data v2.0 No. 7*. Swiss Centre for Life Cycle Inventories, 2007.

[76] *Life Cycle Assessment of Aggregates, EVA025 –Final Report: Aggregates Industry Life Cycle Assessment Model: Modelling Tools and Case Studies*, Waste and Resources Action Programme, August 2009. Available: http://www2.wrap.org.uk/downloads/EVA025-MIRO_Life_Cycle_Assessment_of_Aggregates_final_report.16573fdf.8879.pdf

[77] Z. Darwish, H. Kazem, K. Sopian, M. Alghoul and M. Chaichan, "Impact of Some Environmental Variables with Dust on Solar Photovoltaic (PV) Performance: Review and Research Status," *International Journal of Energy and Environment*, vol. 7, no.4, pp. 152-159, 2013.