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Evaluation of Emissions of CO_2 and Air Pollutants from Electric Vehicles in Italian Cities

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Abstract

The paper analyzes data about recharge of electric cars in Rome during 2013 as a part of a national research project (P.R.I.M.E.). The electric vehicles were recharged through the public Enel Distribuzione recharging infrastructure. For each recharge, the initial and final time were registered together with the electricity absorbed from the grid. The total number of recharges was about 7700. The first step of the investigation is the statistical analysis of the distribution of recharges in daily time slots in order to analyze the recharge behavior of Italian drivers. For each day and for each time slot, literature data from the Italian national grid operator (Terna) were used to retrieve the energy mix used to produce electricity in that day and in that time slot. In the third step, electricity generation mixes were used to obtain emission factors for greenhouse (CO_2) and pollutant emissions (CO, NO_x, HC and particulate). Using information about the electric consumption of vehicles registered in Rome, the emission factors in g/km were obtained and compared with the limits set by European legislation for conventional (gasoline and diesel).

Keywords: electric vehicles, environmental impact, electricity generation mix, pollutant emissions

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1. Introduction

Grid-connected transportation systems have long been proposed as a potential solution to reduce greenhouse and pollutant emissions [1,2,3]. Among them, Battery Electric Vehicles (BEVs) are the most interesting solution. Despite their environmental advantages, significant technological barriers like battery low capacity and high costs [4] and the absence of a widespread charging infrastructure still limit the extensive adoption of plug-in vehicles [3, 5, 6]. By analyzing the results of a survey about the usage of electric vehicles, Egbue et al. [7] found that one of the social barriers to the usage of electric cars is that drivers are not convinced that EVs are better than some currently available conventional vehicles. For this reason, the goal of the authors in the present investigation is to quantify the emissions of pollutant and greenhouse gases produced by electric vehicles and compare them with legislation limits for conventional vehicles.

To evaluate the environmental impact of a transportation system, it is necessary to consider the correct energy pathway [8]. The well-to-wheel (WTW) analysis takes into account the total primary energy consumption yielded by the vehicle for each kWh of energy given at the wheels, including all the steps covered to fill the on-board energy tank (WTT) and the subsequent onboard energy conversion to move the vehicle wheels (TTW), as highlighted by Hu et al. [9].

From a Tank-to-Wheel (TTW) point of view, electric transportation means do not produce either pollutant or greenhouse gases, while the Well-to-Tank (WTT) emissions are strongly dependent on the electricity generation mixes of the country [10-15]. Doucette et al. [10] used numerical simulation of electric vehicles to evaluate the electric consumption and the corresponding CO_2 emissions, according to the electricity generation mixing of different countries. They found that, for countries where electricity has high CO_2 intensity (e.g. China and India), the WTW carbon emissions of BEVs can be higher than those of conventional vehicles.

In addition to carbon dioxide it is important to evaluate the emissions of nitrogen oxides (NO_x), Volatile Organic Compounds (VOCs), carbon monoxide (CO), particulate matter (PM), sulfur oxides (SO_x). NO_x are dangerous for human health in urban environments, but are also responsible for acid rain [16]. Under conditions of strong solar irradiation they also cause secondary photochemical reactions that create the "photochemical smog”. CO causes severe health problems and can also contribute to global warming [17]. As for particulate matter, atmospheric particulate has different effects on human and animal health, depending on the size of the dust. Among the disorders attributed to the fine and ultrafine PM there are acute and chronic pathologies of the respiratory (asthma, bronchitis, allergies, cancers) and cardiovascular (worsening of cardiac symptoms in susceptible individuals). SO_x determines the intensification of chronic diseases in the most exposed such as older people, particularly asthmatics, and children [18]. Finally, VOCs cause irritation of eyes, nose, throat, liver damage, kidney damage and central nervous system and reduce productivity of agriculture [16].

Electric vehicles have a direct positive impact on pollution in urban centers because the problem of emissions is moved from urban centers to fossil fuel chimneys, that are usually outside the cities. Moreover, emissions of power plants are more easily controlled than vehicle tailpipes [2].

Menga et al. [19] compared the emissions of battery electric vehicles with conventional passenger cars by considering literature values of consumption and average Italian electricity generation mix for the production of electricity. Donateo et al. [20, 21], analyzed the electric consumption of a Smart ED and found that it is affected strongly by the use of auxiliaries and weakly by the vehicle speed profile.

Since the electricity generation mix changes over the day and over the year, it is important to analyze the charging habits of BEVs users and, eventually, control them to minimize emissions and costs [2]. In fact, the habit of recharging vehicles at home increases emissions from the grid because of the coincidence between afternoon peaks and drivers arriving at home [2]. In the future, this increase in the peak load could require more generating capacity with an increase of costs and emissions associated to the use of plug-in vehicles. Today the amount of electricity used to recharge electric vehicles in Italy is quite negligible with respect to the total electricity demand as will be shown later in the paper. Thus, electric vehicles are assumed to have no effect on electricity demand (and on the corresponding electricity production mix).

The idea of smart charging has been suggested in literature to charge the vehicle when it is most beneficial, which could be when the environmental impact is lowest [22, 24], demand is lowest [22, 25, 26, 27, 28] or electricity is at its lowest price [25, 27, 28]. In particular Gan et al. [29] conceived a protocol to optimize electric vehicle charging to fill the overnight electricity demand valley. In their study they proposed a protocol that needed no coordination among electric vehicles, with low communication and computational capability needs. Results of their simulations demonstrated convergence to optimal charging profiles. Hu et al. [30] presented a multi-objective (charging time and charging loss) optimal charging protocol for two types of Li-ion batteries. The influence of different parameters (charging voltage threshold, temperature, health status of batteries etc.) on the charging were analyzed and a comparison with other models, that are not able to describe the entire battery behavior, was performed. They found that the use of the upper cut-off voltage to limit the battery voltage in charging benefits in minimizing the charging time and energy loss and that a relatively high is preferred to optimally tradeoff the charging time and energy loss.

In a previous investigation [31], the authors proposed a methodology to quantify the environmental impact of electric vehicles that takes into account the actual electric consumption measured on board, the losses of electricity in the grid and the losses during recharge due to the battery cooling system. The actual mixing of sources used to generate electricity for each recharge was used instead of average values [19]. The methodology was applied to a single Smart ED tested for six months at the University of Salento. The same methodology is used here to evaluate the environmental impact of the whole fleet of electric vehicles recharged in Rome in 2013.

Note that the analysis presented here is not a full WTW approach because the boundary for energy paths is set at the electricity generation plants. The recovery and transport of fuels and feedstock produce both greenhouse and pollutant emissions. While average values of CO_2 emissions in this path are available in literature [8], the upstream emissions of pollutant are not easy to quantify. For this reason, this investigation takes into account only emissions associated to the use of electricity with an approach that can be referred to as PTW (Plant-To-Wheel) [32,33, 34, 35]. A complete approach (Life Cycle Assessment) should take into account also the emissions associated to the building and dismantling of the vehicle and to the production of the fossil fuels [16]. Potter [22] found that of total CO_2 emissions from an average car, 76% were from fuel usage, 9% from manufacturing of the vehicle and 15% from emissions and losses in the fuel supply system. The present investigation concentrates on the emissions associated to the conversion from chemical to mechanical energy, but, for CO_2 only, results of a LCA analysis are also shown in the paper.

The investigation is part of a research project named ‘‘PRIME - Progetto di Ricarica Intelligente per la Mobilità Elettrica’’ funded by Italian Ministry for Environment MATTM (Ministero dell’Ambiente e della Tutela del Territorio e del Mare) and involves several industrial and academic partners. The goal of the project is to collect experimental data of mobility demand, fuel consumption and vehicle performance from a fleet of Smart ED sold to about 100 users in three different Italian cities and two plug-in electric vehicles at the University of Salento. The project also studies the behavior of customers, analyzes the impacts of charging stations for electric vehicles on the stability of the electric grid and estimates the reduction of pollutant and greenhouse emissions. In this project the smart EV Charging infrastructure developed by Enel has been used [36]. All the recharge stations installed by Enel are remotely operated by an Electric Mobility Management

(EMM) system, which supervises all the stations and monitors all the recharge processes in real time, providing end users with information about the present status of each station and past data about electricity consumption. More than 400 public stations have been installed in Italy. The present investigation uses the data from the public stations installed in Rome.

2. Data gathering

The recharges included in the data gathering are all those performed in Rome in 2013 through the public recharging infrastructure described in the following paragraph. In the data collected by the stations there is no information about the model of electric vehicle or the actual range of the vehicles. Thus, some assumptions are required as to the electric consumption of the vehicles. According to the information found on the Internet [37], only 844 electric cars were registered in Italy in 2013, the best sold being the Nissan Leaf. The details of the electric cars registered in Italy in 2013 are reported in Table 1 . For all the electric vehicles, the values of electric consumption declared by the manufacturers were retrieved [38-49]. These data were used only to define a range of variation for the consumption of electric vehicles.

Data in literature and experimental tests performed by the authors [31] show that electric consumption is affected by actual driving conditions (traffic, weather, average speed and acceleration) and by the usage of auxiliaries. In particular, for the Smart ED vehicle, the nominal electric consumption on the New European Driving Cycle (NEDC) is 12.2kWh/100 km [44], but the measured electric consumption [31] ranges from a minimum of 13.1 kWh/100km to a maximum of 30 kWh/100km, with an average of 19.4 kWh/100km. The highest quantity of electricity found in literature for Nissan Leaf [28] is 24kWh/100km, while the nominal electric consumption on the NEDC cycle is 14kWh/100km. Saxena et al. [50] also assumed a maximum of 30 kWh/100km for a low power electric vehicle.

2.1 The charging infrastructure

The recharges were performed through *Enel Distribuzione spa* [28,50] recharging infrastructure consisting of Charging Stations (CS) connected to a central system (Clearing House). These are the main features of the recharging infrastructure:

- Access to recharging procedure through RFID ID card;
- GPRS communication enabled towards the Clearing House;
- Identification and authorization to charge from Clearing House;
- Remote control of the recharging process;
- User interface to support customer on recharging procedure and status (kWh for recharge);
- Power line communication between EV and CS enabled;
- Data acquisition and transmission of every single charge procedure;
- CS remote monitoring and availability check.

The solution is embedded with revenue-grade smart-metering, ready for integration into the upcoming smart grid.

Since the RFID is associated to the owner and not to the vehicle (a user can recharge different vehicles with the same card), the RFID cannot be used to identify the model of electric vehicle.

3. Preliminary analysis of the recharge data

The whole database of electric recharges performed in the public stations in Rome has been analyzed. The total number of records is 7700. Each record contains the information of the date, time, duration, and kWh absorbed during the recharging of electric vehicles that took place in Rome in 2013.

The first analysis refers to the correlation between duration of the recharge time and energy absorbed (see Figure 1). The correlation between the duration and the energy absorbed by the recharge is weak, with a Pearson index equal to 0.32, because of the different specification of the electric vehicles charged in Rome. Each electric vehicle has, in fact, a different charge energy-to-time correlation according to the specification of the battery. The red line in Figure 1 represents the correlation line related to the Smart ED according to the measures of the authors [20].

Note that some vehicles continue to absorb a little amount of energy if they are left connected to the station after they have completed the recharge of the batteries, and they are still registered by the system to be in recharge. These records are not shown in Figure 1.

The daily 24 hours span have been subdivided into eight time slots of three hours each to simplify the computation of the emissions levels.

3.1 Analysis of the charging habits

For every month of the year, the electricity distribution has been calculated by multiplying the number of recharges occurring in each time slot and the energy absorbed by the specific recharge.

The distribution of energy used for the recharge is shown in Figure 2 separately for public holidays and workdays. During holidays the recharges of the vehicles require less energy, are performed later in the day and last longer (because users are at leisure to fully recharge the vehicles).

Note that the highest energy demand occurs between 7am and 3 pm with a peak in the 10-12 a.m. time slot. To analyze the data related to the different months and seasons, the quartiles relative to the duration and the energy absorbed by recharges have been reported in Table 2. December and February were the months with the highest and lowest values of both number of recharges and energy used for the recharges, respectively. As it can be seen from the data, approximately 36.3% of the total electricity was absorbed in autumn months, in winter only 18%. The total electricity and the number of recharges are about constant in the first five months of the year, then they increase from June to July, with a reduction in August (due to summer vacations) and increase again from September to December.

It is possible to conclude that most of the recharges through public stations were performed in autumn in the morning (10-12a.m.). Measured performed at the charging station of the University

Campus showed that the highest power absorption is in the first stage of the recharge [25]. This is also a reason why the peak in Figure 2 is in the morning when users start to charge their vehicles.

In the next section, the electricity mixes will be analyzed to evaluate the environmental impact of these recharge habits.

4. Production of electricity in Italy

According to data on the website of the Italian national grid operator (Terna) [52], the net production of electricity in Italy in 2013 was 277,380 GWh, while demand was 317,144 GWh. The difference is supplied by importing electricity from neighbour countries as shown in Table 3.

Most of this imported energy is produced by nuclear power plants [53].

The energy produced in Italy is divided into traditional and renewable sources, according to the percentage in Figure 3 [52]. In this figure, “Hydroelectric” includes all electricity produced by hydroelectric power plants including hydro-storage plants.

The mix of fuels used for the production of thermoelectric energy, which represents approximately 66% of the total, is reported in Figure 4 (Terna [52]).

For the proposed methodology, it is necessary to associate to each thermal source the corresponding power plant technology, the only problem being the natural gas that can be burned either in conventional gas turbines or in combined cycle power plants. Based on the literature data of the major energy producers [54-56], the installed power can be allocated into the two production systems as illustrated in Figure 5. Note that 53% of the electricity produced in Italy from natural gas is obtained in conventional gas turbine power plants, while the remaining 47% is produced by combined cycle power plants (this percentage rises to 63% if cogeneration is taken into account [54-56]).

4.1 Emissions levels of Italian electricity generation system

The emission factors of the production of electricity depends on the type of fuel, power plants and load level. To estimate their values, the maximum levels accepted for each technology by Italian legislation has been assumed for the nominal load [56]. The values at partial load have been extrapolated on the basis of the experience of the authors. The renewable energy power plants have been assumed to be 100% efficient (zero emissions). As already stated, embedded emissions (e.g., in the construction of Nuclear and renewable power stations) are not considered in the present investigation. The emission levels for pumped-storage hydroelectric power-plants have been obtained by assuming that the electricity required during the pumping phase is obtained from the grid for 8 hours a day at the maximum load (as per experience of the authors). The assumed values of the emission levels are shown in Figure 6 for CO_2 and Figure 7 for the other pollutant emissions..

To evaluate the emissions, the electricity generation mix at the specific date and hourly values of each recharge has been obtained from the Terna website [52]. As an example, the daily diagram of electricity generation mix for the first recharge is reported in Figure 8. The average values in the recharge were calculated as reference values.

Details about the production of thermoelectric energy from different energy sources and in specific kinds of power plants were not found in the literature. To disaggregate the data of Terna about thermoelectric power plants into a specific fuel (natural gas, coal, oil, etc.), the average percentage of Figure 4 were used. Except for natural gas, all fuels were assumed to be burned in conventional steam turbines. To disaggregate the natural gas data into a specific power plant technology, 47% of the electricity produced from this fuel was assumed to be transformed in combined cycle power plants, the remaining in gas turbine plants.

4.2 Load levels

The definition of the load levels is the most critical part of the proposed analysis for two reasons: the difficulty in finding data in literature and the fast evolution of the electricity generation mix in Italy in the last years, due to the unexpected increasing of electricity produced by renewable sources, mostly distributed wind farms and photovoltaic panels, as registered by the Italian Regulatory Authority for Electricity and Gas (IRAEG) [57]. The web site of the IRAEG was also used to retrieve information on the strategy used in Italy to meet daily and seasonal peaks. Natural gas combined cycle power plants are mostly used for base load. Pumping plants are mostly used in Italy for the management of surges and daily peak demand [57,58]. The diffusion of non-programmable renewable sources intended for the production of electrical energy and distributed generation, has determined a different mode of operation of thermal power plants (with particular reference to Combined-Cyle Gas turbine), which were designed to cover the base load, but are gradually becoming installations used to follow the electric load [57]. They are required to work with more flexibility and consequently with a reduce efficiency, as illustrated in Figure 9, where the trend of efficiency for thermal power plants in Italy over the last decade is shown [57]. According to IRAEG, the trend is to reduce the electricity generated by natural gas power plants.

In the present investigation, the load levels were defined according to the same time slots used for the analysis of the recharging habits. To assign load levels the following assumptions were made.

The trend of Figure 9 suggests that combined cycle power plants in 2013 worked at high load (in fact their efficiency is quite similar to the maximum values achieved in 2004).

According to the same trend, gas turbines worked at low-medium load (being the efficiency in 2012 about 57% of the highest efficiency achieved in 2004).

Steam turbines also showed a reduction of efficiency (and so of load level) in the last decade. Moreover, natural gas power plants are preferred [57] to coal and fossil oils. Thus, their load level was considered always lower than 55%.

The load levels of all thermoelectric power plants is considered lower in the morning/afternoon (larger contribution of renewable) and still lower in the night (low electricity request). Their load is assumed to be maximum in the evening when the request of electricity is high and the contribution of renewable sources is low [57].

The daily peaks are assumed to be covered mainly with hydroelectric pumping-storage plants. However, they produce emissions only in the night when they are expected to work with very high loads (90%).

Gas turbines are assumed to be used as “mid merit power plants”, i.e. to serve the extra demand for electricity which is seasonal [59]. Mid merit power stations are a compromise between base load power plants and peak loppers in terms of percentage of utilization [59]. Accordingly, the minimum load for gas turbines was set equal to 50% in the present investigation.

The level of operation of the units abroad, that provide a share of between 10% and 25% of electricity needed in Italy, was supposed to be consistently high (70%) during the whole day because they consist mainly of nuclear power plants [53].

The load levels for each technology and for each time slot presumed in the present investigation are reported in Table 4.The load levels are defined as the percentage of power produced by each power plant with respect to its nominal power. Since this is a critical issue in the proposed methodology, a sensitivity analysis was also performed in the present investigation by changing all load levels of +20 and -20 points . The average uncertainties caused on the emission factor described in the next section is -4.5% when all the load levels are increased and +7.3% when they are decreased by 20 points. They will be taken into account in the final calculation of emissions per km.

5. Emissions levels (g/kWh) of the electricity generation system

The emissions factors of each greenhouse/pollutant species, associated to each recharge have been calculated by considering the time slots occupied for the recharge, the corresponding mix for electricity production, the corresponding load level of each power plant technology and emission levels of power plants (Figure 6 and Figure 7). The load is expressed as a percentage of the nominal power of each power plant.

In the calculation of carbon dioxide, the amount derived from the combustion of gas, Municipal Solid Waste (MSW)/ biomass, biogas has been also been considered. These fuels emit, respectively, the following quantities: 1.489 kg, 0.897 kg, 0.432 kg per kWh produced [56]. They are supposed to be converted always at full load (100%). However, biomasses and biogas could be considered carbon-neutral and the contribution of Municipal Solid Waste could be taken into account at 50% [56].

5.1 Average emission factors per month and per time slot

The average values of the emission factors in 2013 are shown in Figure 10 as a function of the time slot. The graph shows that from the third to the sixth time slot (i.e. from 7am to 6 pm) the emission factors are lower; this is because the contribution of energy from renewable sources is higher than other times of the day and because the load level of the plants is on average much higher.

In fact, the average annual energy mix for electricity from renewable sources in Figure 11 shows that the amount generated by photovoltaic systems presents higher values exactly in those time slots. The total quantities of pollutants associated with vehicle recharging during the year are reported in appendix.

The months in which the highest emission factors are recorded are September, January and December; lower factors are obtained in May and June. The maximum, the minimum and the average of the emission factors recorded during 2013 are reported in Appendix.

In the months of May and June there is a significant increase in the contribution of renewable sources (+71%) compared to the other months (January, December and September) in which emission factors were most critical. During the months of May, June and September the average value of electricity derived from the photovoltaic is 11% of the total, while hydroelectric power is about twice than in September. The significant contribution of the portion of hydropower recorded from the month of May is due in large part to the plants located in mountainous areas, which are fed by glacial melt waters. The emission levels distributions of CO_2 and air pollutant vs time slot for each month are reported in Appendix.

6. Emissions factors (g/km) of the electric vehicle

According to the methodology presented by Donateo et al. [31], the PTW emissions of an electric vehicle in g/km can be calculated as

$$X_i = EC \cdot EF_{i,j} \cdot CF_G \cdot CF_R \tag{8}$$

Where:

- “i” is the index of greenhouse/pollutant species;
- “j” is the recharge ID;
- EC is the electric consumption measured in kWh/km;
- $EF_{i,j}$ is the emission factor of pollutant species i (in g/kWh) during recharge j
- CFG is a dimensionless correction factor, that takes into account the transmission and distribution losses in the national grid, assumed to be 1.075 according to Terna report for years 2011 and 2012 [52];

- CF_R is another dimensionless correction factor to allow for the losses of energy during the recharge. As discussed above, the correction factor CF_R was found to be 1.1 in average with a peak of 1.14. In the present investigation, the correction factor for recharge was assumed to be $CF_R = 1.1$.

The reference conditions for the evaluation of the emission factors are:

- Absolute average emission factors in 2013 for each pollutant emissions (see Appendix);
- Nominal electric consumption of the Smart ED (on the NEDC cycle), i.e. 12.2kWh/100km.

The emission factors of the reference conditions were calculated in g/km and reported in Figure 12. Since the electric consumption depends on the specification of the vehicle and its driving conditions, while the emission levels depend on the month and time slots when the vehicle was recharged, the next paragraphs analyze the effect of seasonality, charging habits, vehicle type and driving conditions. Moreover, the uncertainty about the load level of the power plant used to produce electricity is taken into account by the error bar of Figure 12. As stated before the emission factors decrease by 4.5% when all the load levels are increased by 20 points and increases by +7.3% when they are decreased by 20 points. The effect on the emission levels is quite negligible.

The emission factors of the reference conditions and the percentage variations with respect to the reference conditions are reported in Appendix.

6.1 Seasonality and charging habits: best and worst

The emission factors of the electric vehicle change between 80% and 110% according to when the vehicle has been recharged (in terms of month and/or time slot). Table 5 indicates, for each pollutant emission, the months and the time slots in which the values of emission factors were lowest and highest. The emission factors are lower in May for each pollutant, while the highest values are obtained in September for CO_2, PM, VOC and CH_4 and in January for the remaining substances.

The time slot that has the lowest emission factor is the number 5, while those with the highest factors are the numbers 1 and 2.

6.2 Effect of vehicle specifications and driving conditions

As for the type of vehicle, the emission factors are directly proportional to the electric consumption. Therefore, they are minimum for the Mia vehicle (79% of the reference Smart ED) and maximum for the Tesla car (139% of the Smart ED).

In a previous investigation [20], the authors measured the electric consumption of the Smart ED over different driving cycles performed in different traffic conditions and with different usage of auxiliaries. The measured electric consumption [31] was found to range from a minimum of 13.1 kWh/100km to a maximum of 30 kWh/100km. These two values were used as best and worst driving conditions and take into account the effect of both traffic conditions (average speed) and usage of auxiliaries. Note that the emission factors in real world conditions and with the usage of auxiliaries are almost three times those obtained in the NEDC cycle without any auxiliary (reference conditions).

Similarly, the fuel consumption of the 45kW gasoline version of the Smart for Two was found [20] to range from a minimum of 4.3 to a maximum 11.3 l/100km (in average 6.8 l/100km).

6.3 Comparison with conventional vehicles

To compare the electric vehicle with conventional cars, the emissions of CO_2 were compared with the limits set by European commissions. EU Regulation No 443/2009 [61] sets an average CO_2 emissions target for new passenger cars of 130 grams per kilometer to be phased in between 2012 and 2015 and a target of 95 grams per kilometer that will apply from 2021 [61].

For pollutant species, the limits set by European regulations (Euro VI) for diesel and gasoline vehicles to be registered since September 2014 [63] were taken into account. These limits refer to emissions measured over the NEDC (ECE 15 + EUDC) with the chassis dynamometer procedure.

The results of the comparison are shown in Figure 12. Note that emissions of CO and NO_x of the electric vehicle are well below the legislative limits for passengers cars in all cases. The emissions of unburned hydrocarbon of the electric vehicle were obtained by totaling V.O.C and CH_4. They are below the limit values for conventional passengers except when real world driving conditions are considered. The same result is obtained for particulate and CO_2.

It is necessary to emphasize that the fleet limits refer to the Tank-To-Wheel emissions while the proposed methodology calculates the PTT emissions for the electric vehicles (being their TTW CO_2 emissions assumed to be null). According to Sullivan et al. [62] the emission factor of CO_2 for gasoline and diesel fuel should be corrected multiplying the TTW emissions by 1.162 and 1.121, respectively, to take into account the production and transportation of the fossil fuels. Similar factors would be necessary for each energy source used to produce electricity in Italy. Since they are not available, the approach used in this investigation is Plant-To-Wheel for electric vehicles and Tank-to-Wheel for conventional passenger cars. This means that for conventional vehicles only emissions produced on board are taken into account. For electric vehicles only emission produced in the power plants to generate electricity and losses due to transmission and distribution are considered. However, an LCA comparison of the CO_2 emissions from the gasoline and electric version of the Smart ED vehicle is also reported later in this section.

The Euro VI limits for conventional vehicles refer to NEDC cycle. Data in literature [64,65] show that real world emissions of conventional gasoline and diesel vehicles can be quite higher than those measured with the European procedure. In particular, Pelkmans et al. [65] found that a model year 2000 vehicle, which already complied with EURO 4 limits, may reach CO and NO_x emissions up to

10 times higher in real traffic compared to the NEDC cycle while fuel consumption and CO_2 emissions are generally underestimated by 10–20% in the NEDC. Moreover, Pelkmans et al. [65] found an increasing of 33% of HC emissions in real world tests with respect to NEDC cycle for small petrol passenger cars.

Further issues should be addressed in the future since electric vehicles are also responsible for emissions of SO_x and metals. Moreover, emissions associated to fuel production, tires and so on should be taken into account.

In a previous investigation of the authors [25] a direct comparison of the LCA emissions of CO_2 from the 45kW Gasoline and ED versions of the Smart was performed. Experimental data of gasoline and electric consumption were acquired for the two vehicles. Then, correction factors based on literature data were used to take into account the emission of CO_2 in the manufacture of the two vehicles and in the production and distribution of gasoline. For the gasoline vehicle the TTW emissions were multiplied by 1.33, while for the ED version, the PTW emissions were multiplied by 1.8 [25]. The higher correction factor for the electric version takes into account the impact of battery and power electronics. Applying these same correction factors the results of Table 6 are obtained. The LCA emissions of CO_2 from the electric version are 12% lower than in the case of the conventional 45kW Smart ForTwo.

Unfortunately, this approach could not be used for the air pollutant for the lack of data about LCA emissions for the two vehicles.

7. Conclusions

The paper presents the analysis of the recharging habits of Italian drivers of electric cars and the evaluation of the corresponding environmental impact.

The recharge habits were acquired by analyzing the data obtained from the public stations installed in Rome by Enel. The total number of recharges in 2013 from public stations were 7700. For each recharge, the mix of fuel and power plant technologies used to produce the absorbed electricity was obtained by official daily diagrams and average national data from the Italian national grid operator (Terna). Emission levels, i.e. mass of pollutants associated to the production of 1 kWh of electricity from each technology, were analyzes for each month and time slot showing that the months in which the highest emission factors were recorded in 2013 are September, January and December. Further investigations will be performed to analyze the behavior of the driver of electric car in future. Unfortunately, these were also the months when the highest number of recharges were performed. On the other hand, the time slots with the highest number of recharges (10-12am, 1-3pm) are also the best to recharge from the environmental point of view since the amount of electricity produced from renewable energy sources is maximum in the same time slots.

Using literature information about electric vehicles registered in Italy in 2013 and experimental data obtained by the authors in previous investigations, the environmental impact of electric vehicles has been quantified. The environmental impact was evaluated by estimating the grams of CO_2, CO, NO_x, HC, PM and $HC+NO_x$ per 100 km. A sensitivity analysis has been also performed to assess the effect of recharge timing (month and time slot), vehicle specification and driving conditions. The emission factors of the electric vehicles were compared with the European legislations limits for conventional passenger cars. The results showed that the pollutant emissions of the electric vehicles in the Italian framework are all lower than conventional vehicles on the NEDC driving cycle. In particular, the emissions of CO from electric vehicles are quite negligible. Therefore, electric vehicles are a good alternative to conventional ICE vehicles, in Italy. A comparison with natural gas fuelled cars will be performed as a further investigation.

Real world emissions of HC were found to be critical for electric vehicles. Further analyses are also required to compare electric to conventional vehicles in real world driving conditions since the emissions of all type of vehicles are strongly affected by driving style, traffic and weather conditions and, above all, usage of auxiliaries like air conditioning that are not taken into account in the registration procedure based on the NEDC driving cycle.

List of abbreviations

BEV	Battery Electric Vehicle
EC	Electric consumption
$EF_{i,j}$	Emission factor for species “i” during recharge “j”
HC	Unburned Hydrocarbons
IRAEG	Italian Regulatory Authority for Electricity and Gas
MSW	Municipal Solid Waste
NEDC	New European Driving Cycle
NOx	Nitrogen Oxides
PM	Particulate Matter
PTW	Plant-to-wheel
SO_x	Sulfur oxides
TTW	Tank-to-wheel
VOCs	Volatile Organic Compounds
WTT	Well-to-tank
WTW	Well-to-wheel

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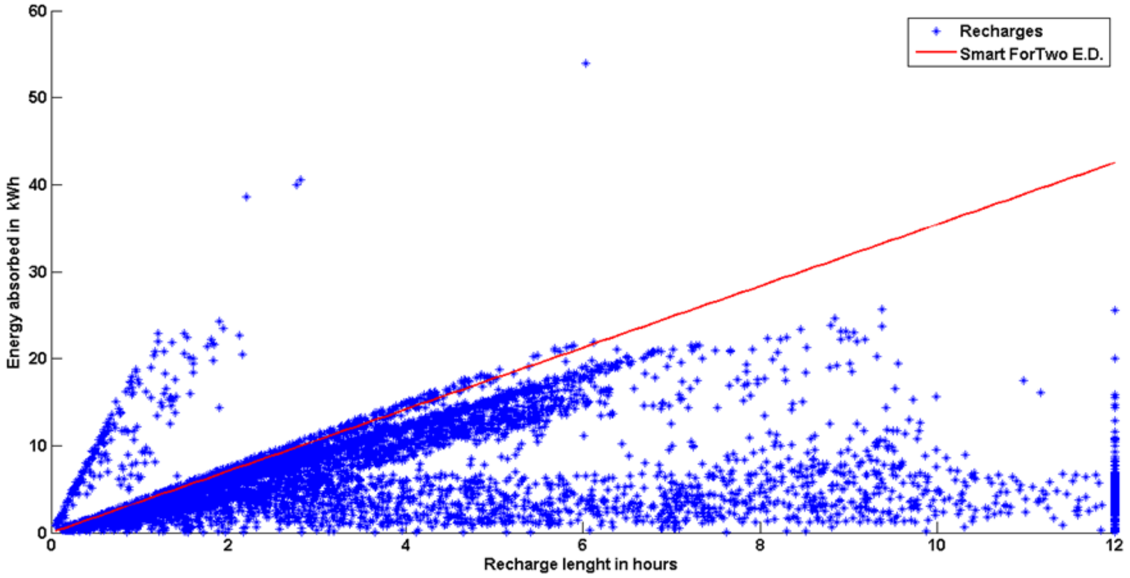

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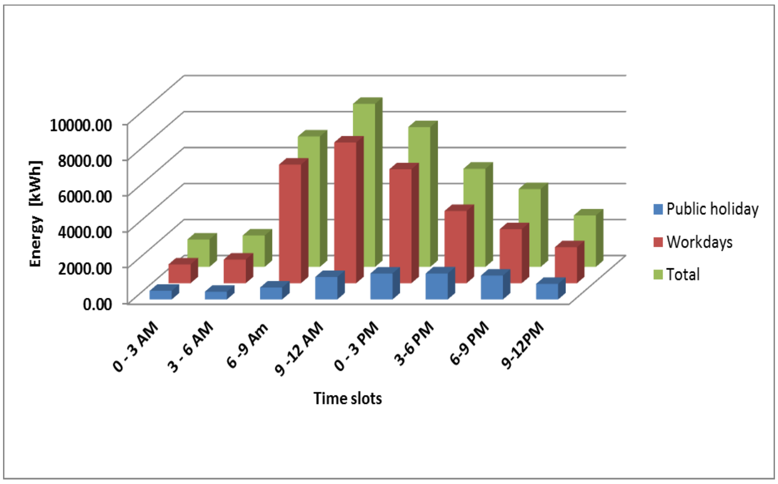

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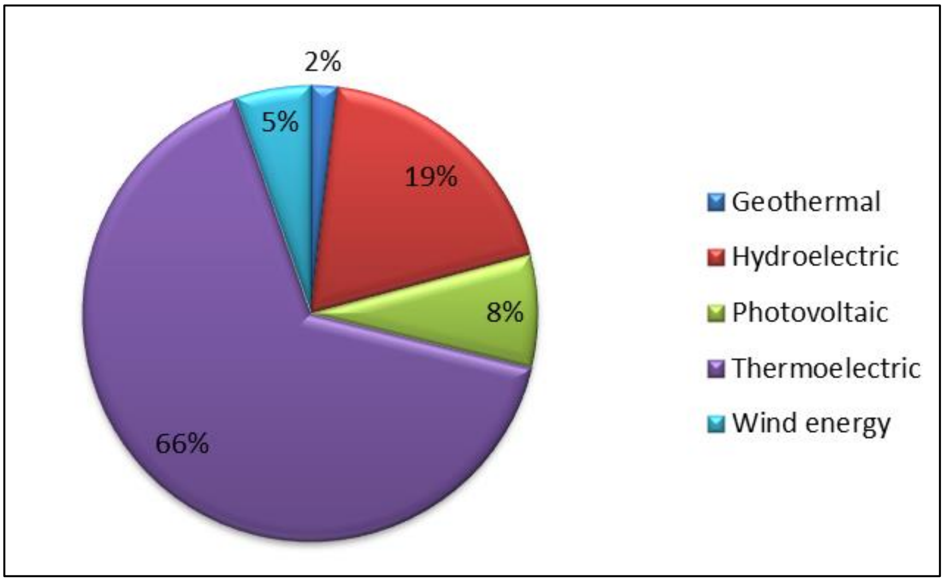

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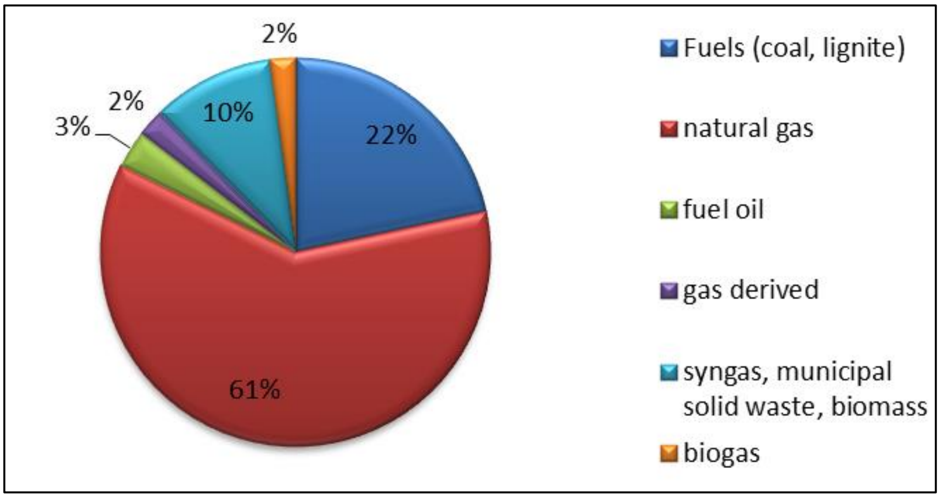

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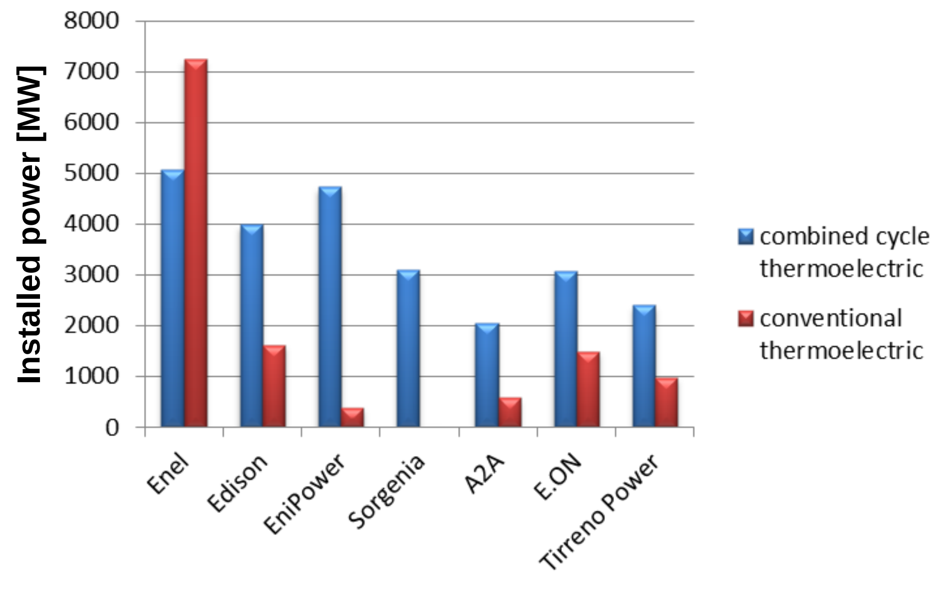

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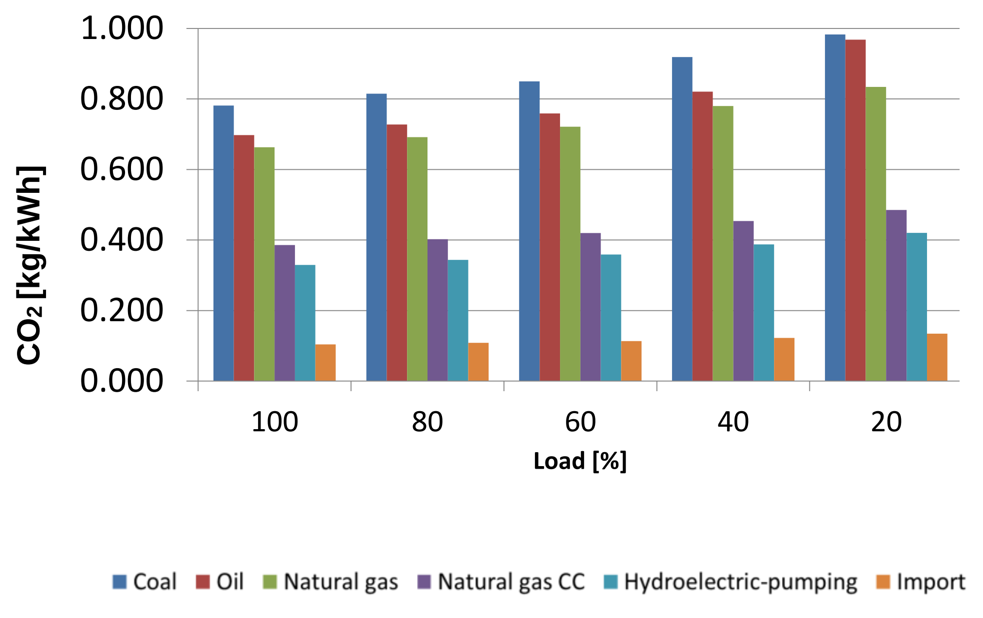

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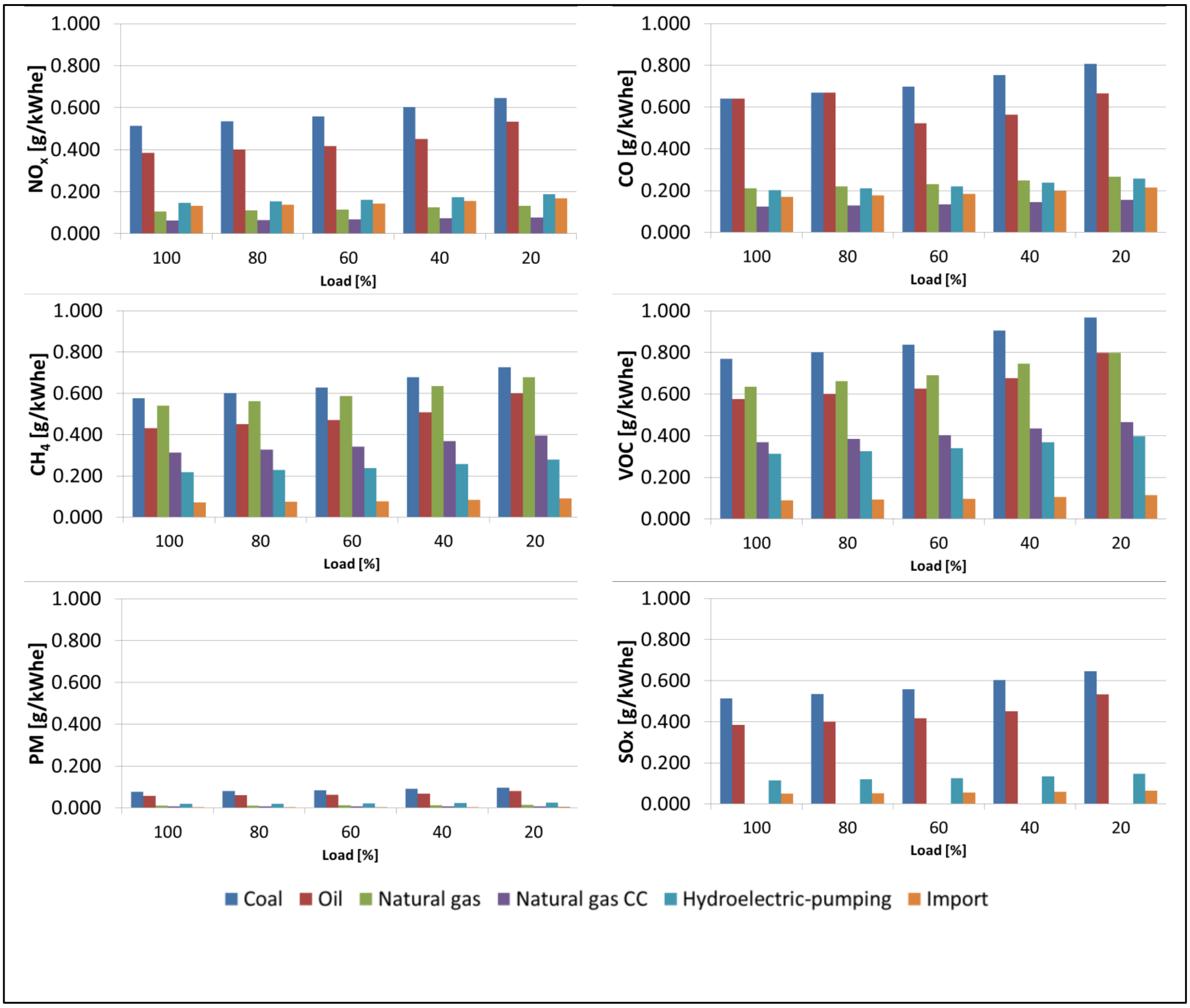

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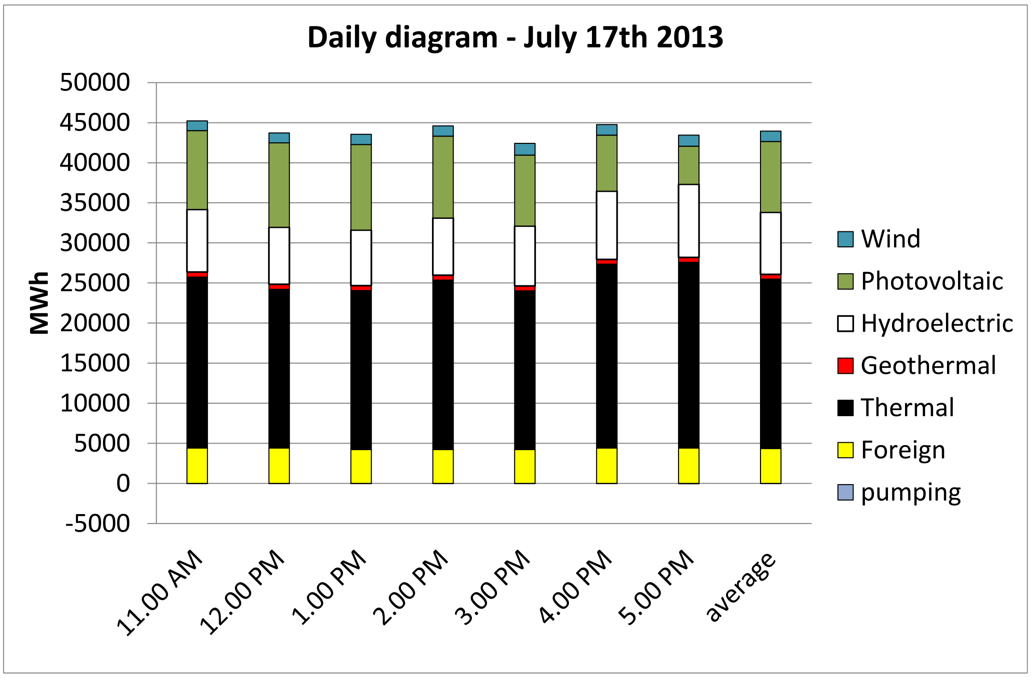

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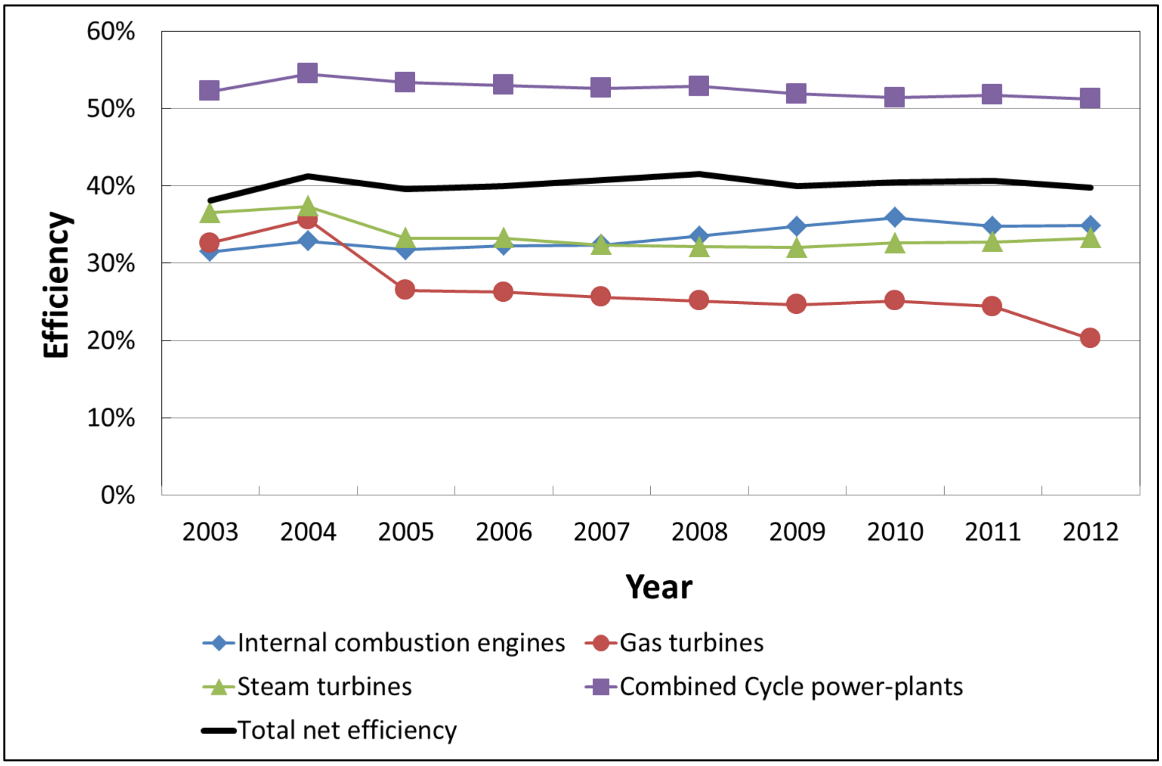

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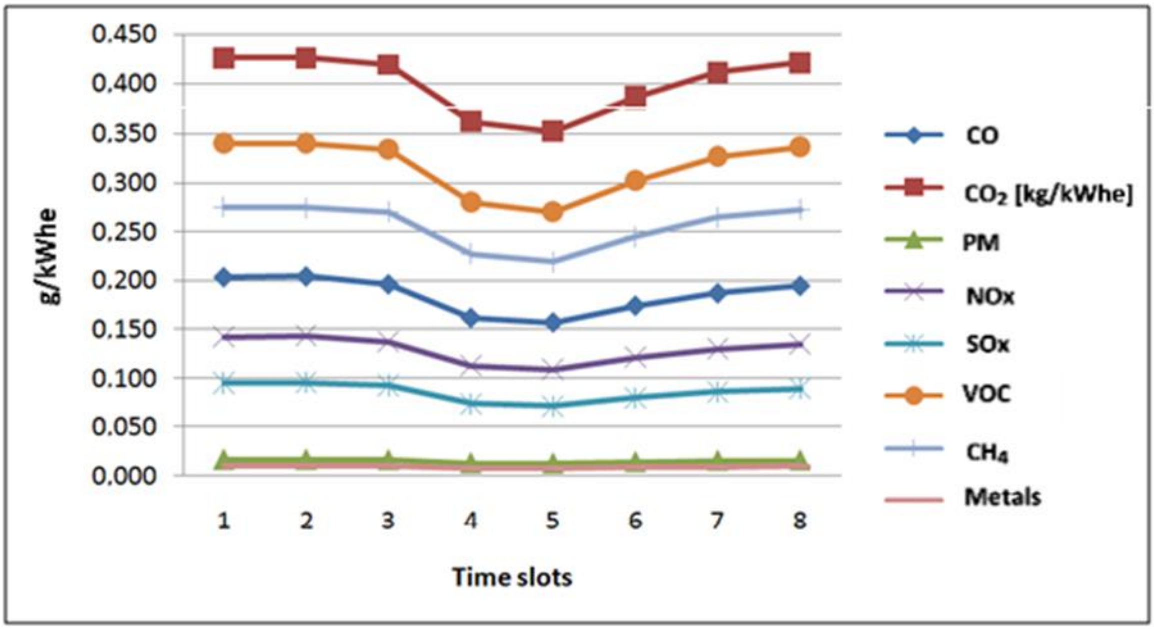

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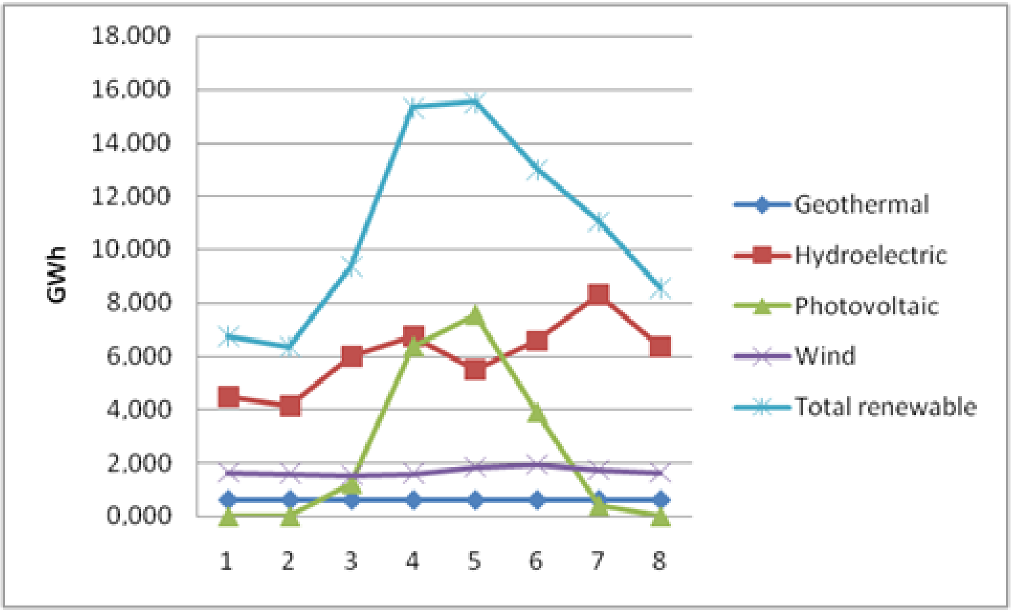

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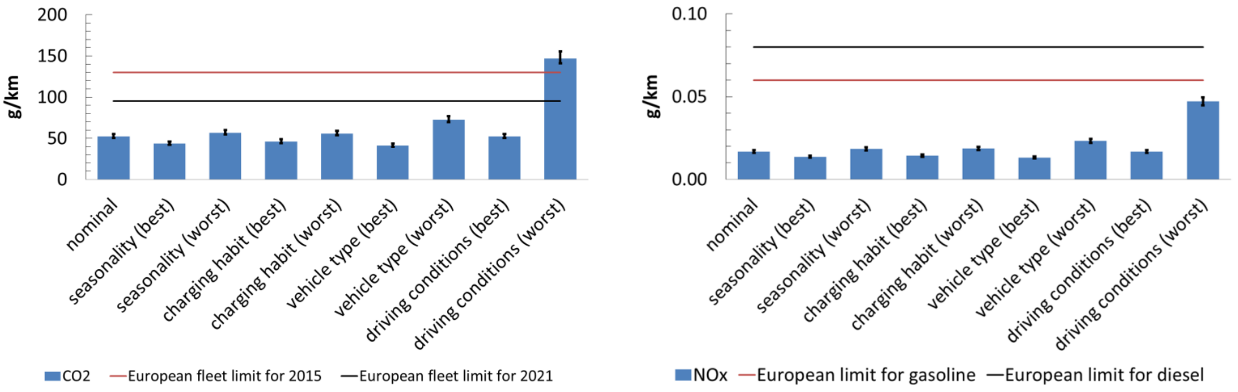
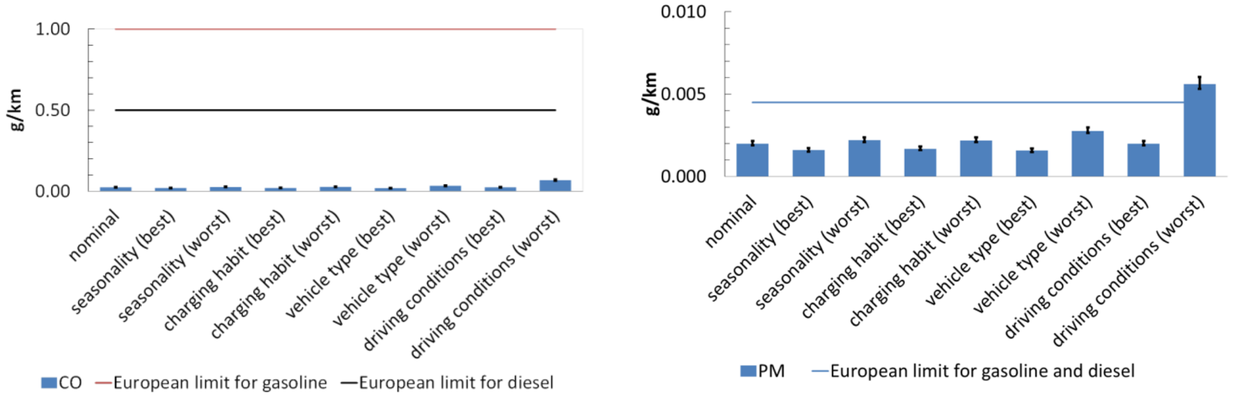
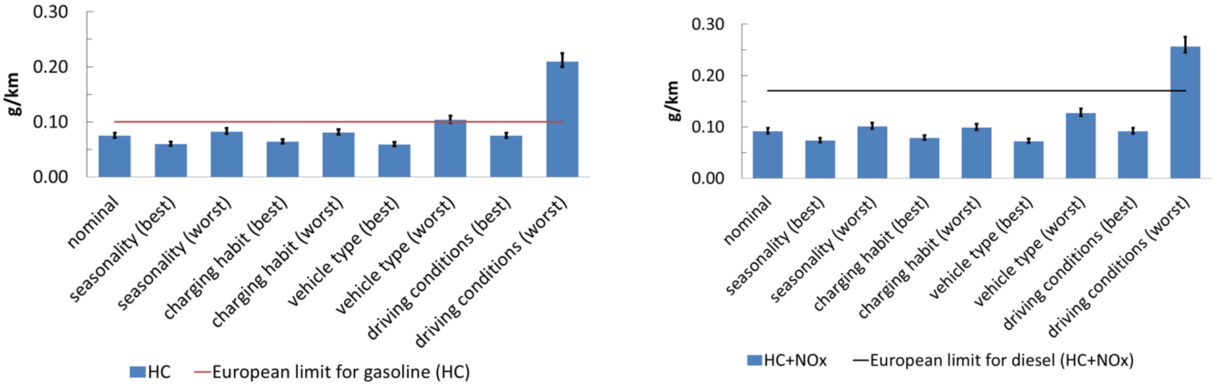


a) CO_2 b) NO_x



c) CO d) Particulate



e) HC f) $HC+NO_x$

Figure 12. Comparison between emissions of electric and conventional vehicles

Tables

Table 1. Electric vehicles registered in Italy in 2013 [38-49]

Model	Number	Battery capacity [kWh]	Nominal range [km]	Nominal electric consumption [kWh/100km]
Nissan Leaf	323	24	160	14.0
Renault Zoe	203	22	200	11.0
Smart ForTwo E.D.	155	16.5	135	12.0
Citroen C-Zero	55	16	150	10.7
Renault Fluence	38	22	170	13.0
BMW i3	34	28	205	16.0
Peugeot iOn	14	16	150	12.0
Tesla Model S	13	85	502	16.9
Mitsubishi i-MiEV	3	16	106	15.1
Mia L	2	12	125	9.6
Tesla Roadster	2	53	386	13.7
Ford Focus	2	23	160	14.4
Think City	1	11.5	85	13.5

Table 2: Statistics on recharges in Rome in 2013

Month	Number of recharges	Quartile - Duration (h)			Quartile - Energy (kWh)			Total energy (kWh)
		1	2	3	1	2	3	
January	397	1.57	2.51	4.44	2.76	5.69	9.85	2614.30
February	322	1.34	2.38	4.01	3.20	5.88	10.76	2201.50
March	350	1.27	2.52	4.23	2.88	5.72	9.55	2338.50
April	362	1.24	2.48	4.52	2.73	5.16	8.89	2240.60
May	469	1.44	2.45	4.04	2.71	4.95	8.69	2892.40
June	544	1.45	2.09	4.42	2.27	4.36	8.28	3244.40
July	667	1.42	2.20	4.30	2.32	4.45	9.04	4094.80
August	332	1.48	3.41	5.40	2.65	5.12	10.00	2195.40
September	634	1.33	2.03	4.14	2.26	4.22	8.01	3680.20
October	715	1.30	2.50	4.39	2.45	4.43	8.23	4166.30
November	757	1.58	2.37	5.00	2.18	4.40	9.60	4762.40
December	914	1.39	3.00	5.49	2.28	4.44	8.67	5572.70
Total 2013	6463							40003.50

Table 3. Production and demand of electricity in Italy in 2013 [52]

2013	**GWh**
Total net production	277.380
Import	44.331
Export	2.178
Foreign balance	42.153
Consumption pumping	2.389
ELECTRICITY DEMAND	317.144

Table 4: Arbitrary load levels (percentage of nominal power) for the Italian electricity generation system

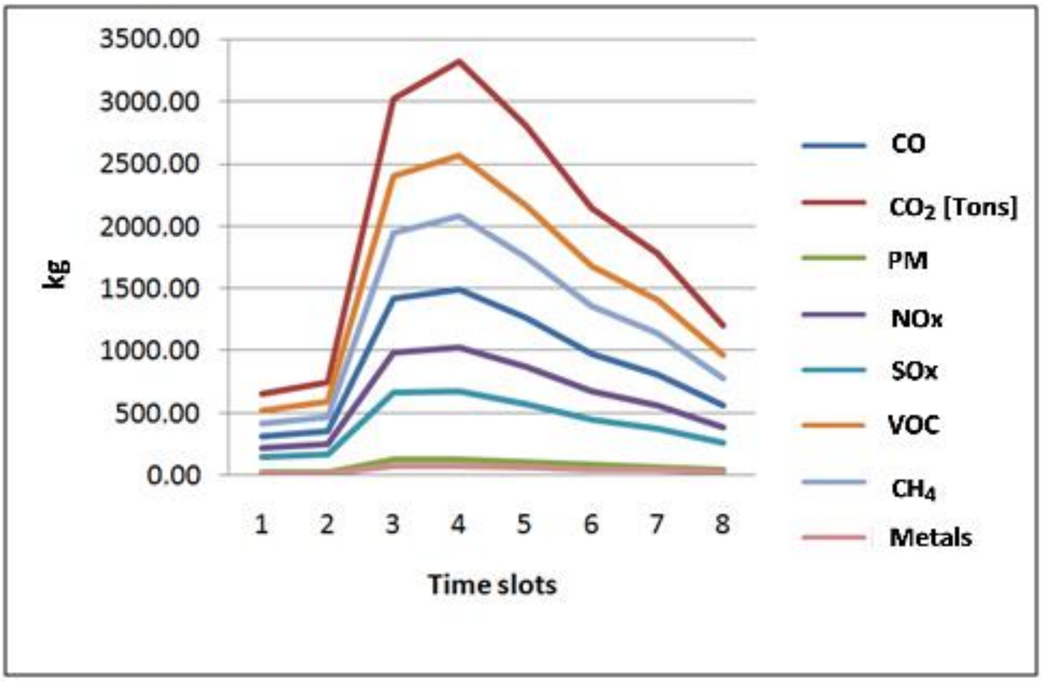
	Time slot							
Power plant	1 – 3 am	4 – 6 am	7 – 9 am	10 – 12 am	1 -3 pm	4 – 6 pm	7 – 9 pm	10 - 12 pm
Coal	40	40	45	50	50	55	55	55
Oil	40	40	45	50	50	55	55	55
Natural gas turbine	50	50	55	55	55	55	60	60
Combined cycle	80	80	80	80	80	85	90	90
Import	70	70	70	70	70	70	70	70
Hydroelectric-pumping	80	90	45	0	0	45	90	90
Renewable	40	40	70	90	90	70	40	40

Table 5: Monthly time slots with highest and lowest emission factors

	CO	CO_2	PM	NO_x	SO_x	VOC	CH_4
Min month	May	May	May	May	May	May	May
Max month	January	September	September	January	January	September	September
Min time slots	5	5	5	5	5	5	5
Max time slots	2	1	2	2	2	1	1
Absolute Min	5, May	5, May	5, May	5, May	5, May	5, May	5, May
Absolute Max	2, Sept	2, Sept	2, Sept	2, Sept	2, Sept	2, Sept	2, Sept

Table 6: LCA emissions of CO_2 of Smart ForTwo

Smart For-Two model	*Average Consumption*	*TTW/PTW emissions (g/km)*	*LCA emissions (g/km)*
45kW Gasoline	6.8l/100km	217.5	289.3
Electric Drive	19.4 kWh/100km	141.7	255.1



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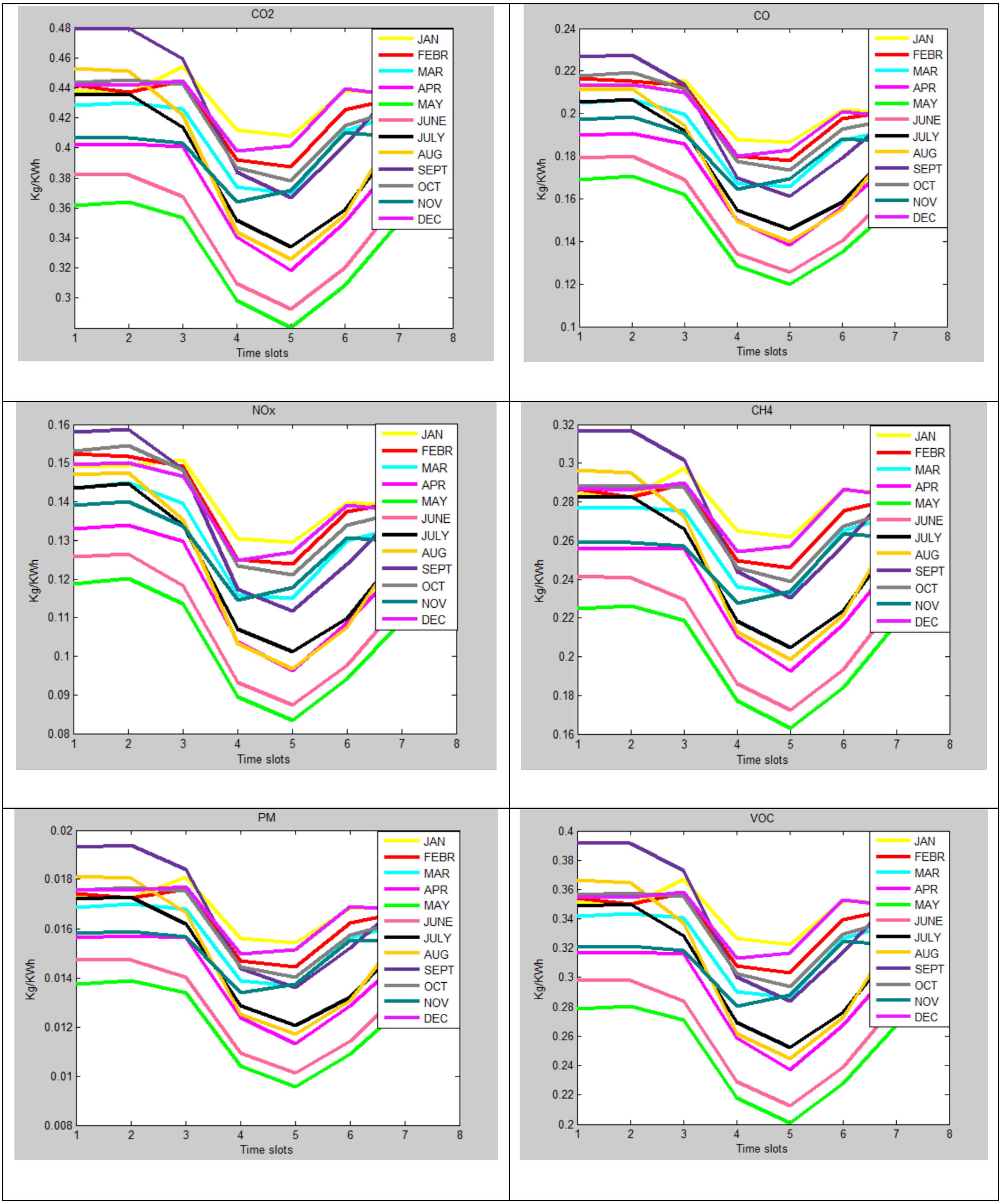

Figure A 2 - - Emission factors of pollutant per kWh of electricity in 2013 vs. time slots

Table A 1 - Overall emissions factors recorded in 2013

Month	**CO [g/kWe]**	**CO_2 [kg/kWe]**	**PM [g/kWe]**	**NO_x [g/kWe]**	**SO_x [g/kWe]**	**VOC [g/kWe]**	**CH_4 [g/kWe]**	**Metals [g/kWe]**
Min Value	0.1197	0.2803	0.0096	0.0835	0.0539	0.2007	0.1629	0.0058
Average Value	0.1850	0.4007	0.0153	0.1289	0.0857	0.3160	0.2560	0.0091
Max Value	0.2276	0.4796	0.0194	0.1588	0.1082	0.3918	0.3167	0.0113

Table A 2 - Reference emission levels and sensitivity analysis

	CO	CO_2	PM	NO_x	HC	HC+NO_x
	g/km	g/km	g/km	g/km	g/km	g/km
nominal	0.024	52.31	0.002	0.017	0.075	0.091
seasonality (best)	81%	83%	80%	82%	80%	80%
seasonality (worst)	110%	108%	110%	110%	110%	110%
charging habit (best)	85%	88%	84%	85%	86%	85%
charging habit (worst)	110%	106%	110%	111%	108%	108%
vehicle type (best)	79%	79%	79%	79%	79%	79%
vehicle type (worst)	139%	139%	139%	139%	139%	139%
driving conditions (best)	100%	100%	100%	100%	100%	100%
driving conditions (worst)	280%	280%	280%	280%	280%	280%