POTENTIAL EXTERNALITIES SAVINGS DUE TO ELECTRIC VEHICLE SMART CHARGE

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Abstract

This work focuses on the analysis developed in order to demonstrate how smart charging, using tailored control algorithms, contributes to minimize the environmental impact and economic costs associated to the electric vehicles under an LCA perspective. The analysis considers the Spanish grid mix profile and specific charging patterns.The LCA methodology adopted implies a comprehensive assessment of the impacts and costs occurring upstream and downstream the charging event. For the environmental analysis, the LCA impact categories are considered, while for the economic assessment, data regarding the costs associated to the electricity price and the pollutants generation have been adopted.

Introduction

Growing of electric vehicles (EV) is one of the most relevant technological challenges to be faced during the next years around the world. One of the main reasons why governments are promoting this kind of vehicles is because they are more environmental friendly and more energy efficient. However, these premises are highly dependent on the way the electric energy EVs consume is produced, as well as the manufacturing, logistic and disposal processes involved in the entire life cycle of them. For this reason, the purpose of this work is to analyse the environmental and energetic impacts of the electric vehicle in Spain using to achieve this goal the life cycle assessment (LCA) methodology. This calculation is the first step before transforming these impacts into economic variable, establishing a comparison between the negative externalities of different technologies.

In the last years there has been a growing awareness about the negative consequences of the vehicle use, as a major participant in climate change or in air pollution. The pollutants emitted by the use of the internal combustion engine vehicles (ICEV) have been proved to be specially dangerous for the environment and harmful for the human health, as well as provoking an important energy dependency problem in the oil non producing countries, as is the case of Spain (Löschel, A. [et al.], 2009), which occupies this work. All this growing interest is in part motivated by the new European energy and transport regulations, among which we can highlight:

- Directive 2014/94/EU, which establishes a common framework of measures for the deployment of alternative fuels infrastructure in the Union in order to minimize dependence on oil and to mitigate the environmental impact of transport. This Directive sets out minimum requirements for the building-up of alternative fuels infrastructure, including recharging points for electric vehicles and refueling points for natural gas (LNG and CNG) and hydrogen, to be implemented by means of Member States' national policy frameworks, as well as common technical specifications for such recharging and refueling points, and user information requirements.

- The Commission's White Paper of 28 March 2011 entitled 'Roadmap to a Single European Transport Area — Towards a Competitive and Resource Efficient Transport System' called for a reduction in the dependence of transport on oil. This needs to be achieved by means of an array of policy initiatives, including the development of a sustainable alternative fuels strategy as well as of the appropriate infrastructure. The Commission's White Paper also proposed a reduction of 60 % in greenhouse gas emissions from transport by 2050, as measured against the 1990 levels.

- Directive 2009/28/EC, which is about the promotion of energy coming from renewable sources. In this directive the obligation to introduce a 10 % of renewable energies in the transportation sector for 2020 is established.

- Regulation (EC) 443/2009 that establishes the standards of the new cars in terms of greenhouse gas emissions. In this Regulation the vehicle manufacturers have the obligation of reducing the CO2 average emissions of the sold vehicles to 130 g of CO2/km for the year 2015 and to 95 g of CO2/km for the year 2020. The Regulation explains that the quantity of electric vehicle sales will play a key role in the capacity of each manufacturer to achieve its objectives.

- Directive 2009/33/EC, which tries to stimulate the use of clean and energy-efficient road transport vehicles, especially in public administrations, by imposing the conversion of the emissions and the air pollution into economic variable, and forcing the purchase, by the European public administrations, of the cheaper technological option, including negative externalities.

All these policy papers and regulations are obviously linked to the European sustainability objectives known as 20/20/20 goals[1] (20 % increase in energy efficiency, 20% reduction of CO2 emissions, and 20% renewable energies by 2020), in which the electric vehicle is seen as a major participant.

In the case of Spain there have also been many public initiatives in national and in regional levels to promote the introduction of the electric vehicle. The MOVELE[2] project, developed by the Ministry of Industry, Tourism and Commerce could be one of the most significant projects in this sense. As well it should be noted the integral strategy[3] to introduce electric vehicles at a national level, also developed by the Ministry of Industry, Tourism and Commerce, under which several EV subsidies programs have been promoted since 2011.

1 http://europa.eu
2 http://www.movele.es
3 *Estrategia integral para el impulso del vehículo eléctrico en España* (in english, *Integral strategy to promote the electric vehicle in Spain*). www.mityc.es

All these regulatory events seem to point out that the electric vehicle has a strong support from the all the public actors in the European Community and in Spain. This technology is seen as a major actor to achieve goals in terms of energy efficiency and sustainability. So this situation has obviously provoked and at the same time is consequence of many research works that analyse deeply the implementation of the electric vehicles, as well as technical aspects, with special interest to energetic impacts produced by the emissions of greenhouse gases.

In this sense it can be said that an important number of studies and articles have been focused on “well to wheel” emissions provoked by electric vehicles depending on the electrical generation mix of the different countries. In the case of Spain the last works point out that the electric vehicle has disperse emissions in the range of 50 to 60 grams of CO_2 per kilometre which is much lower than the emissions caused by the conventional vehicles in forms of direct emissions[4]. This proves the environmental advantage that the electric vehicle has compared to the internal combustion engine vehicle and that will probably be increased as renewable energy systems are introduced into national the power system.

This paper will focus on the analysis of how Smart charging contributes to reduce the environmental and economic costs, and their combination, of this activity. For this purpose, in the methodology section, the mathematical approach adopted to establish the optimized algorithm that leads to minimize either the environmental and economic costs, while the results section presents the outcomes of the application of the applied algorithms. Finally, conclusions are presented in order to summarize the main results and have an outlook on further developments.

Methodology

Specific objectives and scope

This work focuses on demonstrate how an optimised electric vehicle charge process leads to minimise the environmental impacts associated to the electricity consumed but also to minimise the cost of the purchase electricity and the externalities costs associated to the emissions occurring due to the electricity generation.

As mentioned before, the study will focus on the use phase of an electric vehicle and specifically on the charging process; however, the impacts associated to this operation will be assessed under a “cradle to grave” perspective since the full value chain associated to the electricity generation will be considered.

The study is structured in the three main scenarios:

I. Optimisation of the charging pattern under and environmental perspective (minimisation of the normalized environmental impact values due to the electricity grid mix composition)

II. Optimisation of the charging pattern under an economic perspective (minimisation of the costs of the charge due to the electricity consumption considering the hourly final price of the electricity)

[4] Data used: electric consumption of the electric vehicle of 20 kWh/100 km and average emissions from electric mix of 233 g of CO2/kWh produced. (*Source: IDAE, Spanish National Energy Agency and Electricity Observatory (2009)*).

III. Optimisation of the charging patter under an economic and environmental perspective (minimisation of the costs considering the externalities costs due to the emissions of certain pollutants in the electricity generation)

The study analyses the results of the above mentioned scenarios and discuss about the convenience of each of the three optimisation exercises in order to define which scenario the most appropriate when is trying to minimise the environmental or economic effects of the charging.

Impact categories selection and normalization

As explained before, the study has been carried out considering a life cycle perspective approach. For this reason the undertaken analysis and calculation have been performed using specific data concerning the potential environmental impacts due to the electricity generation and therefore the lifecycle emissions of the pollutants considered. The methodology adopted to characterize the emissions occurring through the electricity generation life cycle is CML 2001, updated in April 2013. In 2001 a group of scientists under the lead of CML (Center of Environmental Science of Leiden University) proposed a set of impact categories and characterization methods for the impact assessment step. The CML Guide provides a list of impact assessment categories grouped into:

A: Obligatory impact categories (Category indicators used in most LCAs)
B: Additional impact categories (operational indicators exist, but are not often included in LCA studies)
C: Other impact categories (no operational indicators available, therefore impossible to include quantitatively in LCA)

In this specific study, the following impact categories have been calculated:

- **Acidification Potential (AP) [kg SO2 eq**]: Acidification is caused by release of protons in the terrestrial or aquatic ecosystems. In the terrestrial ecosystem the effects are seen in softwood forests (e.g. spruce) as inefficient growth and as a final consequence dieback of the forest. The substances contributing to acidification can be transported across boundaries via air. Sulfur oxides, nitrogen oxides, inorganic acids (hydrochloric acid, nitric acid, sulphuric acid, phosphoric acid, hydrofluoric acid, hydrogen sulfide), and ammonia are substances contributing to acidification.
- **Eutrophication Potential (EP) [kg Phosphate eq**: Eutrophication can be defined as: enrichment of aquatic ecosystems with nutrients leading to increased production of plankton, algae and higher aquatic plants leading to a deterioration of the water quality and a reduction in the value of the utilization of the aquatic ecosystem. Nitrogen and phosphorous compounds are mentioned as the main origin of nutrient enrichment.
- **Global Warming Potential, incl biogenic carbon [kg CO2-Equiv.]:** Global warming - or the "greenhouse effect" - is the effect of increasing temperature in the lower atmosphere. The lower atmosphere is normally heated by incoming radiation from the outer atmosphere (from the sun). A part of the radiation is normally reflected by the soil surface but the content of carbon dioxide (CO2) and other "greenhouse" gasses (e.g. methane (CH4), nitrogen dioxide (NO2), chlorofluorocarbons etc.) in the atmosphere absorb the IR-radiation. This results in the greenhouse effect e.g. an increase of temperature in the lower atmosphere to a level above normal.

- **Ozone Depletion Potential (ODP) [kg CFC-11 eq]:** Decomposition of the stratospheric ozone layer is causing increased incoming UV-radiation that leads to impacts on humans, natural organisms and ecosystems. Contributors to this decomposition are halocarbons (CFCs, HCFCs, halons, etc.)
- **Photochemical Ozone formation Potential (POCP) [kg ethane eq]:** Photochemical ozone formation is caused by degradation of volatile organic compounds (VOC) in the presence of light and nitrogen oxide (NOx) ("smog" as a local impact and "tropospheric ozone" as a regional impact). The biological effects of photochemical ozone can be attributed to biochemical effects of reactive ozone compounds.
- **Abiotic Resource Depletion Potential, non-fossil (ADP) [kg Sb eq] :** assessment of the scarcity of a given material resource, using a scarcity index.
- **Abiotic Resource Depletion Potential (ADP-fossil) [MJ]** assessment of the scarcity of a given energetic resource, using a scarcity index.

Since every impact category under this assessment has is measured with different units and metrics, a normalization factor has been applied in order to be able to summarize the impact profile into a single value result of the summary of all the normalized values for each impact category. Normalization is regarded as optional for simplified LCA, but mandatory for detailed LCA. For each baseline indicator, normalization scores are calculated for the European 25+3 reference situation. The normalized result for a given impact category and region is obtained by multiplying all the characterization factors by their respective emissions. The sum of these products in every impact category gives the normalization factor, expressed in person equivalent.

Optimization model

As stated before, an optimization model is designed to control the charging process in order to minimize the normalized environmental impact, the charging process costs or a combination of both objectives. Designing a smart charge process must consider not only environmental or technical constraints but the end-user needs. For this reason, a set of constraints is included to assure that the state of charge of the electric vehicle in each time interval takes into account the scheduling of the users trip distance and time and parking times. The mathematical model is defined as follows:

$$\min \quad \sum_{t \in \mathrm{T^{on}}} \mathrm{c_t^{env}} e_t + \mathrm{c_t^{ch}} e_t \qquad (1)$$

$$\text{subject to} \quad e_t \leq \Delta \mathrm{t}\, \mathrm{P^{max}} \qquad \forall \mathrm{t} \in \mathrm{T^{on}} \qquad (2)$$

$$\mathrm{SoC_t^{min}} \leq SoC_t \leq \mathrm{SoC^{max}} \qquad \forall \mathrm{t} \in \mathrm{T^{on}} \qquad (3)$$

$$SoC_t = SoC_{t-1} + \frac{100 * (e_t - \mathrm{d_t})}{\mathrm{E^{max}}} \qquad \forall \mathrm{t} \in \mathrm{T^{on}} \qquad (4)$$

Where the input data are

$\mathrm{T^{on}}$ is the set of intervals in which the electric vehicle is plugged in,

$\mathrm{c_t^{env}}, \mathrm{c_t^{ch}}$ are the environmental impact costs and the energy costs respectively (€/kWh),

Δt is the time interval duration (for this work we consider hourly intervals, i.e. Δt =1h),

$\mathrm{P^{max}}$ is maximum available power, depending on the charging infrastructure (kW),

$\mathrm{SoC_t^{min}}$ are the minimum state of charge requested for each time interval (%),

$\mathrm{SoC^{max}}$ is the maximum state of charge of the battery (%),

$\mathrm{d_t}$ are the expected trip consumption during each time interval (kWh).

$\mathrm{E^{max}}$ is the battery capacity (kWh);

and e_t is the set of decision variables representing the energy charged in the battery during time interval *t.*

The objective function (1) represents the minimization of the sum of the environmental costs and the energy costs, in order to compare the three scenarios defined only the term corresponding to the scenario objective is included:

I. Optimisation of the charging pattern under and environmental perspective:

$$\min \quad \sum_{\mathrm{t \in T^{on}}} \mathrm{c_t^{env}} e_t \qquad (1.\mathrm{I})$$

II. Optimisation of the charging pattern under an economic perspective

$$\min \quad \sum_{\mathrm{t \in T^{on}}} \mathrm{c_t^{ch}} e_t \qquad (1.\mathrm{II})$$

III. Optimisation of the charging patter under an economic and environmental perspective:

$$\min \quad \sum_{\mathrm{t \in T^{on}}} \mathrm{c_t^{env}} e_t + \mathrm{c_t^{ch}} e_t \qquad (1.\mathrm{III})$$

Equations (2) guaranty that the energy charged during time interval *t* is not greater than the maximum allowed depending on the charging infrastructure; equations (3) assure that the state of charge is in between the minimum requested by the end-user to allow its committed trips and the technical maximum of the battery; equations (4) defines the state of charge for each time interval *t* based on the previous state of charge and the difference between the charged energy and the discharged one. The resulting model is a linear programing problem which can be easily solved with commercial software.

Data source

<u>Data for the electricity consumption and grid mix composition</u>

The emissions of pollutants in the electricity generation have been modelled using the Spanish electricity grid mix considering two extreme scenarios. The first scenario considers an electricity mix where the share of fossil fuel is predominant (called High Level) and a second scenario where the share of renewable sources for electricity generation (mainly wind power) is predominant (called Low Level).

Data of the hourly composition of the electricity grid mix has been extracted from the recorded data of Red Eléctrica Española (REE- the National Electricity Network) in year 2013. For the High level Week, data refers to the week comprehended between 21st and 27th of February (week with high electricity demand, mainly covered by fossil fuels energy sources). For the Low Level Week, data refers to the week comprehended between 7^{th} and 13^{th} of March (week with high electricity demand but mainly covered by renewable energy sources such as wind power).

Vehicle and charging patterns selection

As has been introduced, smart charge algorithms could not be implemented if they do not guarantee end-users needs. For taking this aspect into consideration data from electric vehicle trip and charge events has been used. Specifically, the hours in which the electric vehicle is parked and plugged in and the energy needs for performing the scheduled trips during the different hours of a specific day are introduced in the model; this data is based on real electric vehicle Spanish user behaviour (Corchero, C., 2014).

Economic evaluation of the results obtained

As it has indicated in the Goal and Scope section, the economic evaluation of the results obtained covers two different aspects. On one hand, it has been evaluated the electricity final purchase cost. On the other hand, it has been evaluated the potential costs originated by certain pollutant emissions due to the electricity generation.

For the first approach, data related to the daily electricity final cost has been applied using REE reference. In the High Level Week, electricity prices oscillated between 92,49€/MWh and 9,24 €/MWh. During the Low Level Week, electricity prices oscillated between 117,37€/MWh and 10,84€/MWh.

For the second approach, in order to convert the environmental impacts into economic values that allow the economic comparison between negative externalities the instrument used has been the Directive 2009/33/EC[5]. The main objective of this text is to stimulate the market for clean road vehicles by means of promoting public procurement of energy-efficient vehicles for public administrations in need of acquiring a road vehicle. In this sense the directive intends to create a European market of this kind of vehicles by harmonising criteria applied at a European level. One way to create this market is to introduce in public procurement criteria for road vehicles environmental effects, as economic externalities that must be taken into account. The way of applying this idea is including mandatory lifetime costs for CO_2 emissions and other pollutant emissions which are justified as a measure that does not impose higher costs but anticipates operational lifetime costs in the procurement decision, as well as internalizing environmental costs. The information about the costs of environmental externalities has been provided by the European Commission project ExternE Study (Bickel, P. [et al.], 2005), the Commission Clean Air for Europe (CAFE) Programme (Holland, M. [et al.], 2005) and the HEATCO Study (Bickel, P., 2006).

This directive proposes the following values (Table 1) and guidelines to calculate the environmental and energetic externalities in the operational lifetime costs of road transport vehicles:

Table 1: Cost for emissions in road transport

CO_2	NO_X	NMHC	Particulate matter

[5] Directive 2009/33/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of clean and energy-efficient road transport vehicles

0,03-0,04 EUR/kg	0,0044 EUR/g	0,001 EUR/g	0,087 EUR/g

Taking into account the values expressed in Table 1, it has been possible to calculate the hourly cost of the charging activity, considering the hourly life cycle emissions of these pollutants for each of the electricity sources.

Results

The following sections report the results coming from the optimisation exercise of the charging activities considering the 3 scenarios above described: optimisation of the environmental impact, optimisation of the electricity cost, optimisation of the costs of the pollutant emissions occurring in the electricity generation.

Optimisation of the environmental impact

This first section reports the environmental impact profiles when optimisation is carried out to minimise the environmental impact of the charging activity, for both High Level and Low Level week: the orange line describes the hourly evolution of the value of the environmental impact, expressed as European Person Equivalent as described in the normalisation section. The coloured bars described the hourly energy charged: blue bars show the energy charged when no optimisation algorithm is applied, and therefore the charger will supply the required energy to the vehicle taking into account the plugging time and the state of the battery. The red (in High Level Week)-figure 1 and the green (Low Level Week figure 2) bars show the energy charged using the optimisation algorithm. In these cases, results show how the charging activity is focused on the hours with the minimum environmental impact.

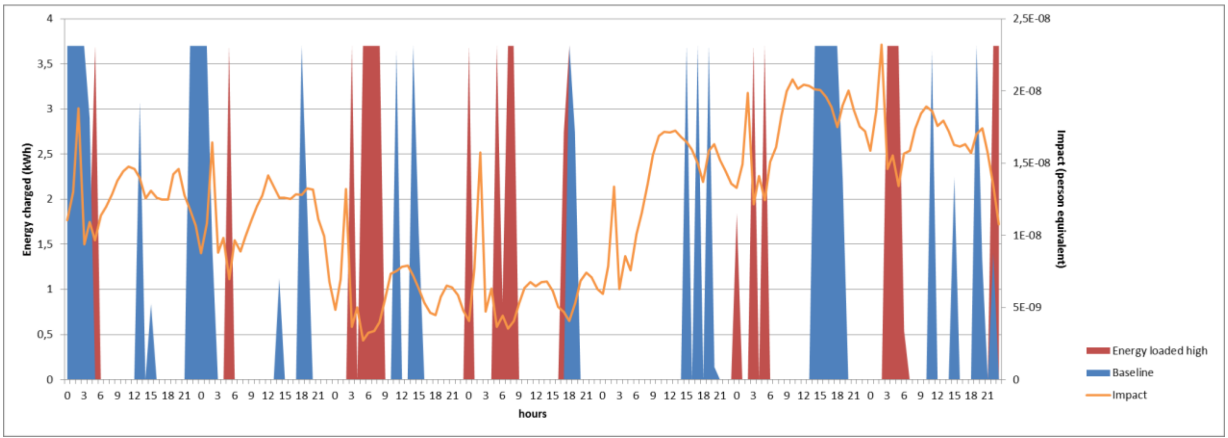

Figure 2: Energy charged and environmental impact during High level Week

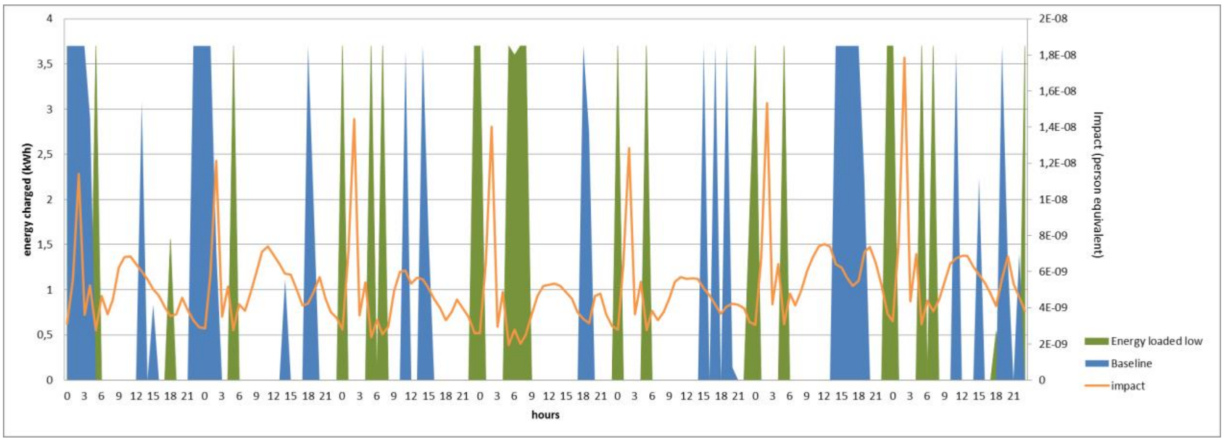

Figure 2: Energy charged and environmental impact during Low level Week

The optimized charging patterns lead to a reduction of the environmental impact around 54% compared to a baseline scenario where no optimisation was performed.

Optimisation of the electricity cost

This second section reports the electricity cost profiles when optimisation is carried out to minimise it due to the charging activity, for both High Level and Low Level week: the orange line describes the hourly evolution of the value of the electricity cost, expressed in Euros. The coloured bars described the hourly energy charged: blue bars show the energy charged when no optimisation algorithm is applied, and therefore the charger will supply the required energy to the vehicle taking into account the plugging time and the state of the battery. The red (in High Level Week)-figure 3 and the green (Low Level Week figure 3) bars show the energy charged using the optimisation algorithm. In these cases, results show how the charging activity is focused on the hours with the minimum electricity costs.

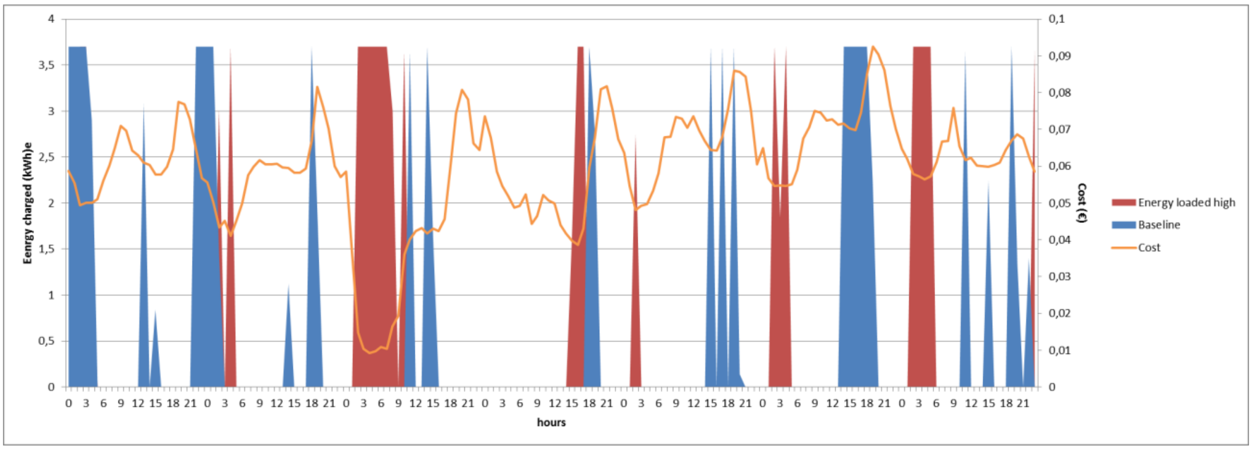

Figure 3: Energy charged and costs during High level Week

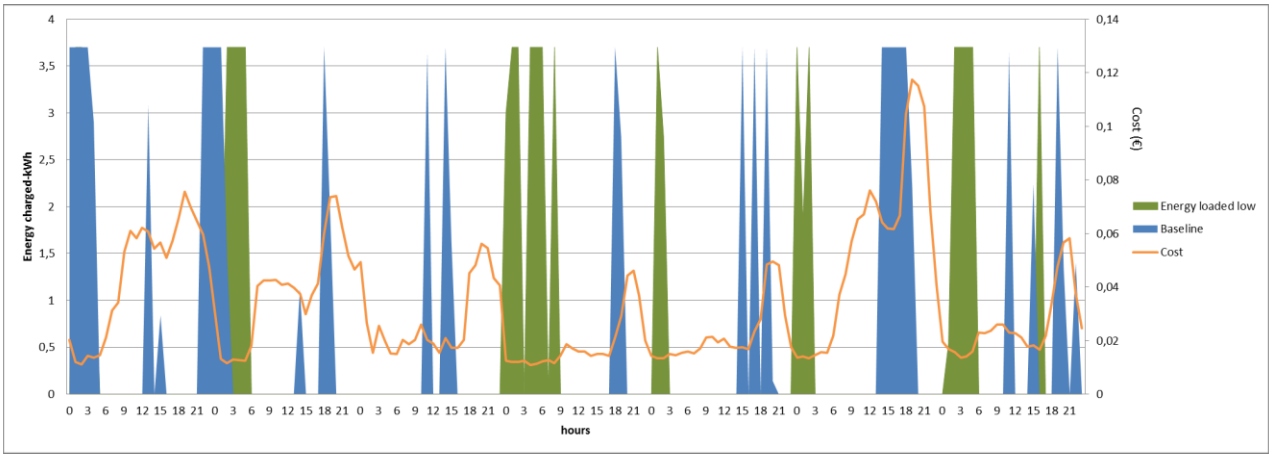

Figure 4: Energy charged and costs during Low level Week

The cost optimisation focused charging patterns lead to a reduction of the costs around 50% during the High Level Week compared to a baseline scenario, and 73% reduction for the Low Level Week compared to the baseline scenario where no optimisation was perfomed.

Optimisation of the cost of the pollutant emissions

This third section reports the pollutant emissions cost profiles when optimisation is carried out to minimise it due to the charging activity, for both High Level and Low Level week: the orange line describes the hourly evolution of the value of the pollutant emission costs, expressed in Euros. The coloured bars described the hourly energy charged: blue bars show the energy charged when no optimisation algorithm is applied, and therefore the charger will supply the required energy to the vehicle taking into account the plugging time and the state of the battery. The red (in High Level Week)-figure 5 and the green (Low Level Week figure 6) bars show the energy charged using the optimisation algorithm. In these cases, results show how the charging activity is focused on the hours with the minimum pollutant emissions cost profile is encountered.

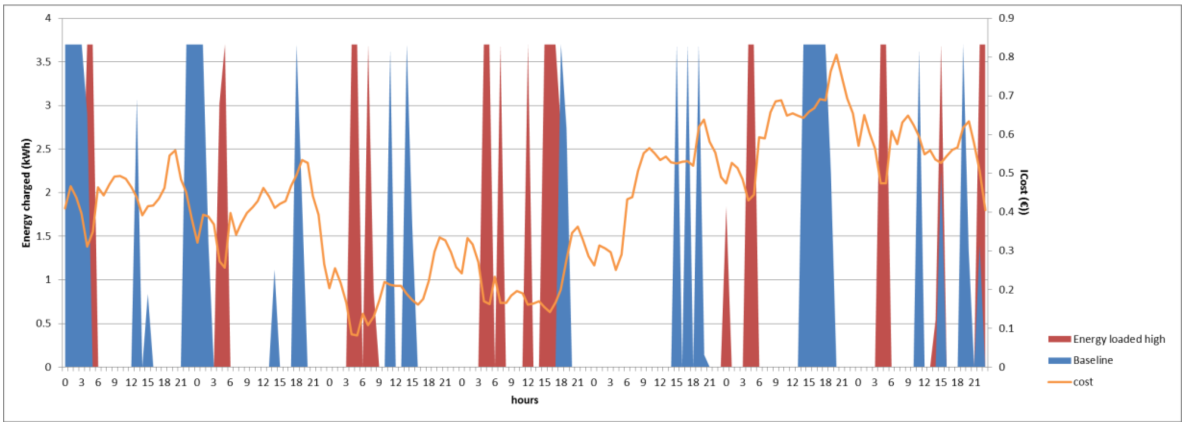

Figure 5: Energy charged and emissions costs during High level Week

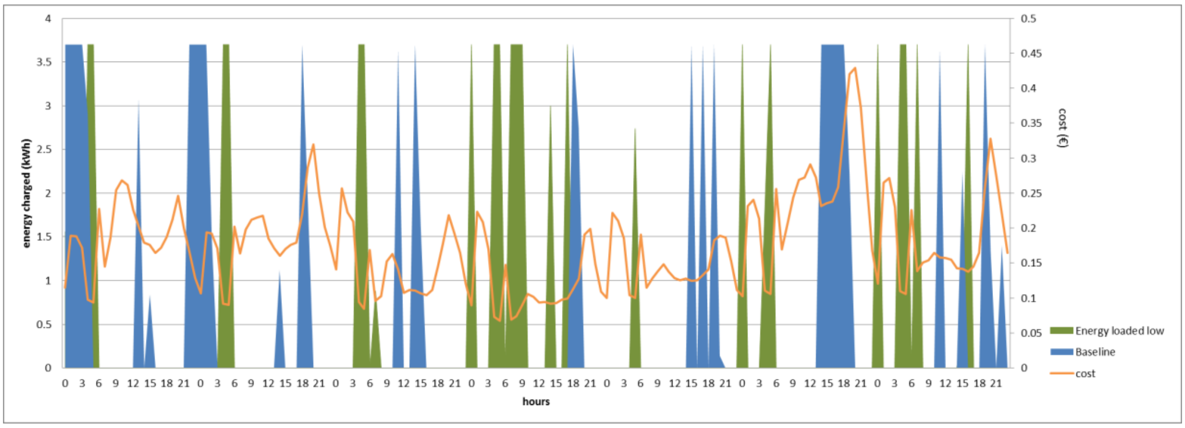

Figure 6: Energy charged and emissions costs during Low level Week

For both High Level and Low Level weeks, the pollutant emission cost optimisation focused charging patterns lead to a reduction of the costs around 57% compared to the baseline scenario where no optimisation was performed.

Results discussion

As shown in the previous section, the optimisation exercises lead to a significant decrease in the environmental impact or costs when applying an appropriate algorithm in the charging event.

However, in order to interpret the results from an environmental perspective, a further analysis has been carried out where those results expressed in economic terms have been translated into environmental impacts. This operation has been done using the optimize charging pattern result of the optimisation exercise (that is to say, the hourly energy values that should be consumed in order to obtain the optimized results for costs and emissions cost) and multiplying each hourly consumption by the normalised environmental impact value of this specific hour.

The aim of this analysis is to understand to what extent each of the cost optimisation exercises contributes to the decrease the environmental impact associated to the charging.

The figure 7 below shows the value of the environmental impact for the High Level and Low Level Week for the following cases:

- Case 0: Baseline scenario, marked as 100% reference, where no optimisation algorithm is applied
- Case 1: Environmental optimisation scenario, where optimisation algorithm is applied to minimize the environmental impact
- Case 2: Pollutant emissions cost optimisation, where optimisation algorithm is applied to minimize the costs due to the emissions of pollutants, and the results are converted into environmental impact

- Case 3 Electricity cost optimisation, where optimisation algorithm is applied to minimize the costs due to the electricity, and the results are converted into environmental impact

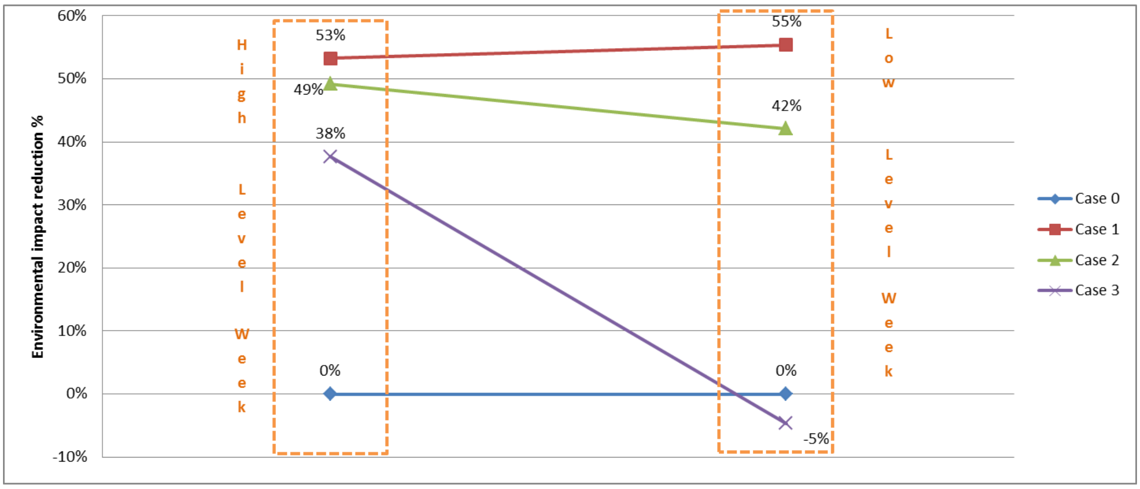

Figure 7: Combined environmental impact optimisation

From the figure 7 it can be depicted that the maximum reduction of the environmental impact is achieved when applying an optimisation algorithm specifically focused on the minimisation of the environmental impact (Case 1) (reduction of 53% and 55 for High Level and Low level week respectively). However, when applying an algorithm that aims at minimizing the pollutant cost emission (case 2), reductions are significant (49% and 42 % respectively).

On the contrary, when applying an algorithm for cost optimisation (case 3), reduction is only found for the High Level Week, while for the Low Level Week, an increment of the environmental equal of 5 % is found. Therefore, this algorithm is not suitable to achieve a combined economic and environmental optimisation.

Conclusions and further research

The study shows how introduction of algorithms in the charging patterns enables a substantial saving in costs and environmental impacts taking into account a Life Cycle Perspective, where all the upstream and downstream aspects related to the electricity generation are considered.

Regarding the environmental optimization, results show that impact could be reduced around 53-55% compared to the baseline scenario, while for the electricity cost optimization results, results show that they could be reduced from 50 to 73% compared to baseline scenario.

The initiative of the Directive 2009/33/EC to internalize the economic costs provoked by the environmental externalities facilitates comparison between different technologies under a monetary unit base. The results obtained applying this methodology express very well the classification of environmental impacts between the different technologies and the existing gap between them. Where the values suggested by the directive are used in the optimisation algorithm, cost reduction is around 57% with respect to the baseline scenario.

However, this directive does not monetize all the pollutant emissions occurring during the generation of electricity throughout its lifecycle, since it is transport emissions oriented. For this reason a different approach has been adopted in order to combine results of the three optimization exercises converting the results into an environmental impact value.

With this approach, and focusing on the achievement of a minimum environmental impact, results have shown that the maximum reduction is achieved when applying an optimization algorithm specifically focused on the minimization of the environmental impact (Case 1) or, for a good enough result, applying an algorithm that aims at minimizing the pollutant cost emission (case 2). On the contrary, when applying an algorithm for cost optimization (case 3), reduction is only found for the High Level Week, while for the Low level Week, an increment of the environmental equal of 5 % is found. Therefore, this algorithm is not suitable to achieve a combined economic and environmental optimization.

Future work will be oriented to a more exhaustive economic evaluation of impacts with more categories as for example energy consumption, including renewable energy consumption and with a complete monetized profile of the emissions occurring in the life cycle of the electricity generation. The study could finally lead to a cost-benefit analysis to quantify environmental and social impact of the electric vehicle expressed in monetary unit. This cost-benefit analysis should raise different penetration scenarios for electric vehicle, in order to try to quantify the social benefits and to find the optimum point for public investment in this technology.

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