PHEV Control Strategy Including Vehicle to Home (V2H) and Home to Vehicle (H2V) functionalities

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***Abstract*—Plug-in Hybrid Electric Vehicles (PHEVs) are seen to be a step forward in vehicle electrification, to replace ICE-based conventional vehicles. On the one hand, using a PHEV means that a part of the vehicle energy comes from the grid or other sources, such as renewable energy, to charge the battery. On the other hand, increasing the number of nuclear and coal power plants to supply these new needs would shift the problem to another place, and will not permit solving the problem of pollution or fossil fuel depletion. The main idea presented in this paper consists in sharing the production between the home and the vehicle and use at the same time the vehicle to supply power to the home appliances during the electricity peak demand (*i.e.*, when the prices are the highest).**

In this study, a general control strategy is designed, taking into account the overall system (grid, local production from renewable, and vehicle, including its battery). Furthermore, a simulation, including the household daily power profile and the PHEV drive cycle is presented. The home power profile takes into account photovoltaic (PV) and wind production as well as home load profile based on real data. The objective of the control strategy is to minimize the total energy cost.

***Index Terms*—Control strategy, electric vehicles, power generation scheduling, vehicle power systems.**

I. Introduction

According studies as recently as 2008, in France, emissions of conventional vehicles represented 23.6 % of the total GHG[1] [1]. Therefore, the two major challenges of the next few years consist in developing Plug-in Hybrid Electric Vehicles (PHEVs) or Electric Vehicles (EVs) and modify the grid to permit all the vehicles to be charged everyday, without significantly increasing the number of nuclear and coal power plants.

In order to avoid the construction of new power plants, local and distributed energy productions have to be built, to increase the amount of renewable energy. As most renewable energy sources are intermittent, storage systems as well as advanced controls have to be developed. The EV can have an important role to play in such an infrastructure as a storage system. According to [2], most of the vehicles are at home between 8 pm and 7 am; moreover, most of the people use their vehicle between 8 am and 9 am and from 4 pm to 5 pm. Therefore, 11 hours are available, to use the vehicle as a storage system: during this time, the EV/PHEV can be charged or discharged, depending on user needs. Thus, the charge can be shifted during the night, when the demand on the grid is low.

Moreover, moving forward, most countries will increase the number of Intermittent Renewable Energy Sources (IRES), like wind and solar power, to respect the Kyoto protocol. The problem with the IRES is that the grid can become unstable (large power variation). Using the PHEV's battery to stabilize the grid could help to solve these problems partially [3], [4].

This article presents a new control strategy, which includes the overall system: the local network where the home is connected, two renewable sources: solar and wind power, and the grid. The series PHEV's battery can be connected to home and so transfers its energy to the home (V2H) [5]. Of course, when the vehicle is connected at home, the main objective it to charge the battery (H2V).

II. Problem formulation

The aim of the home control (HC) strategy is to figure out which energy fits the best for its electrical consumption. There exists a choice between the renewable energy source, the grid, or the PHEV's battery.

The choice first depends on the State-of-Charge (SoC) of the battery. Moreover, the choice also depends on the cost of operation of grid, battery, and the renewable energy source. In this study, the renewable energy cost is assumed to be zero. The battery's energy cost depends on how much energy the battery has been supplied with: from fuel, grid, or renewable energy. The grid cost depends on the energy demand: the higher the ratio demand/production, the higher the prices. In this study, only two different prices for off-peak are considered (between 2 am and 5 am and 1 pm and 4 pm) and peak hours (rest of the day).

[1]Greenhouse gases

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The algorithm's goal is to minimize the energy cost with the following constraints:

1) only surplus of renewable energy can be sold;
2) the ICE cannot charge the vehicle when the vehicle is at home (minimizing the emissions);
3) if possible, the battery must be completely charged in the morning;
4) the battery cannot be charged from the grid during peak times;
5) the ICE cannot charge the vehicle while driving: only charge depleting and charge sustaining are allowed, to minimize fuel consumption.

Knowing each production source and electricity consumption profiles, a prediction can be made of the amount of energy produced by the renewable energy source during the day and how much energy the household needs (Figure 2, Figure 1).

Then, the battery SoC can be anticipated to prepare the vehicle to supply the home when the grid costs are too high, because of a high energy demand.

Each profile (renewable and consumption) have been measured from local wind and solar irradiance conditions. The available power is deduced from the following equations, as shown in Figure 1:

$$\mathrm{P_{solar}} = E \cdot S \tag{1}$$

where E is the solar radiation in (W/m^2) and S the surface of photovoltaic panel.

$$\mathrm{P_{wind}} = \frac{1}{2}\rho S V^3 C_p \tag{2}$$

where ρ is the air density, S the surface of blade (m^2), V the wind speed (m/s) and C_p is the perform coefficient.

The overview of energy management control principle is given in Figure 3: the HC must predict the 8 next hours of electricity consumption and decides which energy profile will fit the best to supply the home demand. Moreover, the HC must compute the level of SoC at which the vehicle will settle down at, when it comes back home. The SoC calculated by the HC is sent to the vehicle controller (VC), which is always linked with the HC. The VC will control the ICE and the battery to reach the SoC (see Figure VI), based on the distance between the house and the vehicle. It will also consider the time when the vehicle will be back at home

III. Battery cost

In order to minimize the energy cost, the cost of three sources are compared in real time: renewable source, grid, and battery. To calculate the battery energy cost, the energy content (from the grid, renewable, or fuel) has to be known. Thus, the following equation has been formulated.The costs are assumed: the renewable energy cost is zero, the fuel cost depends on the trip fuel consumption and the grid cost changes during the day, depending on the demand. During off-peak

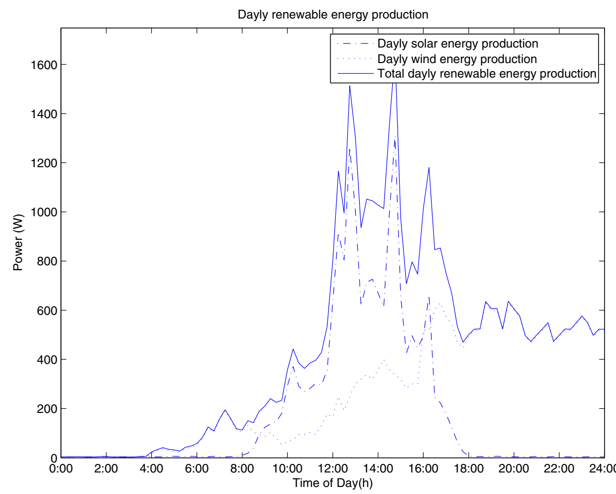

Figure 1. Renewable energy profile

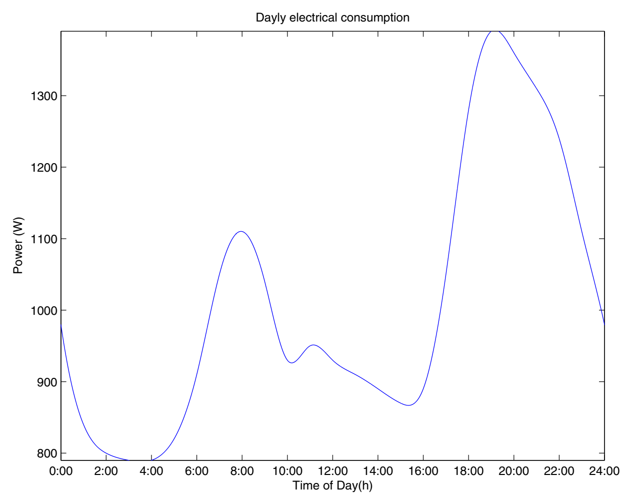

Figure 2. Home electrical consumption profile

hours, the grid energy price is 0.0864 €/kWh and during peak hours, the cost is 0.1275 €/kWh. The schedule and cost of peak and off-peak hours is given by EDF (Electricité de France)[6].

It is assumed that the vehicle can recover the energy during braking phases. Of course, this energy will be free.
The battery's cost is calculated with the following equation :

$$\mathrm{C_{bat}} = \frac{V_f(t)C_f(t) + E_g(t)C_g(t) + C_{bat}(t-1)E_{bat}SOC(t-1)}{SOC(t)E_{bat}} \tag{3}$$

when V_f is the fuel's volume (l), C_f is the fuel's cost, E_g is the grid's energy (Wh), C_g is the grid's cost (€/Wh), C_{bat} is the battery's cost (€/Wh), E_{bat} is the battery's energy (Wh) and SOC is the battery's State of Charge (%)

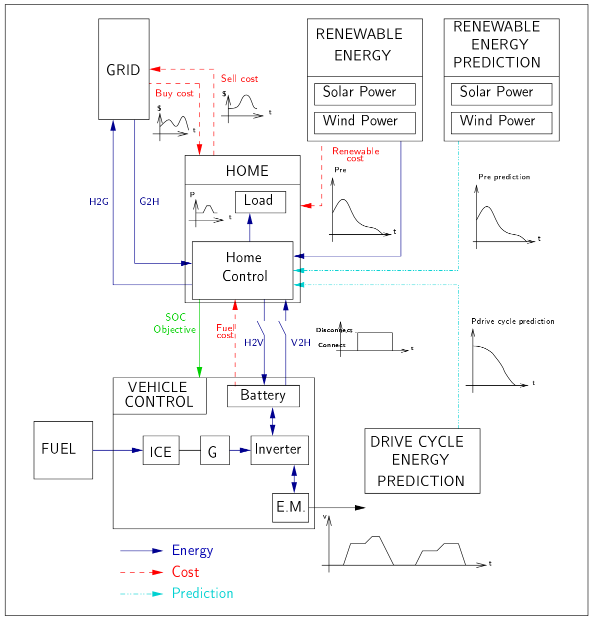

Figure 3. Synoptic: HC has to use the less cost energy and send the SoC objective to VC which must control the battery SoC when the vehicle is moving, and command the ICE

IV. Energy Prediction

A. Consumption and Production of the household prediction

One of the main idea of this paper is to predict how much energy the household consumes and produces. In order to make this prediction, different profiles have been used (Figure 1 and Figure 2). The Figure 5 and Figure 4 shows the 8-hour energy prediction. This means, that at each iteration, the next 8-hour renewable energy production or consumption is computed.

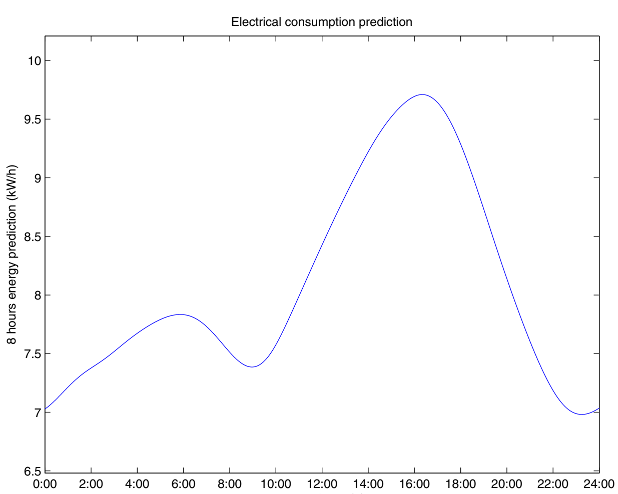

Figure 4. Home electricity consumption prediction: used to know at each instant/time of the day, how much electrical energy will be need in the next 8 hours

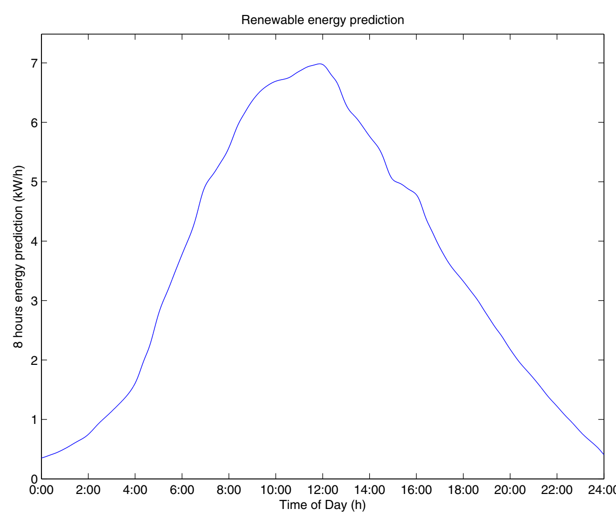

Figure 5. Renewable energy prediction: used to know at each instant/time of the day, how much renewable energy production will be available in the next 8 hours

B. Drive cycle energy prediction

In the investigated system, it is assumed that energy required to return back home is known at each instant/time: this can be known if the vehicle is equipped with a navigation system, such as a GPS. In order to calculate this energy, a predefined driving cycle is used (Figure 6): the energy needed for the vehicle to return back home is shown in Figure 7. Using this prediction, the final SoC, assuming the vehicle is in charge depleting mode, can also be computed. From this, the VC decides whether to switch on of off the ICE.

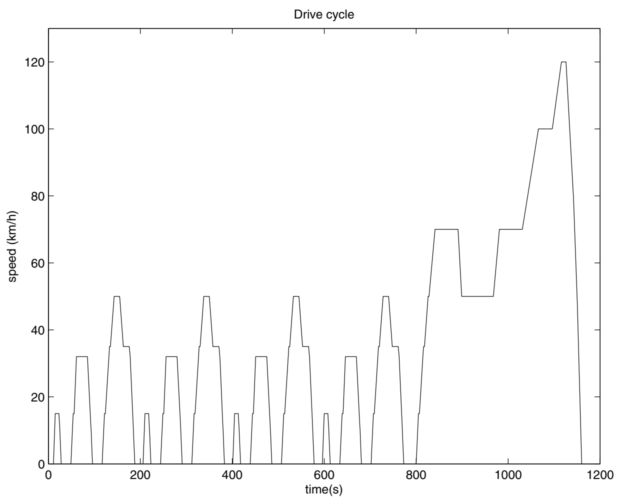

Figure 6. Vehicle drive cycle

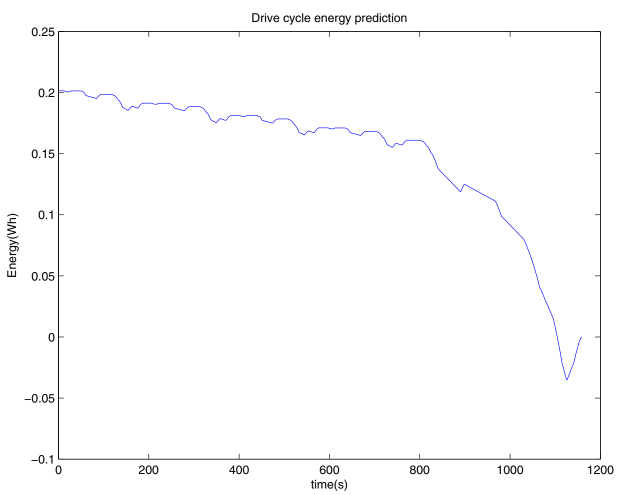

Figure 7. Drive cycle energy prediction: used to know how much energy is needed for the vehicle to return back home

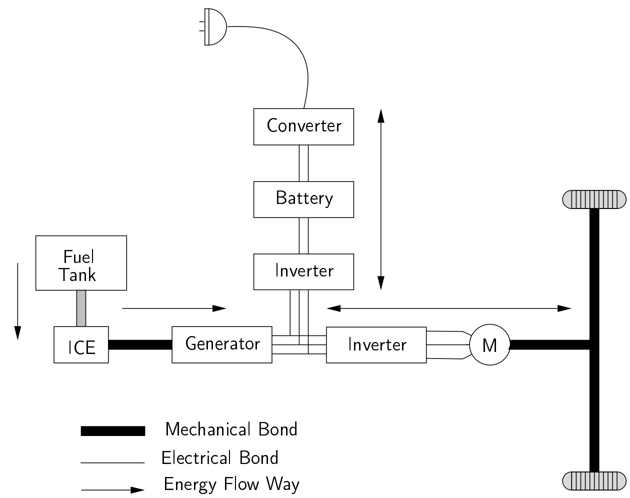

Figure 8. Series PHEV diagram

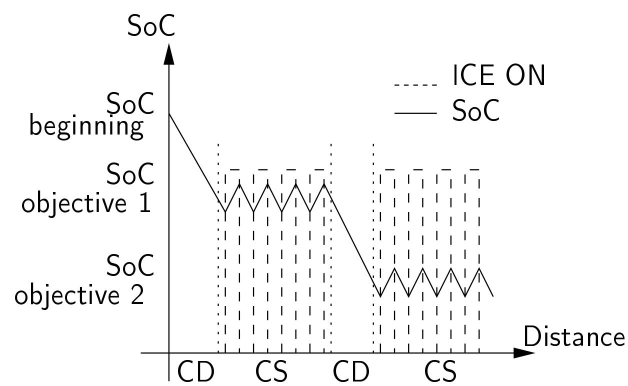

Figure 9. Vehicle Control

V. Vehicle control

The simulation of a series PHEV (Figure 8 [7]) for which the parameters are given in the Table I associated with the vehicle controller described in Figure 9 has been carried out. The vehicle is in charge depleting (CD) mode as long as the SoC set by the HC is not reached (Figure VI). Once the SoC is reached, the VC switches to Charge Sustaining (CS) mode [8], where the ICE works at its best efficiency point, to charge the battery.The vehicle is modelled with AVL CRUISE software [9][10].

VI. SoC objective determination

During a driving cycle, the vehicle is not connected to the grid; the HC must send the SoC objective to the VC, to prepare the battery to supply energy to home, or be charged by the grid or renewable energy source. The SoC objective can vary during the trip time, because the consumption and production predictions vary during the day. The figure below Figure 10 shows the flowchart describing the SoC objective decision algorithm.

VII. Simulation

A. Scenario 1: Weekday

It is assumed at the beginning that the battery is 60 % charged and all of it comes from renewable energy. The vehicle must be ready (*i.e.*, battery fully charged) at 8 am ($T_{morning}$), because the driving cycles start at 8.30 am. The end of the working day is assumed to be at 6 pm. Table II shows a

Table I
Vehicle description

Vehicle Type	Small Car
Vehicle Mass	1 200 kg
Font Area	1.97 m^2
Drag Coefficient	0.284
Rolling Resistance	0.01
ICE type	Gasoline %
Number of cylinders	4
Battery capacity	20 Ah
Battery voltage	320 V
Init SOC	60 %

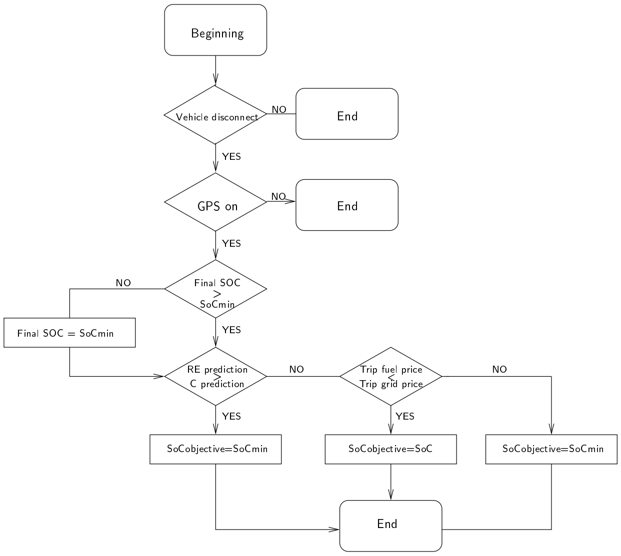

Figure 10. $SoC_{objective}$ decision algorithm

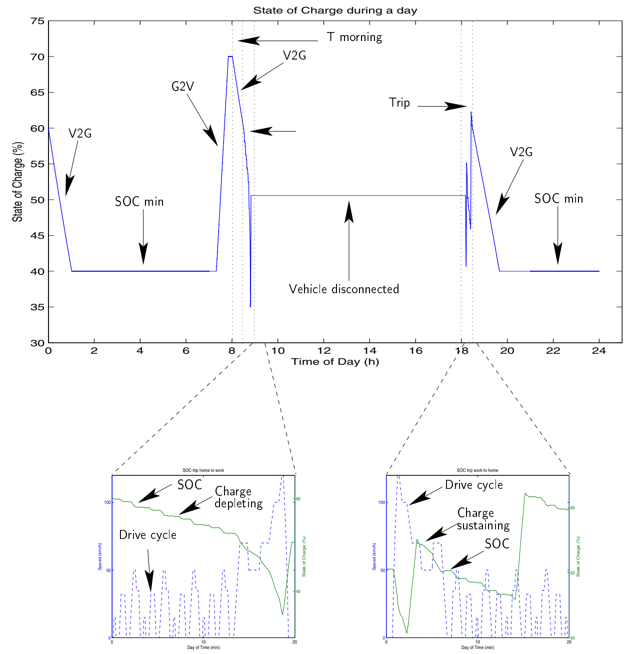

Figure 11. Battery state of charge along a full day

summary of what is considered as a normal day (reference case scenario). The simulation duration is then 24 hours.

Table II
DAY SCHEDULE

Description	Time of day	Connected or Disconnected
Simulation beginning	0 am	Connected
Tm	7 am	Connect
Beginning of work's trip	7:30 am	Disconnected
End of work's trip	7:50	Disconnected
During work's day		Disconnected
Beginning of house trip	5:40 pm	Disconnected
End of house's trip	6 pm	Connected
End simulation	24 pm	Connected

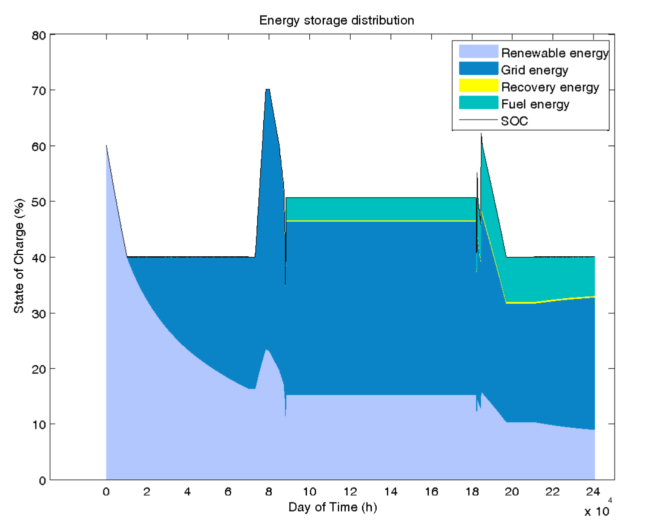

Figure 12. Energy fraction from the grid, renewable recovery, and fuel in the battery, during a week

B. Results

Figure 13 shows the battery SoC variation during the day. At the beginning, the battery discharges, because the battery energy cost is less expensive than the grid's energy.

Indeed, the battery has been previously charged by renewable energy. Then, the grid is used to supply the house, because the renewable energy is not sufficient to charge the battery. At 8 am, the battery must be fully charged: consequently, at 7 am, the grid supplies the battery. Between 8 am and 8.30 am, the HC decides to use the battery to supply the household, because it is cheaper than the grid. At 8.30 am, the car is disconnected from the house, and the driving cycle starts: the vehicle is in charge depleting mode and reverts back to charge sustaining mode at the SoC level indicated by the HC. At the end of its trip, the battery still has some energy that can supplied to the house: once the vehicle is connected, it starts to supply the needed power to the house, as the battery's operating cost is less expensive than that of the grid. Finally, at the end of the day, the grid supplies the home power demand. Figure 14 shows the energy contribution from the grid, renewable energy source, recovered braking energy, and the fuel in the battery.

C. Scenario 1: Weekend

The second simulation is set during a weekend day. The battery will be charged at 60 % with renewable energy at the beginning of the simulation and the driver stays all day at home. This model will show the battery charge with renewable energy at the midday peak. Solar and wind power data does not change.

D. Results

At the beginning, the house supplies the consumer, until the low SOC is reached. Then, the battery waits until renewable energy level is larger than the consumer energy. Thus, the renewable energy source supplies the battery. Then, when renewable energy level is lower than the consumer energy, the battery uses the energy charged by solar and wind power to supply the home, until the low SOC is reached.

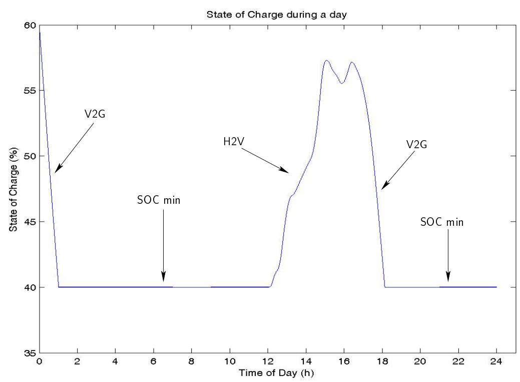

Figure 13. Battery SoC during a full day

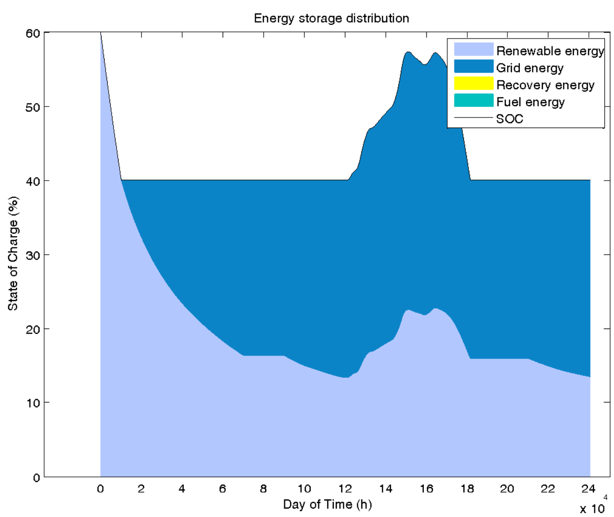

Figure 14. Energy fraction from the grid, renewable energy, braking energy recovered, and fuel in the battery during a weekend

VIII. Conclusion and Future Work

To conclude, a general control strategy has been designed, taking into account the overall system (grid, local production from renewables, and the vehicle, including its battery). A simulation has been carried out, including the household daily power profile and the PHEV driving cycle. The home power profile takes into account photovoltaic (PV) and wind production as well as the home load profile, based on real data. The objective of the control strategy was to minimize the total energy cost. From this study, the total energy cost savings was found to be 20 %.

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