The carbon dioxide life cycle footprint of battery-powered electric vehicles using electricity from biomass-fired power plants in Greece

Dimitrios Georgakellos, Eirini Polychronidou, and Charalampia Florou

Abstract: - The present paper attempts to estimate the carbon dioxide life cycle footprint of battery-powered electric vehicle (BPEV) technologies that use, as energy carrier, electricity produced from biomass-fired power plants in Greece. This footprint is being evaluated through the associated external cost caused to the society. For the interpretation of the energy consumption and the carbon dioxide (CO_2) life-cycle emissions of the examined transport technology, the basic principles of the Life Cycle Assessment (LCA) approach together with the EcoSenseLE tool have been used. The results show that, since biomass-fired power plants have a very good performance as well as BPEVs are generally energy efficient and have quite limited CO_2 emissions, the examined carbon dioxide life cycle footprint seems to be sufficiently satisfactory. Regarding the reliability of the results, the general limitation of the external cost methodology applies to this work, together with data limitations and assumptions related to the LCA methodology. Nevertheless, the findings of the present paper could be important for decision making in environmental and energy policies.

Keywords: - Battery-powered electric vehicle, Biomass-fired power plants, External cost, Life cycle assessment.

I. Introduction

The future development of the economy is closely connected with the contributions achieved by sustainable development including more efficient utilisation of resources, conservation of energy and the reduction of the negative impacts of these processes on humans and the ecosystem by supporting resource conservation and recycling [1]. However, today's energy systems based mainly on fossil fuels cannot be regarded as sustainable [2]. Thus, enhancing energy saving, decreasing global warming and reducing greenhouse gas emissions have become major technological, societal, and political imperatives. Being closely related to the total energy supply and usage, they are of strategic importance in all countries [3].

Lignite is the primary energy source for electricity production in Greece, accounting for roughly 61% of total generation in 2009. Oil-fired and natural gas-fired power plants provide 13% and 15% respectively of Greece's electricity production, 10% is being realized in hydro power plants while the rest 0.5% is being produced in 20 wind farms, 2 photovoltaic parks, 13 small hydro stations and other renewable energy sources (RES) installations [4], [5]. The potential of sustainable technologies for electricity generation in Greece is high. Although the promotion of these technologies has been low until now, such promotion has become one of the basic goals of energy and environmental policy, since relevant analyses show that the highest penetration of renewable energy sources is the best compromise configuration for the Greek power generation sector [6], [7]. Thus, the contribution of RES units in gross electricity production from 8.3% in 2000 is expected to reach 29% in 2020 [8], [9].

On the other hand, transport is the fastest growing energy consuming sector worldwide [10]. Specifically, road transport was responsible for 73 % of this amount, while the relevant shares of aviation and marine transport were both 12 %. Transport energy consumption is growing by about 3 % per year. Growth in road transport was the main cause of the increase in energy use up to 1997 [11]. Apart from energy consumption, the transport sector is the major air pollution source in all developed societies with significant impacts in human health, and natural or manmade environment. Environmental costs arising from transport of one group of persons and imposed to another group of persons, without being fully accounted for by the first group, are considered to be external [12]. The external costs of transport are large (estimated at about 8 % of EU Gross Domestic Product - GDP) but the estimates are uncertain. Road transport, which dominates overall mobility volumes, is responsible for more than 90 % of total external costs. Road vehicles usually also show relatively higher average external costs per passenger-km and tonne-km than other modes – although the newest vehicles perform better from this point of view [13].

In this context, the present work intends to estimate the carbon dioxide life cycle footprint of battery-powered electric vehicles (BPEV) that use, as energy carrier, electricity produced from biomass-fired power plants in Greece. This paper is organised as follows: the next Section presents a concise literature review on global warming, while Sections 3 and 4 presents the methodology used and the external cost of carbon dioxide emissions caused during the life cycle of the biomass-fired power plants in Greece. Section 5 highlights the results obtained

D. Georgakellos is with the Dept, of Business Administration, University of Piraeus, Karaoli and Dimitriou 80, 18534 Piraeus, Greece (+30-210-4142252; fax: +30-210-4142339; e-mail: dgeorg@unipi.gr).
E. Polychronidou is with the Dept, of Business Administration, University of Piraeus, Karaoli and Dimitriou 80, 18534 Piraeus, Greece (e-mail: epolly12@hotmail.com).
C. Florou is with the Dept, of Business Administration, University of Piraeus, Karaoli and Dimitriou 80, 18534 Piraeus, Greece (e-mail: xaraflorou@hotmail.com).

regarding the examined footprint. Finally, there is the conclusions' Section.

II. Global Warming: An Overview

During the last recent years, global warming has been attacking the climate of planet Earth, and it has become even more intense as the current climate progressively exacerbates. Having become a governmental issue or even an international argument, global warming is being dealt with agreements and contracts, so as to protect the climate of aggressive alterations and, wishfully, keep the environmental balance. The scientific evidence is now overwhelming: climate change presents very serious risks and it demands an urgent response, and, form an international perspective, is global in its causes and consequences; thus, international collective action will be critical in driving an effective and equitable response on the scale required, a response which will call for deeper international co-operation in many areas. Not anyone can make predictions with certainty, but we know enough to be aware of the dangers and imminent risks. Mitigation – taking strong action to reduce emissions – must be viewed as an investment, a cost incurred now and in the coming few decades, to avoid the risks of very severe consequences in the future. Wisely made investments mean manageable costs, therefore opportunities for growth and development along the way. What should be kept in mind is that the benefits of strong, early action outweigh any costs.

Because of the complexity of global warming, we should understand the various related procedures, especially those associated with clouds, oceans and carbon round. Furthermore, we ought to improve the systematic observation of climate-related variables, and build improved models of the Earth's climate system. Finally, we may raise the support for both national and international climate research activities and of course to facilitate international exchange of climate data [14].

For the global climate system, water cycle is a procedure of prime importance, which involves the oceans, the atmosphere and the land surface. The main reason for the range of life forms, both plant and animal, is the range of variation in the *availability of water*. In wet tropical forests, the jungle teems with life of enormous variety. In drier regions sparse vegetation exists, of a kind that can survive for long periods with minimum of water; animals there, are also well adapted to dry conditions [15]. The availability of fresh water will suffer considerable changes by global warming. The process of temperature increase means that there will be loss of water on earth's surface due to evaporation [16]. Moreover, the combination of evaporation and less rainfall leads to non moisturized soil for crops to grow and less percentage of run-off, which is especially responsive to precipitation and high temperatures, thus mostly affected by them. This may be proved of vital importance for areas of very low level rainfall. Although increased carbon dioxide also tends to reduce plant transpiration and less water used by plants [17].

The universal character of temperature rising reaches all levels of life sustainability in general. *Agriculture* is seriously affected and so are the *nutritional supplies* that people need. However, with declining rates of population growth and continued economic development, there remains optimism that, in the absence of major climate change, growth in world food supply is likely to continue at last to match growth in demand and that the numbers of undernourished in the world will substantially decline [18]. The future of farming is progressively complicated in the face of global warming and depletion of stratospheric ozone. Alterations in temperature and rainfall will lead farmers to take up activities and apply methods (technical, genetic, biological, and chemical) that would not be of their choice otherwise while the production potential of soils is reduced and animals' resistance to diseases is lowered by the increasing ultraviolet radiation. Moreover the loss of soil and soil carbon contribute further to the problem of global warming [19].

If we want to apply policies in order to deal with the problem of global warming, we should take into consideration that the changes requested by the certain need will restrict carbon in soils and biomass, reduce emissions of methane and nitric oxides, and reduce dependence on fossil fuels. Flexibility and compliance will be questioned on a larger scale and in a shorter time-horizon than ever before [20]. Efforts to restrict greenhouse gases emissions in the atmosphere are being conflicted; by failing to control the emission of greenhouse gases which change the conditions under which farmers must work, we run the risk of undermining the very adaptability of agriculture on which such recommendations depend - a paradox of more than academic importance [21]. Plants and animals' diversity, major particles of the *ecosystem* are responsive to climate changes. The composition of the soil and the availability of water play an essential part too. Minor changes progressively are followed by greater ones to the structure of the ecosystem as its competiveness is altered. If we examine the distribution of vegetation over the world under previous climate conditions, we easily understand that the ecosystems flourish under different climate regimes.

Fossil records indicate that the maximum rate which most plant species have migrated in the past is less than 1 km per year. Known constraints imposed by the dispersal process suggest that, without human intervention, many species would not be able to keep up with the rate of movement of their preferred climate niche projected for the twenty-first century, even if there were no barriers to their movement imposed by land use [22]. Polluted atmosphere, contaminated or insufficient water supplies and poor soil – consequently poor crops and inadequate nutrition, put *human health* in serious danger and help spreading diseases. In addition to these, extreme climatic phenomena, such as droughts and floods, serve the same purpose [23]. Heat stress in extremely high temperatures will become common and extensive among city populations. In large cities where heat waves commonly occur death rates can be doubled or tripled during days of unusually high temperatures [24]. A warmer or wetter world will provide for a range of diseases which evolve in such an environment, reaching or even exceeding the limits of epidemic [25]. Warming of the climate is indisputable. It is really happening, basically due to human activities. Is it late to deal with the problem? The basic concern is to value the environment, preserve, foster and improve it.

III. Methodology

An externality is a third-party effect associated with production or consumption. If the external effect generates costs to a third party it is a negative externality [26]. The calculation of the external cost is based on the EcoSense system. EcoSense is an integrated computer system developed for the assessment of environmental impacts and resulting external costs from electricity generation systems and other industrial activities [27]. On this purpose the EcoSenseLE (EcoSense Look-up Edition) online tool has been used. According to the EcoSenseLE user's manual "EcoSenseLE is an online tool for estimating costs due to emissions of a typical source (e.g. power plant, industry, transport) or all sources of a sector in a EU country or group of EU countries; it is a parameterized version of EcoSense, based on European data for receptor (population, crops, building materials) distribution, background emissions (amount and spatial distribution), and meteorology, while the input required is annual emissions of NO_x, SO_2, PM_{10}, NMVOC, CO_2, N_2O, CH_4 and the pollutants considered are O_3, SO_2, PM_{10}, sulphates, nitrates and greenhouse gases" ([27] and tool website[1]). EcoSense, which is based on ExternE exposure-response function, was developed to support the assessment of priority impacts resulting from the exposure to airborne pollutants. Specifically, it assesses impacts on health, crops, building materials, forests, and ecosystems.

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. There is consensus among the scientific community that the impact pathway approach should be followed provided that sufficient data and information are available [28]. The ExternE project is the first comprehensive attempt to use a consistent bottom-up methodology to evaluate the external costs associated with electricity production [29], [30]. A more detailed analysis about the methodology used could be found elsewhere [27], [31].

To apply the ExternE methodology, the software package called EcoSense is used. Features of this software tool are, for example, a database containing information about receptor distribution (population, production of crops and inventory of materials) as well as meteorological data (wind speed, wind direction and precipitation) [32]. The input data in this tool are (a) the country where the emissions are produced, (b) the quantity of emissions in terms of mass per year (for pollutants at low or high height release), (c) the characterization of local environment for the emission source (agglomeration, urban city or rural), and (d) the type of emission source for low release emission values (ground-level, domestic heating, industry). In addition user defined values for mortality and greenhouse gas emissions are possible [33].

Consequently, for the EcoSenseLE application, specific data are necessary. These data concern the CO_2 emissions through the life cycle of each power generation technology under examination. For this purpose the Life Cycle Assessment (LCA) approach is being used. LCA is a decision-making support tool, which is aimed at a systematic assessment of the environmental performance of products systems [34], [35]. Results from an LCA can be used for identification of parts and aspects of a life cycle where improvements in the environmental performance are important [36], [37]. LCA can enable an existing situation to be improved by providing suggestions for modifications or substitutions of materials or manufacturing procedures that have the greatest environmental impact [38].

In the present work, the life cycle inventory concept is being used in order to quantify the CO_2 emissions associated with the power generation technology under examination. The energy system is 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 [39]. In the power sector, the assessment should include extraction, processing and transportation of fuels, building of power plants, production of electricity and waste disposal.

IV. The Biomass-fired Power Plants

As it has been already mentioned, biomass-fired power generation systems of the Greek electricity sector are being examined here. Table 1 contains the electricity generation in Greece for the year 2009 per power generation technology [4], [9] and [40].

Table 1. Electricity generation per power plant type in Greece for the year 2009

Type of Power Plant	Electricity Production (MWh)
Lignite-fired	30,561,000.0
Oil-fired	6,513,000.0
Natural gas-fired	7,765,000.0
Hydro	5,0105,000.0
Wind	239,277.6
PV	375.8
Biomass-fired	10,846.7
Total	50,099,500.0

[1] http://www.externe.info/tools.html

The life cycle stages (LCA system) of the power generation technology under examination are given in Fig. 1. From this figure, it is obvious that the construction and operation in each stage (e.g. transportation, electricity generation etc.) were examined, while the decommissioning in each stage was excluded.

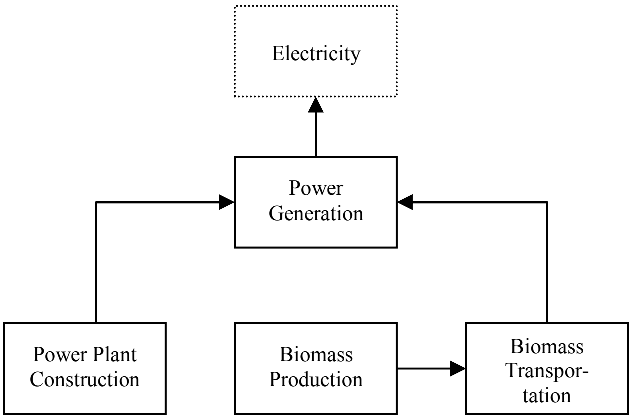

Fig. 1. The process stages of electricity generation in biomass-fired power plants in Greece

Table 2 contains the CO_2 emission factors per LCA stage, of the power generation technologies examined here. This table includes data concerning actual plants of the electricity sector in.

Table 2. CO_2 emission factor per life cycle stage of biomass-fired power plants in Greece (in kg/MWh)

Life Cycle Stage	CO_2 Emission Factor
Power Plant Construction (*)	38.50
Biomass Production (**)	14.79
Biomass Transportation (**)	1.71
Power Generation	-
Total	55.00

(*) Estimation, (**) Source [41]

In our case, biomass conversion is considered as CO_2 free (even if about 40% of the estimated biomass available resources in the long term in Greece concern agricultural residues and wood processing [42]) while the power plant construction CO_2 emission factor (for which no data are available in Greece) has been estimated assuming that it is 70% approximately of the total. This assumption is based on Jungmeier et al. [43] who reported that, for a similar case, CO_2 emissions during construction account for about 70% of the total, while CO_2 emissions during operation and dismantling account together for 30%. This assumption seems sound since, then in our case, the full life cycle CO_2 emissions factor becomes 55 kg/MWh, which is very close to the average value of 62.5 kg/MWh reported in the literature [44]. Regarding the biomass-fired power plants, one should note the following: Power production from biomass is often said to be carbon neutral [45]. 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 is contributing to the global warming phenomenon is that released from the combustion of fossil fuels used for biomass production and transportation [46], [47]. 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 [45]. 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 green-house gases (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 [48]. The net benefit of using biomass energy depends on the carbon emission rates (amount of carbon emitted per unit of energy) of the displaced fossil fuels (e.g. oil, or natural gas). For example, the net emission reduction of switching from coal to biomass will be greater than that of switching from natural gas to biomass, assuming all other factors such as conversion efficiencies remain unchanged [49]. Therefore, using sustainably grown biomass as the sole fuel, or co-fired with coal, is an effective way of reducing the net CO_2 emissions from a combustion power plant [50], [51]. For some authors, biomass is assumed to be neutral only when its production is dedicated for this purpose. For instance, according to Heller et al. [52], electricity generation with willow biomass is nearly GHG neutral (40–50 kg CO_2 eq./MWh) because willow biomass is grown specifically for electricity generation and thus willow production is considered to be within the power generation system boundary. However, the original growth of residue biomass is not considered within the power generation system boundary and a CO_2 absorption credit is not taken for the growth of this biomass.

Based on the data of Table 2 and applying the EcoSenseLE tool, the external cost associated with CO_2 emissions of the power plants under examination was calculated. It should be noted that, in this calculation, the climate change valuation used were the ExternE standard values, i.e. 19 € abatement cost per tonne of CO_2 equivalent. In addition, regarding the population density close to the emission sources, it is assumed that their locations are surrounded by rural areas including small towns. The calculated climate change external cost per life cycle stage (accumulated in annual basis) is given in Table

3. For the calculation of the latter, the annual electricity production presented in Table 1 has been used.

Table 3. Climate change external cost per life cycle stage of biomass-fired power plants in Greece

Life Cycle Stage	Climate Change External Cost	
	k€/yr	%
Power Plant Construction	7.92	69.96
Biomass Production	3.04	26.86
Biomass Transportation	0.36	3.18
Power Generation	0	0
Total	11.32	100.00

Comparing the findings of the present analysis with the results of similar estimations concerning other geographical areas, a remarkable, in many cases, variation in the external costs can be observed. However, this variation may be quite justifiable considering the different characteristics of each case (for example, the life stages considered in the analysis, since most studies examine only the operation phase, or that there is a significant difference in damage costs from pollutants emitted at different sites, which is mainly caused by variations in population distribution), as well as the uncertainties, which, in this kind of estimations, are very large leading to a range of possible damage costs. In addition, almost always, the external cost estimates given in various studies are, at least, of the same order of magnitude with the findings of the present research [53].

V. The Case Study

The present case study concerns the carbon dioxide life cycle footprint of battery-powered electric vehicle (BPEV) technologies that use, as energy carrier, electricity produced from biomass-fired power plants in Greece. This technology is analyzed for a typical mid-size passenger car, which in principle has the same performance as present conventional cars in terms of speed, acceleration, size and comfort. The only exception is that battery-powered electric vehicles are assumed to have a shorter driving range (about 200 km) as a consequence of the problems of carrying large batteries in the vehicle. The study concerns a period from 2011 to 2015 when the examined here technology will be "closer" to the market and more probable its selection by the potential car buyers. The main sources of data that have been used here for the vehicles studied are the relevant work of Johansson and Åhman [54]. According to this work, the energy consumption of BPEV is 1.7 kWh/10km [54].

The total number of passenger cars in Greece in 2015 has been predicted as 7.20 million vehicles. This estimation is based on the trend of an aggregate car ownership and bus fleet model, which has been developed by Paravantis and Georgakellos [55] in order to forecast and compare fuel consumption and CO_2 emissions from passenger cars and buses in Greece. Percent adults in the population, per capita gross domestic product, inflation, unemployment, car occupancy and bus kilometers were predictors included in the car ownership and bus fleet multiple regression model. The relevant forecast for the car fleet is given in Fig. 2.

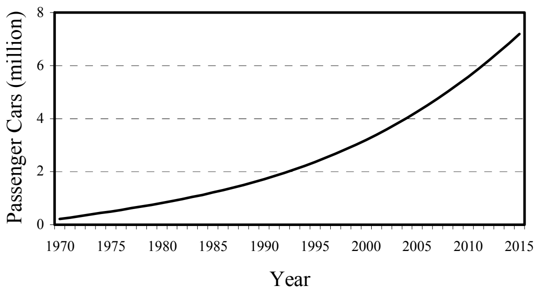

Fig. 2. Total number of passenger cars in Greece from 1970 to 2015 (forecast). Adapted from Paravantis and Georgakellos [55]

According to this figure, for the period 2011 to 2015 the passenger car fleet in Greece seems to have a growth of 1.62 million vehicles in total. In this figure one should add the number of new car acquisitions that correspond to a, more or less, equal number of old car withdrawals, during the examined period. This number has been estimated here as 2.80 million vehicles approximately (for the five years of the examined period), considering a 10% annual replacement factor of the existing fleet cars (the mean passenger vehicle age in Greece is about 10.5 years [56]). Therefore, the total number of new car acquisitions from 2011 to 2015 is about 4.42 million vehicles [57].

Based on this estimation and according to the average life-cycle energy consumption of BPEV (1.7 kWh/10km), the annual energy consumption of the car fleet part acquired from 2011 to 2015 (if every single one vehicle of it is exclusively BPEV that use, as energy carrier, electricity produced from biomass-fired power plants in Greece) is calculated as 9.77×10^6 MWh/y. For these calculations, it has been used the average annual mileage per vehicle in Greece, which is 13,000 km/y approximately, depending on their engine capacity and technology [58,59]. Therefore, based on the data of Table 2 (i.e. 55 kg/MWh life cycle CO_2 emissions of biomass-fired power plants in Greece), the relevant annual carbon dioxide emissions are calculated as 537.35×10^6 kg CO_2/y.

Subsequently, using this finding and applying the EcoSenseLE tool, the external cost associated with "climate change" damage categories, of the car fleet part acquired during the examined period (if it consists exclusively of BPEV) is calculated as 17.81 million € per year. The mortality climate change valuation used in this calculation were the ExternE standard values, i.e. 19.00 € abatement cost per tonne of CO_2 equivalent

VI. Conclusions

Concluding, the present work attempts to estimate the carbon dioxide life cycle footprint of battery-powered electric vehicle (BPEV) technologies that use, as energy carrier, electricity produced from biomass-fired power plants in Greece. First, it been has estimated the external cost of CO_2 related with electricity generation from biomass in Greece, applying the EcoSenseLE online tool. Results show that biomass-fired power plants have a very good performance, i.e. very low external cost (11.32 thousand € per year). Regarding the life cycle stages, the climate change external cost made of CO_2 emitted during biomass production and transportation is 30.04%, while the climate change external cost associated with CO_2 emitted during the plant construction stage is 69.96%.

Subsequently, the BPEV LCA CO_2 footprint has been estimated through the following scenario concerning Greece: adoption of this technology by all new car acquisitions during the period from 2011 to 2015. The findings show that the examined footprint, i.e. the external cost associated with "climate change" damage categories, of the car fleet part acquired during the investigated period (if it consists exclusively of BPEV) is calculated as 17.81 million € per year. The results show that, since biomass-fired power plants have a very good performance as well as BPEVs are generally energy efficient and have quite limited CO_2 emissions, the examined carbon dioxide life cycle footprint seems to be sufficiently satisfactory.

The contribution of the present paper lies in two levels. First, the use of recent data for the estimation of the external costs associated with the CO_2 emissions during through all life cycle stages of power generation systems using biomass as fuel allows an understanding of the changes in the climate change external costs from these specific power plants in Greece. This may be quite important for decision making concerning environmental and energy policies development and appraisal. On the other hand, the findings of the present paper could be important for decision making in environmental and energy policies in the car industry. Specifically, its aim is to provide a useful platform for future transportation strategies evaluation. However, it should be mentioned that, regarding the reliability of the present findings, a very important issue is the influence of time, which, in almost all analyses, is neglected. Nevertheless, the effects of a certain amount of a particular element released over some period of time may be very different compared to the effects of the same amount released all at once [60]. But issues like this could be the subjects of future work.

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