Introduction of Plug-in Hybrid Electric Vehicles in the Fleet Mix of an Island

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Abstract. This paper presents an overview of the electricity consumption profile and the characteristics of the power supply system in the São Miguel Island in order to assess and analyze the potential impact of the plug-in hybrid electric vehicle (PHEV) technology on the local grid. To this end, The Integrated MARKAL-EFOM System (TIMES) is employed to examine a number of scenarios with different levels of PHEVs penetration under the grid-to-vehicle (G2V) energy transferring paradigm. In the context of our analysis, the established Government policies, regarding the increase in renewable energy production quotas, are taken into account for the evolution of demand and supply over time. The results obtained indicate that the PHEVs integration into the local grid system under the G2V model can be realized without immediate technical barriers and bears the potential to yield significant benefits to the energy mix, reducing thus the environmental impact.

Keywords: Energy system analysis · Grid-to-vehicle (G2V) · Plug-in hybrid electric vehicle (PHEV) · TIMES model generator · Transportation sector electrification.

1 Introduction

There is general consensus that the increasing concerns regarding reliability and security of energy supply, as well as environment impact, pose new technological challenges for the electricity and transportation systems. In this direction, the electrification of the transportation sector could also contribute to lower the dependence on oil and reduce the greenhouse gas (GHG) emissions, however the potential benefits from the large scale deployment of electric vehicles (EVs), mainly of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), are neither clear-cut nor can their realization be taken for granted, especially in cases where fossil fuels are the

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dominant energy sources of the electricity generation system [1]. PHEVs recharge from the power grid and offer the advantage of extending the driving range by running on a secondary fuel (gasoline or diesel), once the battery is discharged, providing thus a transition technology from conventional vehicles to BEVs that have no internal combustion engine (ICE) [2].

In this context, PHEVs may contribute to the optimization of the electric power systems as well, if they can play a role not only as electric power consumers when recharging their batteries, but also as small distributed energy storage under predefined conditions when they are grid-connected [3,4]. Vehicles are typically used for transportation purposes for less than 5% of their life time [5], constituting an idle asset with associated maintenance, insurance and parking costs. Thus, PHEVs can be charged preferably during off peak hours, using grid-to-vehicle (G2V) technology, with cheaper base load generation or intermittent renewable sources and be used as a storage system during the day parking hours or during low demand times to provide regulation and spinning reserve services to the grid or to match the demand in peak hours with vehicle-to-grid (V2G) technology [6,7].

Moreover, energy systems in isolated areas, such as islands, are typically dependent, to a great extent, on fossil fuel imports. Since the transportation sector accounts for a significant part of the imported fuels, PHEVs could reduce [8] or even eliminate the fuel consumption of the vehicle fleet [7]. In this framework, this paper analyzes the characteristics of the power supply system of the São Miguel Island, in the Azores archipelago, and employs a number of scenarios using The Integrated MARKAL-EFOM System (TIMES) in order to assess the impact of introducing PHEVs in the local grid system up to the year 2020 in a G2V approach, taking into consideration the local Government plans for expanding renewable energy sources. To this end, this work examines whether energy policies that include large-scale integration of PHEVs would positively contribute to the local energy mix.

The rest of the paper is structured as follows. Section 2 describes in detail the development of the model to represent the energy system of the São Miguel Island using the TIMES model generator, and provides a brief outline of the scenarios considered within the frame of this work. Section 3 presents the results obtained, followed by a discussion of their significance in section 4, while section 5 draws the main conclusions.

2 Methodology

In this paper, the TIMES model generator, developed and maintained by the Energy Technology System Analysis Programme (ETSAP) of the International Energy Agency (IEA), is chosen as a bottom-up energy modeling tool capable of capturing the interplay between the electricity and transportation sectors. The aim of a TIMES model is to determine the least cost configuration of the energy system (in terms of technologies and energy flows) that satisfies the constraints of supply and demand, as defined in the following objective function [9]:

$$C_{tot} = C_{inv} + C_{sun} + C_{fix} + C_{var} + T + C_{sur} + C_{dec} - S - M - V \quad (1)$$

where C_{tot}, C_{inv}, C_{sun}, C_{fix}, and C_{var}, are the total, investment, sunk material, fixed and variable costs respectively, T is the taxes, C_{sur} is the surveillance costs, C_{dec} is the decommissioning costs, S is the subsidies, M is the recuperation of sunk material costs and V is the salvage value (note: sunk materials refer to those embedded in a technology at construction time, such as the uranium core of a nuclear reactor [10]).

To satisfy the demand for energy services at the minimum system cost in a TIMES model, decisions on equipment investment and operation, primary energy supply and energy trade are made simultaneously, while all cost elements are appropriately discounted to a selected year according to the following equation [11]:

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} * ANNCOST(r, y) \quad (2)$$

where NPV is the net present value of the total costs, $ANNCOST$ is the total annual cost, d is the general discount rate, R is the set of regions under study, $REFYR$ is the reference year for discounting and $YEARS$ is the set of years for which costs occur.

In the context of this work, a medium-term model based on the demand-driven and technology-oriented approach of the TIMES framework is employed to represent the energy system of the São Miguel Island. The demand side of the model includes agriculture, industry, services and commerce, domestic sector, and transportation, each one characterized by specific (disaggregated) energy service demands, while the supply side of the model includes fossil fuels (oil) and renewable (hydro, wind, geothermal) resources. The available supply side technologies are characterized by a number of techno-economic parameters, such as capacity, energy efficiency, availability factor, lifetime, capital costs, as well as operating costs (both fixed and variable). The model chooses among the competing supply side technologies in order to minimize the total energy system costs, taking into account the sectoral energy demands along with assumptions on energy prices and trades, resource availabilities, as well as the different penetration levels of EVs. The necessary data for the model assumptions are obtained from the several studies made for the Government of Azores [12].

2.1 São Miguel Island

São Miguel is located in the southern part of the Azores cluster of volcanic islands, 1,564 km west of Lisbon. It is the largest and most populous island of the Azores, covering an area of about 760 km^2 with roughly 140,000 inhabitants. The primary energy and electricity consumption in São Miguel presented a strong increasing trend as a result of the significant economic growth over the period 1994-2010 [13], however the situation has changed over the last few years following the economic conditions of the other islands of Azores and mainland Portugal.

The Azores islands are highly dependent on the import of fossil fuels, as a consequence of their geographic isolation. At present, there is no power connection to the continental grid or interconnection among the islands, considering that the wide geographic spread along with their remote location from mainland Portugal renders the installation of a submarine power cable inapplicable. Given the abundance of local natural resources, the Government of Azores plans to bring the level of renewable electricity production to 50% and 75% in 2013 and 2018 respectively, on average for all islands [14]. These targets are aligned with the energy strategy of the Electricity of the Azores (EDA - Electricidade dos Açores) company to invest, among others, on geothermal power plants in major islands, including São Miguel, in order to increase the renewable energy penetration. In this context, it is within the governmental goals to increase the share of renewable sources in primary energy production up to 40% (considering the partial substitution method), a particularly ambitious target that requires actions to be taken for all sectors of energy consumption, as well as consideration of the potential synergies between electricity and transportation sectors [15].

2.2 Reference Energy System (RES) of the São Miguel Island

The TIMES framework employs the concept of reference energy system (RES) to represent the energy system of interest, consisting of processes represented as boxes, commodities as vertical lines, and commodity flows as links between process boxes and commodity lines. In this context, the optimal system configuration over the defined time horizon is determined on the basis of the energy technologies and flows in the RES, while taking into account any additional constraints, e.g. targets for the penetration of renewable energy sources and/or EVs.

The energy situation in 2007 regarding the island of São Miguel is presented in Fig. 1(a), which indicates that there is high dependence of the primary energy production on oil (87%), with the renewable sources having only a small share of 6%. The share of total oil quantity used in the transportation sector amounts to 47.3% (or equivalently 41.2% of the total primary energy source) and the rest 52.7% is used in the electricity production for the other sectors (e.g., agriculture, industry, etc.), with a total import cost for the local Government of approximately 55.4 million €. Fig. 1(b) clearly shows the importance of the transportation sector, which presents the highest share (equal to 49.2%) of the final energy consumption, followed mainly by industry, construction, services and commerce, residential sector, and finally by agriculture and fishing with a significantly lower percentage.

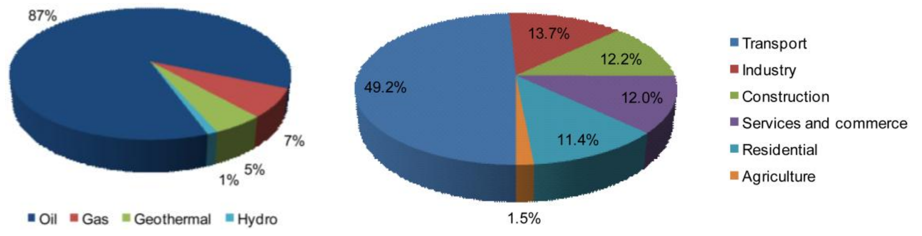

Fig. 1. Percentage breakdown of: (a) primary energy production by source, and (b) final energy consumption by sector of activity, in the São Miguel Island, in 2007

The 47.3% of the oil as a primary energy source or the 49.2% of the final energy consumption of the transportation sector (in the form of diesel and gasoline) corresponds to the usage of a total number of 54,221 vehicles, according to data given for the year 2007 with a price of 0.492 €/lit of fuel used in the vehicles. The data series in

Fig. 2 show an annual increase on the total number of vehicles in the local fleet from 2003 to 2007, which is assumed to be linearly constant with an average value of 2.2% for the scenarios examined in this study. A close examination of Fig. 2 reveals that the annual increase of the total number of vehicles is attributed primarily to the gradual increase of the light duty vehicles (LDVs), while comparably lower variations are observed for the rest the vehicle fleet, i.e. high duty vehicles (HDVs), 2-wheelers (2Ws) and others. Thus, a first indication is that the majority of the oil consumption and the increase of the CO_2 emissions are driven strongly by the annually increasing number of the LDVs (also as percentage of the fleet). The average mobility of the cars in Azores from 1994 to 2003 presents an increase of 4.6%, corresponding in the case of gasoline as car fuel to 9,397 km/year and of diesel to 15,708 km/year. These numbers are similar to the ones for the case of the São Miguel Island, i.e. 9,478 km/year (or 25.96 km/day) and 15,446 km/year (or 42.32 km/day) respectively, which are taken into consideration in the scenarios of this work, as they appear to be especially attractive for the use of EVs.

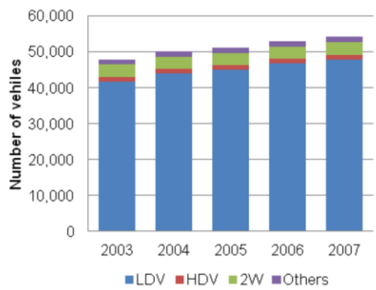

Fig. 2. Composition of vehicle fleet in the São Miguel Island, from 2003 to 2007

Since the available data on the vehicle fleet is till the end of 2007, this is considered to be the base year for the fuel consumption of the island. In the frame of the scenarios in this work, a small amount of the vehicles that correspond to agricultural or small motors and do not influence the final results are excluded from further consideration. In this context, Fig. 2 presents the amount of the LDVs plus a small amount of urban buses, as well as that of HDVs and 2Ws.

Furthermore, the oil imported, bought and consumed on the transportation sector has the same price as the one in the electricity sector (i.e. 0.492 €/l for diesel and gasoline). For the island of São Miguel, the amount of energy consumption in 2007 in the terms of gasoline is 805.06 TJ that corresponds to a quantity of about 21,543,353 l or 17.2 x 10^6 kg, while in the terms of diesel amounts to 2,377.57 TJ that corresponds to a quantity of about 63,625,241 l or 52 x 10^6 kg, resulting in final import costs for the local Government of approximately 48.4 million €. With the then-current price of diesel fuel at 1.01 €/l and that of gasoline at 1.22 €/l [16], this results in a total amount of 99 million € to be distributed to the different stakeholders, given that the final price of the fuels includes the product cost, logistics and commercial margins, taxes for the autonomous region of Azores, value-added tax (VAT), and special VAT on hydrocarbons. More specifically, the taxes for the autonomous region of Azores are the 4% of the final fuel price, and therefore, in this instance, it may be observed that there is an amount of approximately 4 million € that the local Government profits from the sales of diesel and gasoline to the consumers used as fuel on their vehicles.

2.3 Electricity Situation in São Miguel

The total electricity production in the island of São Miguel reached 429 GWh at the end of year 2007, while the average annual electricity growth rate was 6.6% with the previous three years (2005-2007) falling to 4%. Electricity production is not very diverse in terms of sources, yet the development of renewable sources in the previous ten years resulted in attaining a significant percentage of 47% out of the total production of the island (Fig. 3). The system uses mainly fuel oil (≈53%), while a significant share of the electricity produced comes from renewable sources, such as geothermal and to a lesser extent from small hydro and biomass. The electricity accounts for about 35% of the total primary energy consumed in São Miguel, being the main reason for the import of large quantities of fuel oil. Table 1 shows the capacities of the different existing power plants with the electricity produced by each source in the year 2007.

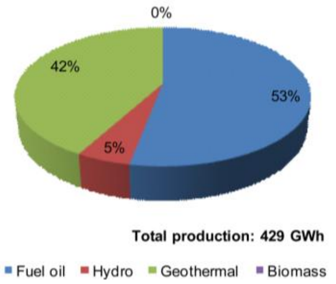

Fig. 3. Electricity production situation in the São Miguel Island, in 2007

Table 1. Capacities of existing power plants in the São Miguel Island, in 2007.

Energy source	Plant	Capacity (MW)
Fuel oil	Caldeirão	115
Geothermal	Pico Vermelho	10
	Ribeira Grande	14
Hydro	Several plants	5

Fig. 4 indicates that the electricity consumption patterns are very similar throughout the year [17]. The main differences reside on the fact that the summer months have maximum consumption during the day, while in the winter the consumption is higher during the night. In both cases, however, the consumption is at a minimum level during the first hours of the day, with the weekends also presenting lower consumption compared to weekdays.

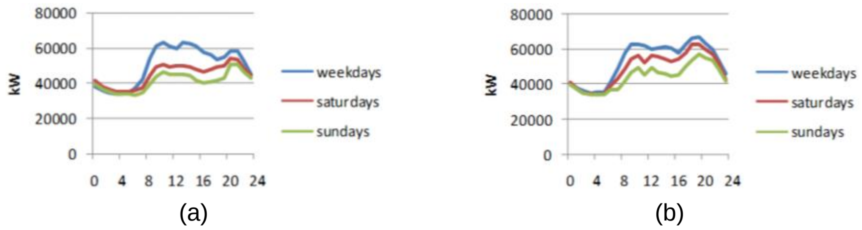

Fig. 4. Daily electricity load curves in 2007 during (a) summer, and (b) winter

2.4 G2V and scenarios

It becomes clear that the overall system efficiency (vehicles and grid) would be enhanced, if effective communication is realized between the EVs and the utility regarding the appropriate times to charge. Although in practice the need for charging EVs may occur throughout a day, the present study examines the case that the charging process can be controlled, so that it takes place at beneficial times for the system, given that the electric range of a typical PHEV can cover the average daily distance traveled by gasoline or diesel cars in Sao Miguel (subsection 2.3), while vehicles remain parked for more than 95% of their life time [5]. Data up to the year 2003 [18], provided by the Government of Azores, show that the largest share of the cars in Azores is in the capacity range of 2001-2500 cc (52%), followed by the category of 1751-2000 cc (35%), 1501-1750 cc (8%) and finally that of 2500 cc (6%). To identify the more robust solutions and minimize the effect of uncertainties, TIMES is employed to analyze different scenarios with respect to the replacement of ICE vehicles of the fleet with EVs. Specifically, scenario 1 corresponds to the case of no PHEVs in the fleet, scenario 2 assumes 32% replacement of ICE vehicles with 18,109 PHEVs in the year 2013 (according to the scheme of Table 2), while scenario 3 considers that the penetration of PHEVs gradually increases to 32% from 2013 to 2020 (based also on the scheme in Table 2).

Table 2. Plan for the penetration of PHEVs considered in this work.

Vehicle type	Percentage of vehicles replaced	# of vehicles replaced
Bus	50%	55
2W	50%	3,492
LDV	30%	14,562
	Fleet replaced: 32%	Total: 18,109

The business-as-usual (BAU) situation, described in the form of scenario phases in Table 3, contains initially only the production from renewable energy sources, namely geothermal of 24 MW and hydro of 5 MW. Table 3 includes also the EDA plan (till year 2013) for the further enhancement of the island in green energy, along with further steps proposed by the authors, namely addition of a 10 MW geothermal power plant, i.e. Geo(3), and 32% of EVs. A previous study in [19] examined different scenarios for the island and identified that the capacity increase by 3 MW of geothermal energy in 2010 and the addition of another 10 MW in 2013 would be limited by the fact that the generation of base load electricity exceeds the off-peak demand. Taking this into account, scenario 2 of the present study considers the penetration of the EVs (32%) in that same year (2013), as a means of counterbalancing the excess off-peak electricity with EV charging, while at the same time reducing the systematic imports of fossil fuels by shifting to local renewable energy sources.

Table 3. Description of the BAU scenario evolution.

	Year of investment					
	2007	2010	2011	2011	2013	2013
BAU	29 MW					
+Geo		(1)-3 MW		(2)-10 MW		(3)-10 MW
+Wind			9 MW			
+EVs					32%	
Total capacity of renewable energy sources (MW)	29 MW	32 MW	41 MW	51 MW		61 MW

3 Results

Fig. 5(a) illustrates the spring load profile (the lowest consuming season) of 2007 in São Miguel with its peak load time in the morning and early afternoon as expected. This figure clearly shows the straight lines of the base load covered by geothermal and hydro energy, while the valleys (during the early morning hours) and the peaks (at the afternoon-evening hours) of the electricity load are covered by the energy produced by fuel. Moreover, this figure indicates that the load demand is higher during the weekdays (black line), whereas it is lower during Saturdays and Sundays (red and blue lines), a fact that is fully aligned with Fig. 4 for the summer and winter periods.

Fig. 5(b) represents the case of the addition of a new 3 MW geothermal power plant (or an expansion of the already existing geothermal power plant) in the year 2010, where the load profile (area below the dark black line) still remains the same, since it is accompanied with the corresponding annual increase of the energy load. As expected, there is also an increased percentage of the renewable penetration in the energy system, which is higher on Sundays and weekdays; yet no environmental benefit on the CO_2 emissions is observed from the electricity sector, as shown in Table 4. At this point, it is noted that the calculations in Table 4 are based on a CO_2 emission rate of 0.83 kg/kWh for the electricity production from fuel oil.

In 2011, the addition of 9 MW of wind energy brings the total capacity of renewable energy sources up to 41 MW and its contribution is indicated by the reduction of the grey space area that corresponds to the fuel use (Fig. 5(c)), as well as by the increased percentage of the renewable sources that is now higher on Saturdays and Sundays, and thus presents a shift compared to the previous case. No significant changes expressed in the form of new peaks in the load profile occur, with a second important observation being the benefits of the wind energy integration into the system without creating any problems in the load profile and simultaneously reducing the CO_2 emissions (Table 4).

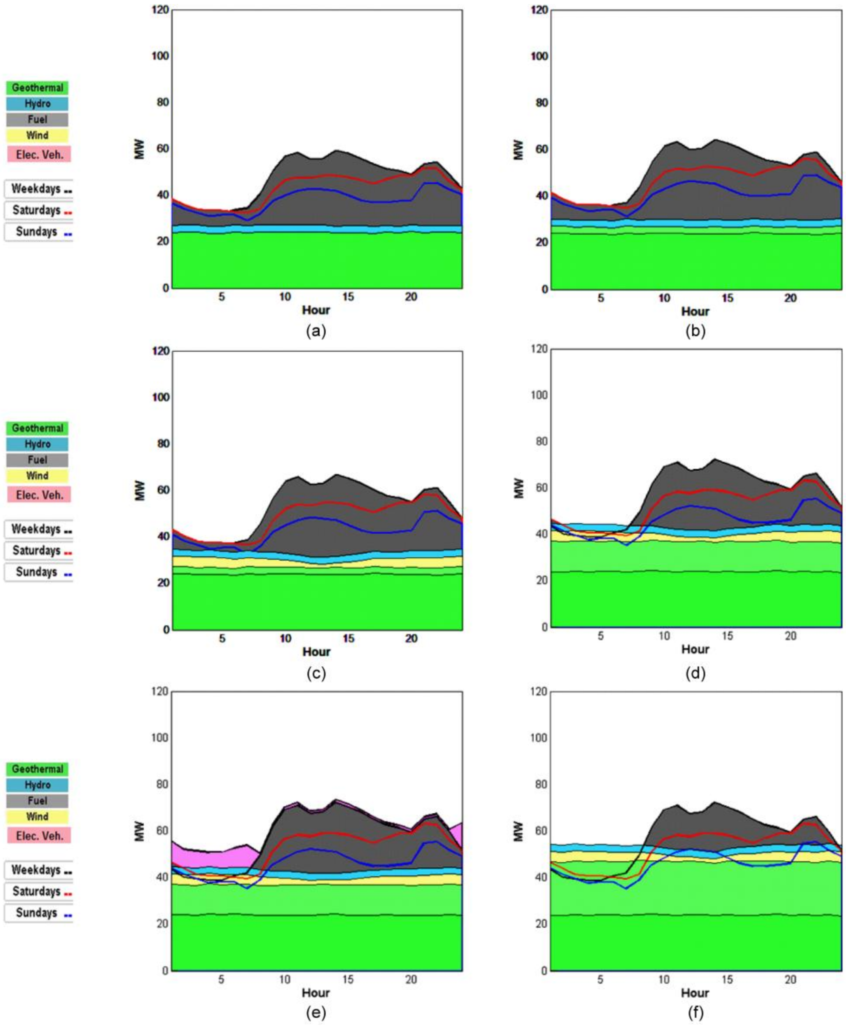

Fig. 5. Spring electricity load profile: a) Base year (2007), b) Addition of 3 MW geothermal (2010), c) Addition of 9 MW wind (2011), d) Addition of 10 MW geothermal (2011), e) Addition of 32% EVs (2013), and f) Addition of 10 MW geothermal without EVs (2013). Cases b to f are accompanied by a 4% increase of electricity demand

For the same year, the further addition of a new geothermal power plant, namely Geo(2), expands the capacity of renewable energy sources to 51 MW, resulting in a larger substitution of fuel by geothermal energy in the load profile (Fig. 5(d)), and as expected, it yields a higher renewable penetration percentage, especially on Sundays.

A closer examination of the load profile in Fig. 5(d) reveals that during the early morning hours (up to 09:00) the energy becomes from the combination of different renewable sources (geothermal, hydro, wind), in contrast to the previous cases that, for the same period of a day, energy is also generated from fuel. This new load profile also corresponds to a significant reduction of CO_2 emissions (Table 4), while there is once again the shift of the increased renewable penetration to weekdays and Saturdays compared to the Sundays and Saturdays of the previous case.

Table 4. CO_2 emissions as a function of weekdays, Saturdays and Sundays.

	Daily emissions (tons of CO_2)			Spring load penetration of renewable energy sources (%)		
	Weekdays	Saturdays	Sundays	Weekdays	Saturdays	Sundays
BAU	401	320	216	57	63	71
+Geo(1)	418	320	217	59	64	73
+Geo(1)+Wind	387	296	180	63	69	79
+Geo(1)+Wind+Geo(2)	294	192	80	74	82	91
+Geo(1)+Wind+Geo(2)+EVs	327	223	102	67	72	81
+Geo(1)+Wind+Geo(2)+Geo(3)	158	61	2	86	94	100

As already pointed out, scenario 2 that refers to the penetration of EVs at a percentage of 32% of the whole fleet (Table 2), and thus the extra demand for charging the EVs, is assumed to take place in 2013. The electrical connection for charging the vehicles is based on the regular household plug-in power of 3.45 kW per PHEV with a 50 Hz frequency (nominal value) and under a EU voltage of 230V (2-phase) with fuses of 10-16-20 A, corresponding to the first generation of PHEVs. Admittedly, the early penetration of EVs into the existing fleet with a percentage of 32% faces many practical difficulties, including the capacity constraints of existing production lines or difficulties encountered by automotive and battery manufacturing companies in ramping up production. For the purpose of this work, it is considered that this was made possible in 2013, a year for which a number of car manufacturers have announced their plans, expecting to launch mass production of PHEVs at prices potentially comparable to those of existing ICE cars. If EVs are charged during off-peak hours, under a controlled charge scheme through the use of information and communication technologies that enable the connection of an aggregator, responsible for coordinating the charging of EVs with the charging stations, and the characteristics of each EV, then this could enable the increased use of renewable energy capacity in the island with lower emissions rates. Even more, if an intelligent recharging strategy is adopted, then EVs penetration can be an important factor in the management of the current electricity system as the future recharging of the batteries could take place in periods with low consumption or in periods of excess of electricity production derived by the renewable energy sources. Such a scenario would be very beneficial for the proposed energy system, since the simulation tool used here shows that in case of having the PHEVs charged (in a G2V approach) during the night till the early morning hours (off-peak hours), namely from 22:00 to 08:00 (before most people go to work), the impact of such changes on the load profile is not negative, as the load peaks remain rather the same while valleys are filled (Fig. 5(e)). Even though the penetration level of renewable energy drops compared to the previous case, there are still remarkable environmental benefits in terms of the reduction of CO_2 emissions compared to the BAU scenario in spite of the extra load demand for recharging the vehicles (Table 4), which is primarily covered in this case from renewable sources and to a lesser extent from fossil fuels.

The last case in Fig. 5(f) considers the further addition of 10 MW of geothermal energy with Geo(3) for the same year without the presence of EVs. Even though the peaks observed for the load profile do not change in this case, a striking feature of the results in Fig. 5(f) is the level of renewable penetration that reaches a maximum of 100% during Sundays, as derived from the full coverage of the electricity load (blue line) from the renewable sources. Additionally, there is a significant shift of the load covered by fossil fuels to the right compared to Fig. 5(d), as the initial point of the fuel peak starts in this case at 08:30 instead of the one at 07:00, implying that less fossil fuel is used during the morning hours. This result is also indicated by the smaller surface of the area below the fuel curve (or similarly by the smaller created valley). It is important to note, however, that in this case the base load electricity generation by the additional geothermal capacity significantly exceeds the off-peak demand, resulting to a large extent in waste of available resources due to the absence of sufficient electricity load.

Based on the load profiles of Figs. 5(a)-(f), this work compares the impact of scenarios 1, 2, and 3, on electricity supply until 2020. Specifically, scenario 1 corresponds to zero penetration of PHEVs in the power grid, while the increase of electricity supply is considered only as a function of the load demand (4%). Since 2007 is the base load case considered in this study, all the scenarios have the same electricity supply, given that no additional renewable sources are available, as shown in Table 3. Figs. 6(a) and (b) show that a large fraction of the electricity supply corresponds to the fuel source (54.6%), followed by the other existing renewable sources (geothermal and hydro), a characteristic expressed earlier with the large percentage of renewable sources in the electricity supply of São Miguel Island. Between the years 2007 and 2013, new renewable energy sources are introduced into the system, i.e. geothermal and wind (Table 3), while scenario 2 further considers a 32% penetration of EVs into the fleet mix and the addition of a 10 MW geothermal power plant in 2013. As expected, the available electricity supply increases by 5.4% compared to scenario 1 (no EVs), since the new addition of the geothermal power plant for the year 2013 is accompanied by the electricity demand from the EVs in a G2V approach. This combination leads to a beneficial decrease of 14.7% in fuel used for electricity supply to the grid, of which the largest share corresponds to the new addition of the geothermal plant. In scenario 3, PHEVs are progressively introduced into the system, starting from a 4% penetration in 2013 and following a linear increase over the years to reach the value of 32% in 2020, however no significant differences are observed compared to the previous scenario for the year 2013.

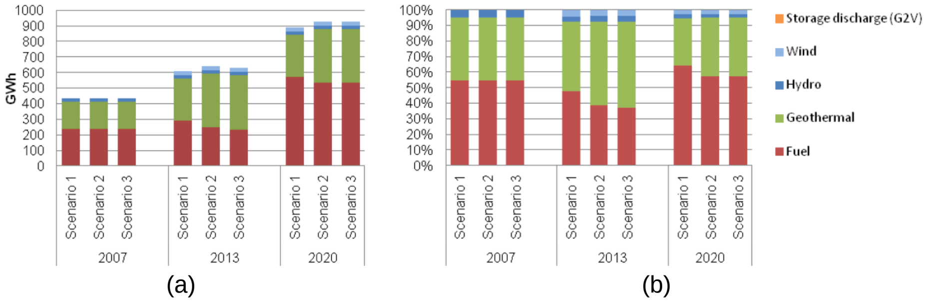

Fig. 6. Electricity supply in scenarios 1, 2, and 3 in (a) absolute values, and (b) percentage terms

A comparison of the results in Figs. 6(a) and (b) for the year 2020 indicates that the electricity supply using fuel is still higher in scenario 1, represented by a share of 64.1% and coupled with a lower percentage of renewable energy sources, since no other additions of new power plants are considered up to that year. On the other hand, scenarios 2 and 3 show no difference between them, as they both have the same penetration of EVs for 2020. The importance and impact of the EVs on the fuel consumption for this year is higher compared to 2013, providing an indication that the existing energy system needs to be upgraded, although a percentage of the local energy demand can be covered by the local renewable energy sources, which are used and applied at a relatively limited level compared to their potential.

4 Discussion

The primary energy used under the current state in the island of Sao Miguel is heavily dominated by the consumption of oil. Yet, examining the electricity sector reveals that this changes and a large part of the electricity is provided by the use of renewable sources under the BAU scenario. When there is an increase of the renewable energy in the form of new installed wind units or new geothermal power plants, then there is still more of a fuel decrease in the reference system, something observed to a higher extent during the weekends.

Moreover, as the penetration of renewable energy sources in the energy mix increases, either in the form of wind or geothermal energy, while at the same time the increase of electricity demand is considered to be 4% in this study, there is a need for additional capacity from renewable sources to enter to the local energy system of the island. As already pointed out, a large proportion of the primary energy is used in the transportation sector, hence the implementation of a solution that considers the electrification of the vehicle fleet bears the potential to deliver synergistic benefits.

Combining the results obtained in Table 4 with the different EV penetration schemes (in scenarios 2 and 3) indicates that the introduction of EVs does not expose the system at the risk of relying solely on renewable sources that could create potential problems to the main grid (e.g., due to sudden shortage of relevant power plants), thus the deployment of EVs in the vehicle fleet mix of the island could take place either at once or gradually. In the first case, the use of EVs for leveling the power consumption diagram resulted in the decrease of the renewable energy penetration compared to the scenario BAU+Geo(1)+Wind+Geo(2) in Table 4, implying that part of the savings on vehicle fuels is replaced by fuel oil for the thermal plants. However, the renewable energy penetration is still higher compared to the cases considered before that, e.g. BAU+Geo(1) and BAU+Geo(1)+Wind, meaning that the further addition of renewable sources shows that EVs under a flexible time of recharging strategy (charged during night hours) do also run with the use of renewable electricity, something that is in favor of the local energy system and avoids a great amount of fossil fuel imports. This flexible (during night hours) recharging of EVs would be required in order to regulate the recharging according to the availability of excess renewable electricity so as to maximize the share of renewable energy sources.

On the other hand, implementing scenario 3 with a gradual deployment of the EVs in the energy system (considering also a 4% increase of electricity demand) till 2020 shows that such a policy does not create, as also expected, any problems to the main grid. On the contrary, this might be a better and more realistic solution since it is less likely to have such a large amount of EVs (32%) at once, given that this would require of course major infrastructural changes; and more important, this gradual implementation does not decrease in a very significant percentage the corresponding penetration of renewable sources in the energy system.

In terms of CO_2 emissions, the introduction of EVs with a policy based on an immediate deployment results in an increase compared to the scenario BAU+Geo(1)+Wind+Geo(2) in Table 4, since the energy system covers the extra demand by fossil fuels, while if this happens gradually then it enables a better handling with possible light reductions in the transportation sector. Nonetheless, a further penetration of renewable sources in the energy mix in the following years and till 2020 will only be possible to be done if more than the proposed power plants will be built based on the criteria of the 4% yearly increase of energy demand. If the system will be left as it is from the year 2013 and afterwards then as expected due to the better and more economic technology characterizing the fossil fuel energy will result once again in an increase of used fuel even with the gradual or immediate penetration of EVs. This is in accordance also with simulations and scenarios of different penetration levels reported in [20] regarding the case of Portugal.

5 Conclusions

The scenarios examined in this work for the São Miguel Island show that local energy demand can be covered by the increase on energy penetration of renewable sources and EVs up to the year 2013. A key finding of this work is that the local electric power grid does not seem to present any immediate technical barriers for introducing EVs under the G2V mode. As a direction for future work, it would be of great interest to examine the system in a V2G context, in which a potentially significant percentage of the electricity supply provided by the EVs could compete and replace power plants that use fuel oil, thus yielding substantial economic benefits, which are even more important for remote islands compared to mainland cases, because of the cost of transporting fuel. In this direction, the dispatchable power from EVs can be a feasible option for shaving the peaks of the electricity load profile, while valley filling can be effective once control practices for charging the vehicles are implemented.

The results obtained from the scenarios under consideration also reveal that the introduction of renewable sources initially, and afterwards of the charging of EVs has the potential to deliver significant environmental benefits in terms of reduction of CO_2 emissions, while promoting a more environmentally friendly image of the local communities to the tourists who visit the island. However, if electricity consumption continues to grow at high rates up to the year 2020 and no further actions are taken (e.g., use of more renewable energy sources, V2G approach, or both), the positive effects in environmental and economic issues are expected to decline even with the presence of a large share of PHEVs in the fleet mix. It is anticipated that the latter will have a more important impact on electricity supply compared to year 2013; yet it is considerably better, both in economic and environmental terms, when compared to the scenario where no EVs are present.

Moreover, no significant difference is observed in the electricity supply if the penetration of EVs is realized under a high or a low/gradual rate scenario for the period 2013-2020. Overall, the analysis shows that PHEVs will have a positive environmental contribution either in the short or long run. Along these lines, PHEVs can lead to the increase of renewable energy sources under the G2V mode and, in parallel, provide the necessary storage and backup power in a V2G approach. This, in turn, will allow a higher level of renewable penetration either by a larger share of PHEVs or in collaboration with other storage systems, such as water pump storage or compressed air energy storage (CAES). A potentially higher fuel price in the future would result in an increased percentage penetration of renewable sources, which combined with demand side management strategies and an intelligent planning of the system (including storage) will facilitate the pathway towards a fully renewable island. In this context, a sensible and foresighted design of the local energy system would prove beneficial in terms of quick response and high value electric services, which are needed and purchased by the grid operator to balance the load fluctuations or adapt to unexpected equipment failures.

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7 References

1. Göransson, L., Karlsson, S., Johnsson, F.: Integration of plug-in hybrid electric vehicles in a regional wind-thermal power system. Energ. Policy 38, 10, 5482-5492 (2010)
2. Weiller, C.: Plug-in hybrid electric vehicle impacts on hourly electricity demand in the United States. Energ. Policy 39, 6, 3766-3778 (2011)
3. Kadurek, P., Pina, A., Ioakimidis, C., Ferrão, P.C.: São Miguel Island as a case study on a possible usage of electric vehicle to store energy. In Proceedings of the 24th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition, (2009)
4. Kempton, W., Tomić, J.: Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. J. Power Sources 144, 1, 280-294 (2005)
5. Kempton, W., Tomić, J.: Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. J. Power Sources 144, 1, 268-279 (2005)
6. Kadurek, P., Ioakimidis, C.S., Ferrão, P.C.: Electric vehicles and their impact to the electric grid in isolated systems. In Proceedings of POWERENG 2009 - 2nd International Conference on Power Engineering, Energy and Electrical Drives, pp. 49-54. IEEE, (2009)
7. Pina, A., Ioakimidis, C.S., Ferrão P.C.: Introduction of electric vehicles in an island as a driver to increase renewable energy penetration. In Proceedings of 2008 IEEE International Conference of Sustainable Energy Technologies, pp. 1108-1113. IEEE, (2008)
8. Camus, C., Farias, T.: The electric vehicles as a mean to reduce CO 2 emissions and energy costs in isolated regions. The São Miguel (Azores) case study. Energ. Policy 43, 153-165 (2012)
9. Alfstad, T.: Development of a least cost energy supply model for the SADC region. Master's Thesis. University of Cape Town, (2005)
10. Loulou, R., Lehtilä, A., Kanudia, A., Remne, U., Goldstein, G.: Documentation for the TIMES Model - PART II. Energy Technology Systems Analysis Programme, (2005), `http://www.iea-etsap.org/web/Docs/TIMESDoc-Details.pdf`
11. Loulou, R., Remne, U., Kanudia, A., Lehtila, A., Goldstein, G.: Documentation for the TIMES Model - PART I. Energy Technology Systems Analysis Programme, (2005), `http://www.iea-etsap.org/web/Docs/TIMESDoc-Intro.pdf`
12. ARENA: Projecto ERAMAC Recursos Energéticos Endógenos Energia para os Açores. Agencia Regional da Energia da Regiao Autonoma dos Açores, (2005)
13. SREA: Statistical Yearbook of the Azores Region 2011. Serviço Regional de Estatística dos Açores, (2012)
14. EDA: Renováveis podem ser 75% da produção de electricidade nos Açores em 2018. Eletricidade dos Açores, (2010)
15. Pina, A., Baptista, P., Silva, C., Ferrão, P.: Energy reduction potential from the shift to electric vehicles: The Flores island case study. Energ. Policy 67, 37-47 (2014)
16. DGEG: Estatísticas-Preços de Energia. Direcção-Geral de Energia e Geologia, (2008)
17. EDA: Characterization of the Electricity Transport and Distribution Networks of the Açores. Electricidade dos Açores, (2006)
18. RAA: Plano Integrado de Incentivos a Modernizacao Tecnológica do Parque Automovel na Regiao Autonoma dos Açores Estudo Preliminar. Região Autónoma dos Açores, (2006)
19. Camus, C., Farias, T.: The electric vehicles as a mean to reduce CO 2 emissions and energy costs in isolated regions. The São Miguel (Azores) case study. Energ. Policy 43, 153-165 (2012)
20. Camus, C., Farias, T., Esteves, J.: Potential impacts assessment of plug-in electric vehicles on the Portuguese energy market. Energ. Policy 39, 10, 5883-5897 (2011)