International Conference on Renewable Energies and Power Quality (ICREPQ'17)
Malaga (Spain), 4th to 6th April, 2017
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.15 April 2017

Reduction of CO_2 emissions using RES to recharge EVs: the Spanish case

A. Triviño[1], M. Longo[2] and F. Foiadelli[2]

[1] Department of Electrical Engineering
E.T.S.I.I., Universidad de Málaga
C/ Doctor Ortiz Ramos s/n, 29071 Málaga (Spain)
Phone/Fax number:+0034 986 812685, e-mail: **atc@uma.es**

[2] Departament of Energy
Politecnico di Milano
Via la Masa, 34, 20156 Milan (Italy)
Phone, fax: +39 02 2399 3759 email: **michela.longo@polimi.it**, **federica.foiadelli@polimi.it**

Abstract. This paper focuses on the field of transportation, which is greatly responsible for air pollution, mainly in cities and urban areas such as towns, airports and seaports. This work analyses the feasibility of integrating EVs and RES, focusing on the air pollution reduction benefits. To do so, we use the data collected in Spain. After an analysis of the energy production by RES and the size of the vehicle fleet over time in Spain, an evaluation of the number of completely green EVs as a function of the State Of Charge (SOC) and green energy used to charge the EV is proposed. Finally, the expected emissions reduction is derived when the vehicle fleet is changed by fully EVs fuelled with the wind and photovoltaic sources currently installed in Spain.

Keywords

Electric vehicles; air pollution, renewable energy sources, environmental, citizen

1. Introduction

World Health Organization reports that in 2014, approximately 7 million people died because of air pollution exposure. This represents one in eight of the global total of deaths, which doubles previous estimations and confirms that air pollution is now the world's largest single environmental health risk. In Europe alone, approximately 40 million people are exposed to harmful levels of air pollution [1]. Thus, reducing air pollution could be the key to saving millions of lives [2, 3].

The environmental benefits and reduced dependency on oil are certainly the most significant reasons that are prompting the extensive use of Renewable Energy. In the transportation sector, Electric Vehicles (EVs) constitute a partial solution to mitigate the environmental problems as well as other electrical problems [4]. However, their supply should also be considered to have a completely environmentally-friendly solution [5,6]. Supplying electric vehicles using renewable energies is a clean and sustainable means to approach the economic, political and environmental threats. This study addresses the feasibility of this solution. In particular, it focuses on the practicality of using EVs exclusively fueled by Renewable Energy Sources (RESs). By RES, we include wind and photovoltaic energies. In this scenario, the vehicle is totally green and, consequently, it does not produce any pollution, including CO_2. Specifically, we derive the reduction of the daily emissions of this type of air pollutant when using RES-fueled EVs in the Spanish scenario.

The remainder of the paper is structured as followed. Section 2 reviews the status of RES in Spain. Section 3 analytically derives how many EVs can be charged with the current situation of RES in Spain. Basing on this number and on drivers behaviours, Section 4 shows the computation of the CO_2 reduction. Finally, Section 5 draws the main conclusions of our work.

2. Status of RES deployment in Spain

Renewable energy sources or RES allow sustainable development for an indefinite period without damaging nature. The most important sources of renewable energy are geothermal, solar, thermal and thermodynamic solar, photovoltaic (PV), wind, biomass and biofuels. The use of these green energy sources contributes to solving the problem of global warming and reducing pollution, in particular CO_2 emissions. In this work, the focus is on the spread of renewable energy in Spain. Figure 1 reports the percentage of renewables as a share of the total primary energy supply (TPES) in Europe. It can be observed that this value is between 25% and 50% in Spain.

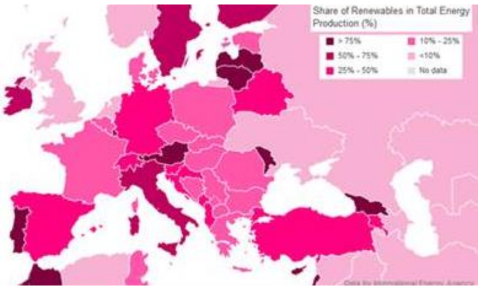

Fig. 1. CO_2 emissions/TPES from fuel combustion [6]

In Spain, PV and wind energy have fulfilled more than a third of the country's total electricity demand. In 2014, the share of wind energy was approximately 22% while that of PV was 3.3%. In particular, the wind energy sector has been consistently increasing. In 2013, wind energy had the highest share among all technologies in the country's generation mix. Renewable energy technologies, in particular wind, solar PV and solar thermal, represented 49% of the total power generation capacity added in 2013. In contrast, generation from coal and natural gas-based power plants and nuclear power generation fell in 2013 [7]. This aspect is very important for the environment because greenhouse gas emissions from the electricity sector in the Spanish peninsula fell 23.1%. Figure 2 shows the production of renewable and non-renewable energy in Spain over time.

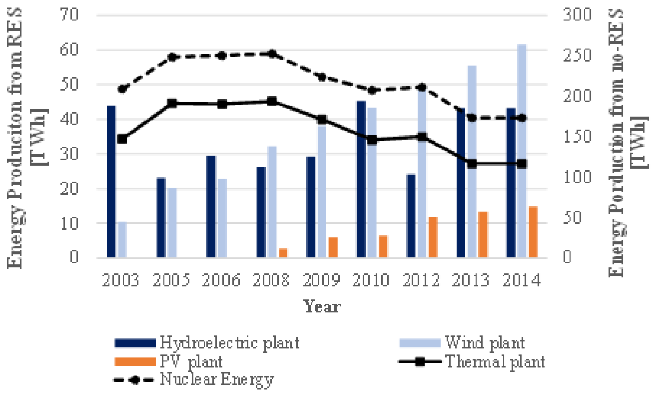

Fig. 2. Energy production by RES and non-RES in Spain in different years [6]

Since renewable sources are geographically distributed around that country, it is possible to calculate the spatial exploitation E_s of their potential in Spain as a ratio between the energy production and the total surface area of the country. The results, calculated for the year 2014 in Eq. 1, are:

$$E_s = \frac{RenewableEnergy}{Area} = \frac{111919\ GWh}{505510\ km^2} \qquad (1)$$

$$E_s = 0.221\ GWh/km^2$$

We can also compute the exploitation degree by considering the population (E_p). In this way, we derive the ratio between renewable production and the population, as shown in Eq. 2:

$$E_p = \frac{RenewableEnergy}{Population} = \frac{111919\ GWh}{46.6\ Mpeople} \qquad (2)$$

$$E_p = 0.0024\ GWh/person$$

Analysing these two indicators we can state that Spain presents a good diffusion of RES. This aspect is very important because the new energy produced is totally green and the situation also leads to improvements in terms of quality of life. However, the energy produced from renewable sources is insufficient for all the needs of the country. To increase the exploitation of renewable sources, the only option is to diversify the primary sources. In particular, it will be required to increase the photovoltaic systems in Spain.

3. Vehicle Fleet and Potential EVs Recharged with RES

The transport sector is a major contributor to air pollution in most nations, although the industrial sector releases a large percentage of pollutant emissions into the air [8]. At this moment, in the transport sector, different types of fuel are used, such as gasoline or diesel. Obviously, when speaking of gasoline cars or diesel, it is natural to think that they might cause more environmental harm than electric vehicles. In fact, the absence of the tailpipe is a clear edge for EVs because in this case, there are no emissions, no pollution and no environmental problem apparently. However, it is important to evaluate the environmental impact of recharging these vehicles too. Although the EVs do not cause any environmental damage on the road during their use, there are consequences on the electric grid because it is necessary to increase the production of energy, and clearly, the emissions are incremented. For this reason, to make the EVs totally green with zero pollution and emissions, it is a demand to recharge these vehicles using only renewable energy.

The number of new hybrid vehicles in 2014 was 12082 in Spain [9]. If we look at purely electric vehicles, the number is 1463. Figure 3 shows the evolution of the vehicle fleet. Precisely, 43% are fueled with gasoline, 51% with diesel and 6% with another type of fuel in 2014.

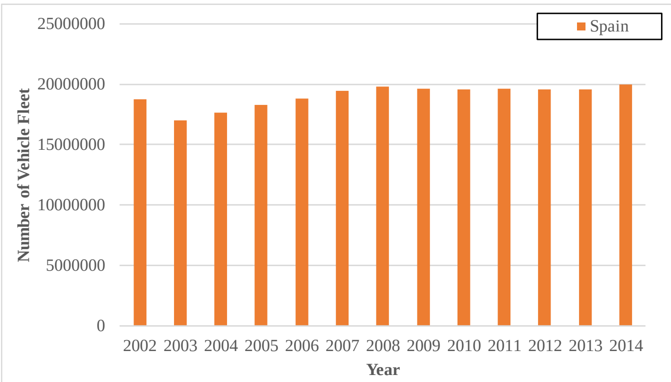

Fig. 3. Vehicle fleet over different years in Spain

For electric vehicles, we assume that they have a total battery energy capacity ($C_{battery}$) of 24 kWh, which is an extended commercial feature. The energy that must be provided to a vehicle depends on the difference between the initial and the final States of Charge of the battery (ΔSOC). The energy required (E_{req}) for each type of EV is computed using Eq. 3:

$$E_{req} = \Delta SOC \cdot C_{battery} \qquad (3)$$

where $C_{battery}$ is the typical value of battery capacity of the electric vehicles and ΔSOC is the difference in the states of charge, which can be derived from the users patterns. For example, in the morning, ΔSOC will be equal to 100%.

To determine the charging time, it is necessary to refer to several cases of output power offered by the current chargers [10]. There are the following 4 charging scenarios:

- Case 1. Single-phase system with current up to 16 A, which implies a maximum theoretical power (P_{th}) equal to 3.7 kW.

- Case 2. Three-phase system with current up to 32 A, leading to a maximum theoretical power (P_{th}) power of 7 kW.
- Case 3. Three-phase system with current up to 32 A, with a maximum theoretical power (P_{th}) power equal to 11 kW.
- Case 4. Three-phase system with current up to 32A, with a maximum theoretical power (P_{th}) power equal to 22 kW.

For each case, different potential values of ΔSOC, from 1 to 0.1, have been considered. Different potential values allow for the consideration of all situations with different states of charge depending on the use of the vehicle. Given the theoretical power (P_{th}) supplied from the charging station, the power (P_{real}) accumulated in the car batteries can be computed as Eq. 4:

$$P_{real} = P_{th} \cdot \eta \qquad (4)$$

where the efficiency of the charging system (η) is assumed to be equal to 85%. Using Eq. 3 and Eq. 4, it is possible to calculate the time required (a very important factor) to recharge the battery (t_{req}) as follows:

$$t_{req} = E_{req}/P_{real} \qquad (5)$$

Table I indicates the time values for recharging the electric vehicle depending on the state of charge (ΔSOC) for the four recharging cases. It can be noted that Case 1 presents a higher time with respect to the other cases. This corresponds to the case of recharging at home, for example when the vehicle is charged during the night. For instance, when the EV has ΔSOC equal to 0.6, t_{req} is 4.6 hours. Nevertheless, considering the median working time during which the vehicle is parked, this value of t_{req} becomes irrelevant.

Table I. - Recharge time for EVs for different ΔSOC and different cases

ASOC (%)	Case 1	Case 2	Case 3	Case 4
100	7.63	4.03	2.57	1.28
90	6.87	3.63	2.31	1.16
80	6.10	3.23	2.05	1.03
70	5.34	2.82	1.80	0.90
60	4.58	2.42	1.54	0.77
50	3.82	2.02	1.28	0.64
40	3.05	1.61	1.03	0.51
30	2.29	1.21	0.77	0.39
20	1.53	0.81	0.51	0.26
10	0.76	0.40	0.26	0.13

Another relevant aspect is the distance that must be covered by EVs. Given a battery charge (E_{req}), the maximum distance that a car can travel ($D_{travelEVs}$) is computed according to Eq. 6:

$$D_{travelEVs} = \frac{E_{req}}{C_{ave}} \qquad (6)$$

where the average consumption (C_{ave}) is equal to 0.213 kWh/km. This value is derived from the average consumption of electric vehicles (EPA) [7]. Table II shows the possible distance travelled ($D_{travelEVs}$) in a day for different states of charge (ΔSOC).

Table II.- Travelled distances for EVs with different ASOC

ΔSOC (%)	E_{req} [kWh]	Distance per day [km/day]
100	24	112.68
80	19.2	90.14
60	14.4	67.61
40	9.6	45.07
20	4.8	22.54
10	2.4	11.27

The next step is to study the ΔSOC that an electric grid based on renewable energies can support. The data collected according to the assumptions described above have been processed using Minitab software to estimate the correlation between the number of electric vehicles fully fueled by the RES identified in Section 2, difference in state of charge (ΔSOC) and percentage of energy obtained from renewable sources that is required to support that number of EVs with the ΔSOC [11]. In particular, attention is paid to photovoltaic systems and wind farms because these are very widespread in Spain.

The correlations have been characterized using the contour plot. This representation permits exploration of the potential relationship between three variables, in this case RES, ΔSOC and EVs. Contour plots display the 3-dimensional relationship in two dimensions, with x- and y-factors (predictors) plotted on the x scale (different percentages of PV systems and wind farms) and y scale (different states of charge) and response values (the possible number of EVs fueled with RES) represented by contours. Figure 4 shows a contour plot exploring the potential relationship between ΔSOC and the different percentages of energy obtained from wind farms and photovoltaic systems for Spain. It takes into account the current deployment of these types of RES installations.

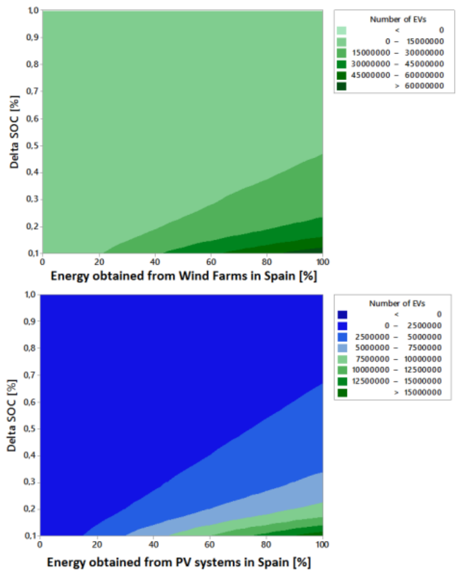

Fig. 4. Number of EVs as a function of ΔSOC and Energy

It is necessary to consider different percentages of green energy from diverse renewable sources as their use may not be used for EVs exclusively. For example, in an industry the energy may be used not only for the company fleet but also for lighting, heating, etc.

For the ΔSOC assumed in this study as reported in Table I, which is derived from the most popular batteries' features,

the maximum number of EVs that it is possible to recharge using 80-100% of the energy provided by photovoltaic systems is approximately 15-20 million vehicles. However, the situation is different when it employs the energy obtained from wind farms. In fact, the number of EVs is equal to 50 million in the range of 80-100% RES for this kind of source. Considering a high percentage of RES in the grid, the number of electric vehicles that can be fueled by green energies is also large. A lower rate of energy used from renewable sources, for example 20-40%, will lead to a decrement in the number of vehicles exclusively propelled by RES. However, this number undoubtedly helps to reduce air pollutants.
To determine the reduction of the pollutant emissions, the number of vehicles has been estimated at a minimum of 2.5 million to a maximum of 15 million. These values depend on the distribution in the region of the renewable sources.

4. Expected Reduction of emissions derived from the change of the vehicle fleet

Carbon dioxide (CO_2) is the primary greenhouse gas emitted through human activities. This is naturally present in the atmosphere as part of the Earth's carbon cycle. The main human activity that emits CO_2 is the combustion of fossil fuels (coal, natural gas, and oil) for energy and transportation. With EVs completely fueled by RES, we can suppress the pollutant emissions due to tailpipes and due to the energy generation. We now proceed to quantify the CO_2 reduction. Firstly, it must be considered that the population travels along different distances on different types of road (D_t). Thus, different distances have been assumed for different roads with the following variables:

- km_H: kilometers travelled on a highway;
- km_R: kilometers travelled on a rural road;
- km_U: kilometers travelled on an urban road;

$$D_t(\Delta SOC, E_{req}) = km_H + km_R + km_U \qquad (7)$$

Based on an analysis of mobility patterns [13], it is possible to express, in Eq. (8), the distance that people drive in one day in every road type as a percentage of the total distance:

$$D_t(\Delta SOC, E_{req}) = D_t \cdot \gamma + D_t \cdot \beta + D_t \cdot \alpha \qquad (8)$$

where γ is equal to 15%, β is equal to 35% and α is equal to 50%. These variables (γ, β and α) are derived from the daily habits of the people. Eq. (6), which obtains the effective vehicle kilometers as a function of the difference in state of charge, is very important. From this equation, based on the different percentages of γ, β and α, the kilometers travelled on different types of road are obtained. Table III shows the distances for difference in state of charge (ΔSOC) and road (urban, rural and highway).
Considering the total vehicle fleet for Spain, it is supposed that 50% of the vehicles are fed with gasoline and other 50% fueled with diesel. Table IV shows different emission factors for three types of road (Highway (H), Rural (R), Urban (U)) for two vehicles fueled with Gasoline (G) and Diesel (D).

Table III.- Distance for EVs obtained with different type of roads

ΔSOC [%]	Erich [kWh]	Urban road [km/day]	Rural road [km/day]	Highway [km/day]
100	24	56.34	39.44	16.90
90	21.6	50.71	35.49	15.21
80	19.2	45.07	31.55	13.52
70	16.8	39.43	27.61	11.83
60	14.4	33.81	23.66	10.14
50	12	28.17	19.72	8.45
40	9.6	22.54	15.77	6.76
30	7.2	16.90	11.83	5.07
20	4.8	11.27	7.89	3.38
10	2.4	5.64	3.94	1.69

Table IV.- Travelled distances for EVs with different ASOC

Road Type	Fuel	CO_2 [mg/km]
H	G - Gasoline	156
	D – Diesel	222
R	G - Gasoline	148
	D – Diesel	188
U	G - Gasoline	190
	D – Diesel	247

With these chemical features, we study the reduction in the emissions for each pollutant when using EVs recharged with renewable energy. Figure 5 reports the expected daily reduction of CO_2 emissions when incorporating full-RES EVs. This graphic shows the relationship as a function of the number of vehicles and ΔSOC. In particular, wind farms and photovoltaic systems are the RES taken into account.

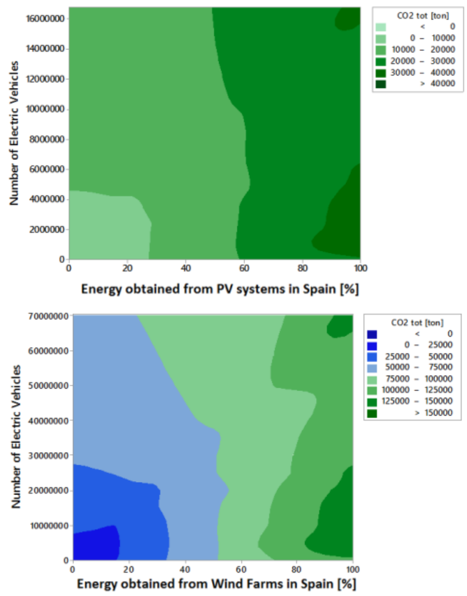

Fig. 5. CO_2 emission as a function of EVs and Energy obtained from different RES in Spain]

We can observe that we use 80-90% of energy obtained from PV systems in Spain, it is possible to avoid 30,000 – 50,000 tons of CO_2 being emitted into the atmosphere whereas if energy is obtained from wind farms, it is possible to avoid 100,000 – 125,000 tons of CO_2 emissions. Instead, if one considers the case in which only 20-30% of the energy obtained from RES is used to fuel electric vehicles, the quantity of avoided CO_2 emissions is 10,000-20,000 tons with PV systems, whereas for wind energy, the reduction on CO_2 emissions is equal to 25,000-50,000 tons.

4. Conclusion

The aim of this work is to study the potential reduction in the emissions of air pollutants obtained by employing Renewable Energy Sources (RES) to charge Electric Vehicles (EVs) when they replace the current vehicle fleets fueled with gasoline and diesel. Taking into account the present deployment status (in particular for PV systems and wind farms) in Spain, this work computed the reduction that fully RES-fueled EVs could produce in terms of CO_2. For this study, it has been necessary to make assumptions. The first step has been to consider the characteristics of the electric vehicle (battery, state of charge - ΔSOC, etc.) and to understand the effective number of vehicles that could be fueled using different percentages of energy obtained from different RES. In the case of using 80-90% of the green energy, the number of vehicles is approximately 45 million-60 million electric vehicles when fueled by wind farms. Alternatively, when employing just 20-30% of the green energy (the remaining part of the energy could be used for other applications such as lighting), the number of vehicles that can be supported by wind farms is approximately 15 million-30 million electric vehicles.
The results show the avoided daily emissions as a function of different percentages of energy obtained from RES, different ΔSOC and the practical distances traveled with electric vehicles. The work done shows that incorporating fully green EV, that is, recharged by RES can lead to a significant reduction of the CO_2 emissions. We have assumed that only 20-30% of the RES are used for this purpose. A notable decrement will be achieved when the share of RES used to recharge the EV is increased.

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