Optimization of a Battery Charging Schedule in a Net Zero Energy House using Vehicle-to-Home functionality

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Abstract

Electrification of transportation is a step forward to reduce greenhouse gases. Using a plug-in hybrid electric vehicle gives a lot of possibility to reduce this pollution. Indeed, due to the integration of battery in vehicles, the system gives the opportunity to implement the *vehicle-to-home* functionality which allows grid support to smooth the global energy production.

This study discusses a microgrid composed of a net zero energy house and a plug-in hybrid electric vehicle which has the capability to be charged at home and at workplace. It may also be used to help in supplying household loads. Two case studies: one in summer and one in winter are presented. The energy bill is reduced by 10 % for the winter case whereas in summer, the cost of production is higher than that of energy consumption.

1 Introduction

Since transportation is one of the main contributors of carbon dioxide emissions (Tie & Tan 2013) promoting the use of greener vehicles could have a significant positive impact. Plug-in Hybrid Electric Vehicles (PHEVs) are a step forward in reducing these emissions (Eppstein, Grover, Marshall & Rizzo 2011). On the other hand, Net Zero Energy Houses (NZEHs) or near NZEHs can be instrumental in reducing our carbon footprint. A coordinated interaction of PHEVs with NZEHs is thus very promising (Thomas & Duffy 2013).

In spite of these prospects, one of the challenge of integrating electric vehicles in smart grid is how to deal with the battery charging schedule to minimize the energy cost (Berthold, Blunier, Bouquain, Williamson & Miraoui 2012).

This paper studies a microgrid composed of a near NZEH called ÉcoTerra which is located in Eastman (Québec, Canada) and a series PHEV. This paper describes the home and PHEV control strategy. On one side, the PHEV strategy uses a fuzzy logic control which provides the Internal Combustible Engine (ICE) power, by considering the State of Charge (SoC) (Li, Sharkh, Walsh & Zhang 2011), the drive cycle power and an ICE timer. On the other side, a linear algorithm is used for the home controller which use on peak and off peak price as defined in France. However, the electricity cost can be extended as a dynamic price as shown in (An, Huang, Kang & Zhou 2013) The last section presents the two case studies: one in winter and one in summer.

2 System presentation

The system shown in the schematic of Figure 1 is composed of a near NZEH house named ÉcoTerra and a PHEV. The ÉcoTerra, built in 2007, has a 3kW building-integrated photovoltaic (BIPV) system covering the south facing side of its roof.

The BIPV system and the electric grid supply the ÉcoTerra house. The PHEV is connected to the house by a bidirectional AC/DC converter which allows the power flows : *home-to-vehicle* when the PHEV battery is being charged and *vehicle-to-home* when the vehicle helps to supply the home.

The control of the all system is done with two controllers : one in the house and one in PHEV. The PHEV controller manages the PHEV powertrain which determines if the ICE is turned on or off and how much power it has to deliver. This controller will be presented in section 3. The house one decides if the battery has to be charged or if the power should be used to supply the household loads when the PHEV is connected to the house.

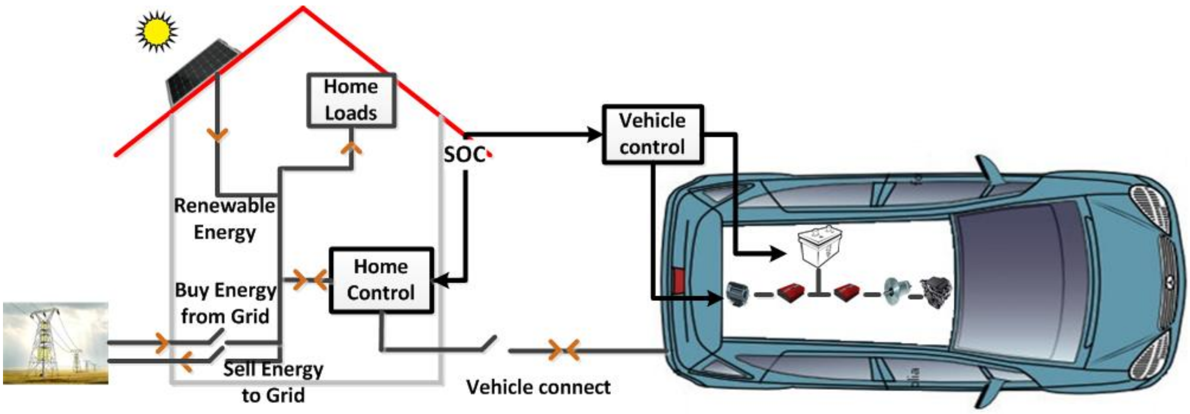


Figure 1: System Diagram

Description of ÉcoTerra

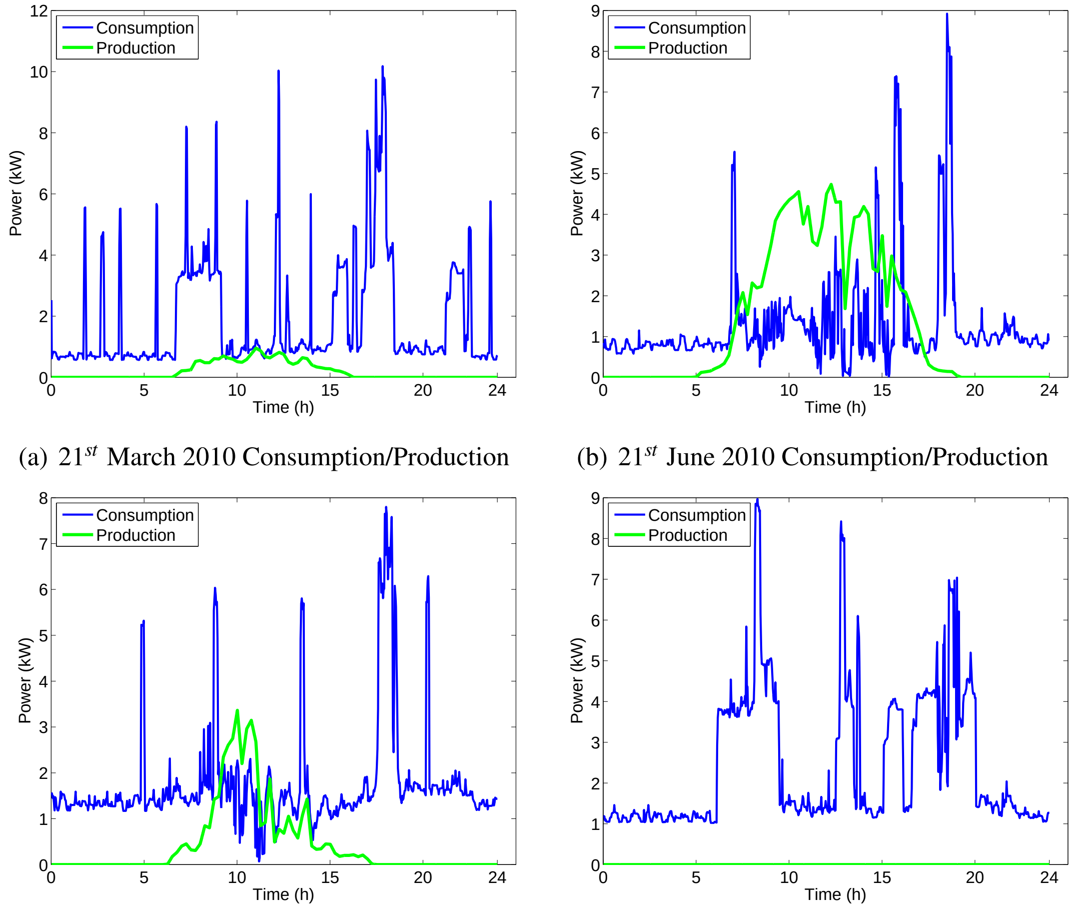
The Écoterra house shown in Figure 2, is a near NZEH (Bucking, Athienitis, Zmeureanu, O'Brien & Doiron 2010) located in Eastman (Québec, Canada) (CMHC 2007).

Figure 2: The Écoterra house

This 141 m^2 (without the basement) individual house which has 2 stories. The first floor is composed by a living room, a kitchen, a washroom and a laundry. The second floor has two bedrooms, an office and a bathroom (Noguchi, Athienitis, Delisle, Ayoub & Berneche 2008).

The Écoterra house was designed to produce energy to meet its consumption. To achieve this, 3 kW amorphous silicon (a-Si) system BIPV are installed on the roof (Chen, Athienitis & Galal 2010). In addition, a regenerative thermal device located behind BIPV and a geothermal pump are used to heat indoor space air and the domestic hot water.

The house is inhabited by a couple and was instrumented in 2010. Figure 3 presents the production and the consumption in the four seasons at solstice and equinox dates.



(a) 21st March 2010 Consumption/Production (b) 21st June 2010 Consumption/Production

(c) 21st September 2010 Consumption/Production (d) 21st December 2010 Consumption/Production

Figure 3: ÉcoTerra house Production/Consumption in four relevant dates

PHEV presentation

The series PHEV shown in Figure 4 is based on a 41 kW internal combustion engine (ICE), a 32 kW generator, a 75 kW electric motor and a 15 kWh lead acid battery which is directly connected to the 300 V DC bus.

Experimental data for the ICE (FC SI41emis), the generator (GC PM32), the electric motor (MC AX75) and the battery (ESS PB25) are extracted from the ADVISOR software. The battery is configured as two branches of 25 cells each.

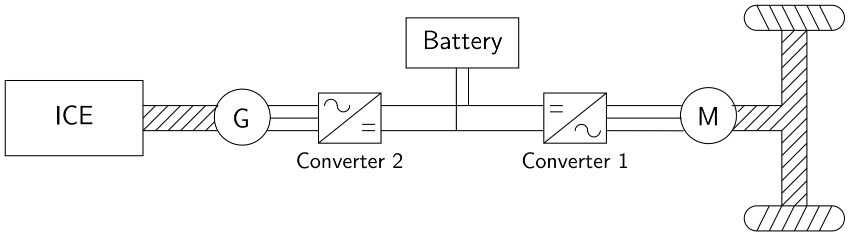


Figure 4: Series PHEV

3 Home controller

Figure 5 presents the house controller algorithm where P_{grid} is the grid power, P_{bat} is the battery power, P_{bat_max} is the maximum battery power, Pc is the household consumption and P_{solar} is the solar production power. The battery power is limited by the bidirectional AC/DC converter which respects level I charging (120 VAC, 16 A) from the SAE J1772 standard.

When the battery power is negative, the battery helps to supply household loads and when is positive, the battery is charging. The grid power can also be positive and negative, depending on the power flow. When it is positive, the system sells to the grid, and the counter hold for power being supplied to the system. The algorithm prioritizes the charging of the battery by solar energy.

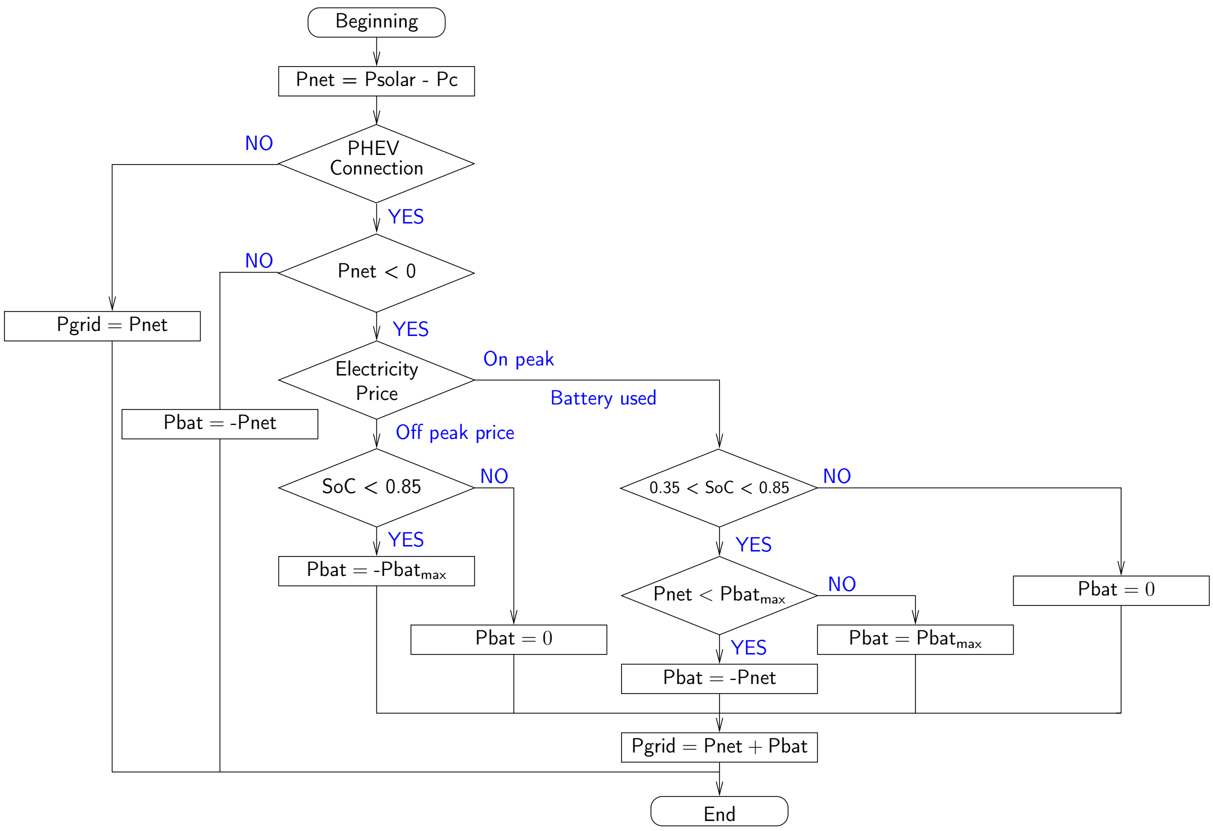


Figure 5: House control algorithm

The battery operation depends on its State of Charge (SoC) and the electricity price depending on on-peak and off-peak price. The battery operates in its linear part which falls between 30% and 90% of its SoC.

4 PHEV Controller

Figure 6 shows the algorithm which is used to manage the PHEV powertrain energy. The fuzzy logic controller is described in Figure 7. When the vehicle is connected to the house, the PHEV controller is turned off and the home controller takes over the battery management When, the vehicle is connected to a marketplace or at workspace station the PHEV controller is used and allows battery charging if the SoC is below 85 %. At workplace or marketplace, the PHEV is allowed to use level I and II (240 VAC, 80 A) battery charging.

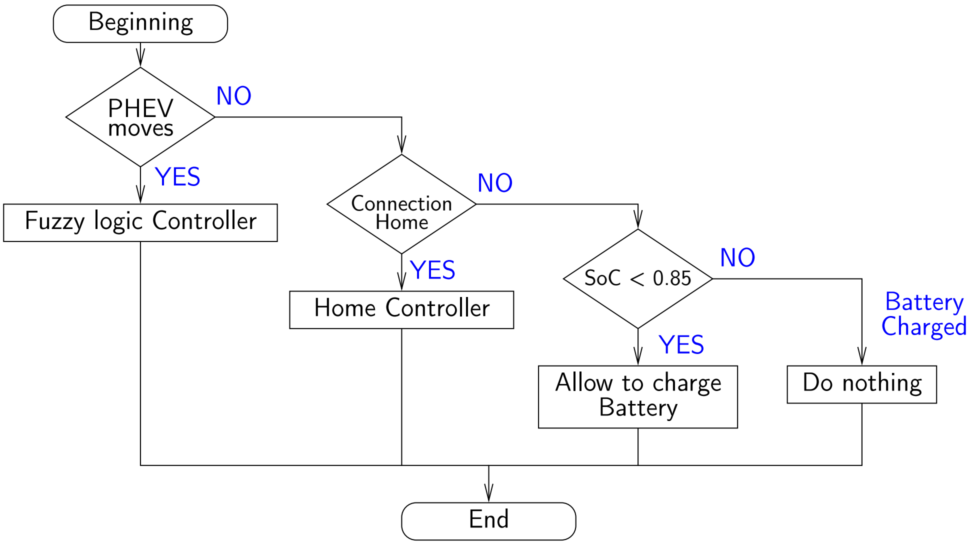


Figure 6: Master PHEV controller algorithm

The PHEV fuzzy logic controller manages the ICE power in terms of turning the engine on or off (Ravey, Blunier & Miraoui 2012). The fuzzy logic describes in Figure 7 has three inputs : the battery SoC, the drive cycle power and a ICE timer. Last input acts as a penalty preventing the untimely ignition and extinction of the ICE. The fuzzy logic output is the ICE power.

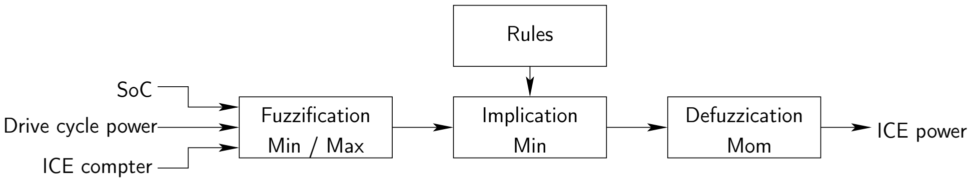


Figure 7: Fuzzy logic controller

"Fuzzification" is done with the min/max method, the Mandani method (Min) is used as implication method and the defuzzification is made with the mean of maximum method.

This section describes the membership functions and the rules applied to this controller.

Input membership function : State of Charge

The SoC membership function is divided into 5 parts : very low, low, medium, high and very high (Figure 8). The battery is restricted to operate at 30 % and 90 % of its SoC, which prevents deep cycling and overcharging.

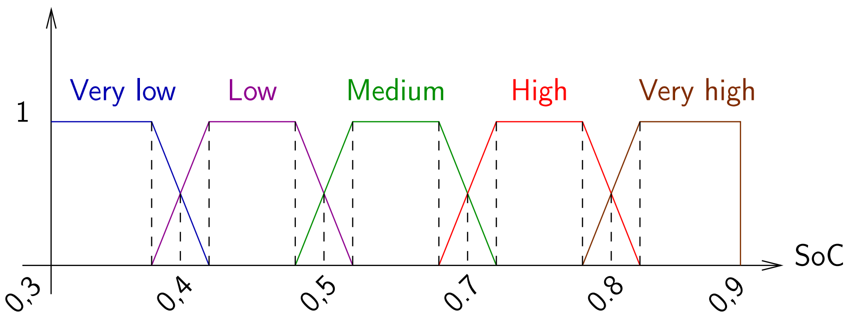


Figure 8: State of Charge Membership Function

Input membership function : Drive cycle Power

The second membership function is the drive cycle power describes in Figure 9.

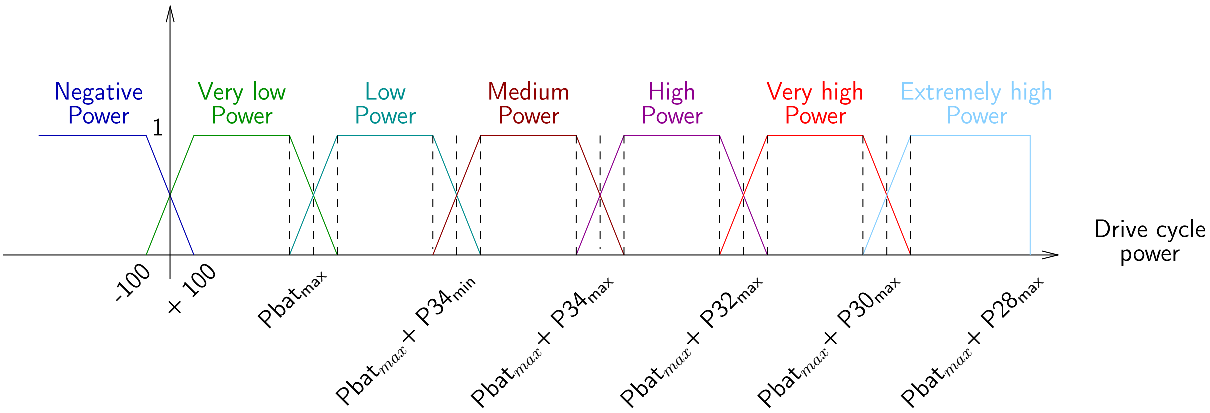


Figure 9: Drive cycle Power Membership Function

The drive power, P_{traction}, is calculated from the Newton's Second law enunciated in (1), where M_{v} is the vehicle mass (kg), v is the vehicle speed (m/s), F_{air} is the aerodynamic drag, F_{r} is the rolling resistance, and F_{g} is the grade resistance. These forces are a function of vehicle characteristics, acceleration, and vehicle speed. When the driver is braking, only 60 % of the torque is available for the regenerative breaking mode.

$$P_{\text{traction}}(t) = \vec{v}(t) \cdot [M_{\text{v}} \frac{d\vec{v}(t)}{\text{d}t} + \vec{F}_{\text{air}}(t) + \vec{F}_{\text{r}}(t) + \vec{F}_{\text{g}}(t)] \tag{1}$$

The drive power membership function is built from the ICE map which is presented in Figure 10 where red curve gives the ICE power at its best efficiency. From this curve and the efficiency iso-curves, the maximum and minimum power are extracted for each area. For example the maximum and minimum power for the first area (efficiency upper 34 %) is noted as P34_{max} and P34_{min} respectively. The maximum efficiency in this area is written $\eta 34_{\text{max}}$.

The very low power function is limited by the maximum battery power Pbat_{max} given by the manufacturer. The low function is limited between the Pbat_{max} and the minimum power delivered by the ICE P34_{min}. It is important to note thaht the ICE can work below P34_{min} but in this control, it is constrained due to the lower efficiency. The fuzzy logic controller goal is

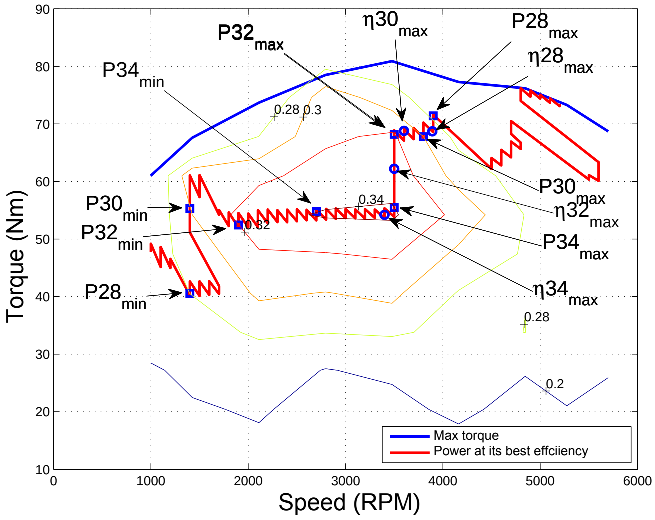


Figure 10: ICE map

to allow the ICE to operate only at its best efficiency: in the area of 34 % and above. The only case where the the ICE can work in another region is when the required power is higher than the maximum power of the $\eta 34$ region.

The negative power function is the area where the PHEV is using the regenerative breaking mode. The other functions are related to the ICE efficiency.

Input membership function : ICE timer

The last fuzzy logic input is the ICE timer. Indeed, it is important to take into account the ICE ignition. It is not possible to take the decision of turning on and off the ICE every second. Therefore, an ICE timer is implemented in this controller which guarantees that continued operation will last for at least 25 seconds. The only case where the ICE can be turned off before 25 seconds is when the driver removes the key from the dashboard.

Figure 11 presents the ICE time where three modes are described :

- ICE OFF where the ICE was not used in the last iteration the controller can turn on the ICE or keep it off,
- ICE ON where the ICE was used in the last iteration and has to be used in the next one,
- ICE ON/OFF where the ICE was ON in the previous iteration but the controller can take the decision to turn it off or not.

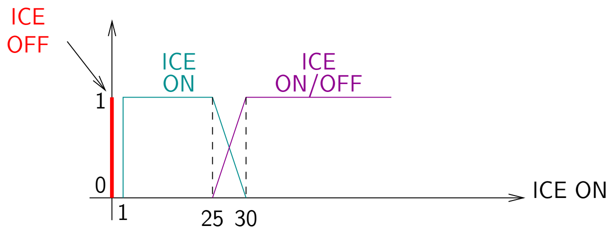


Figure 11: Time ICE ON Membership Function

Output Membership function : ICE power

The fuzzy logic output is the ICE power which is presented in Figure 12. Membership functions use the ICE map (Figure 9). The maximum power for each area is identified by the maximum power at its best efficiency. These points are represented on the ICE map by η_{34} for 34 % area efficiency, η_{32} for 32 % area efficiency, η_{30} for 30 % area efficiency and η_{28} for 28 % area efficiency.

When the ICE power is equal to 0 that means the PHEV is running in All Electric Range (AER) mode.

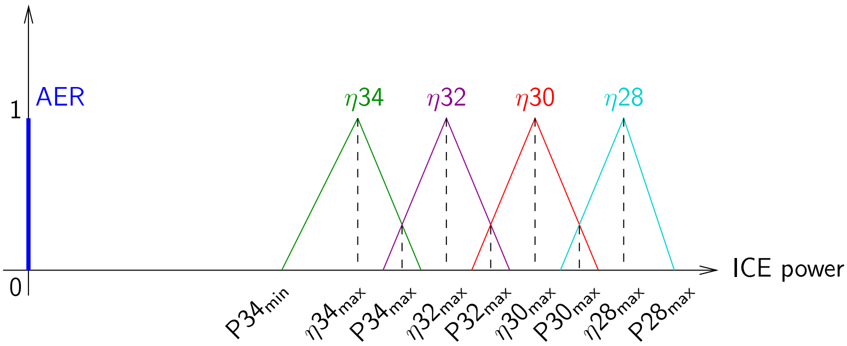


Figure 12: ICE Power Membership Function

The battery power is given in (2) when the drive cycle power ($P_{\text{drive cycle}}$) is positive. In case it is negative the equation becomes (3). Where P_{bat} is the battery power, $\eta_{\text{converter1}}$ is the converter between the electric motor and the DC bus efficiency, η_{motor} the electric motor efficiency, P_{ice} the ICE power, $\eta_{\text{generator}}$ is the generator efficiency, and $\eta_{\text{converter2}}$ is the converter between the generator and the DC bus efficiency. These two equations are linked with Figure 4.

$$P_{\text{bat}} = \frac{P_{\text{drive cycle}}}{\eta_{\text{converter1}} \cdot \eta_{\text{motor}}} - P_{\text{ice}} \cdot \eta_{\text{generator}} \cdot \eta_{\text{converter2}} \quad \text{when} \quad P_{\text{drive cycle}} > 0 \tag{2}$$

$$P_{\text{bat}} = P_{\text{drive cycle}} \cdot \eta_{\text{converter1}} \cdot \eta_{\text{motor}} \quad \text{when} \quad P_{\text{drive cycle}} < 0 \tag{3}$$

Fuzzy Logic Rules

Fuzzy logic rules are listed in Table 1. These rules fit when the controller can choose to switch on or off the ICE. When the ICE has to be switched on, AER is replaced by the ICE power membership function: η_{34}.

$P_{\text{cycle}} \rightarrow$ SoC $\downarrow$	**Negative power**	**Very low power**	**Low power**	**Medium power**	**High power**	**Very high power**	**Extremely high power**
Very low	η 34	η 34	η 34	η 34	η 32	η 30	η 28
Low	AER	AER	AER	η 34	η 32	η 30	η 28
Medium	AER	AER	AER	AER	η 34	η 32	η 30
High	AER	AER	AER	AER	AER	η 34	η 32
Very high	AER	AER	AER	AER	AER	AER	AER

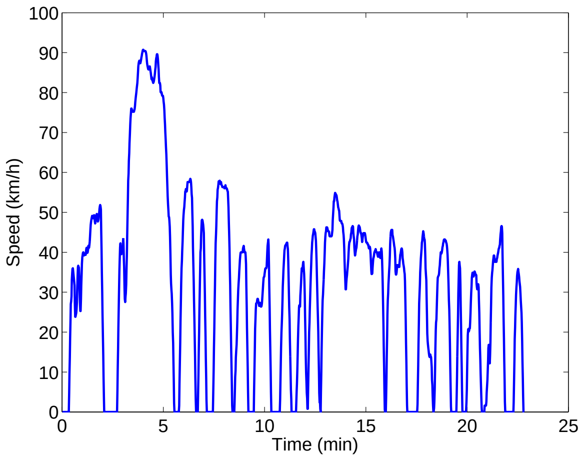
Table 1: Fuzzy logic rules

The controller goal is to minimize the fuel consumption (Desai, Berthold & Williamson 2010) by using the battery . However, some cases the ICE has to be used at its best efficiency even if the drive cycle power is lower than the minimum ICE power. In this case the ICE provides energy to the battery to charge it and also to the electric motor to satisfy the drive cycle power.

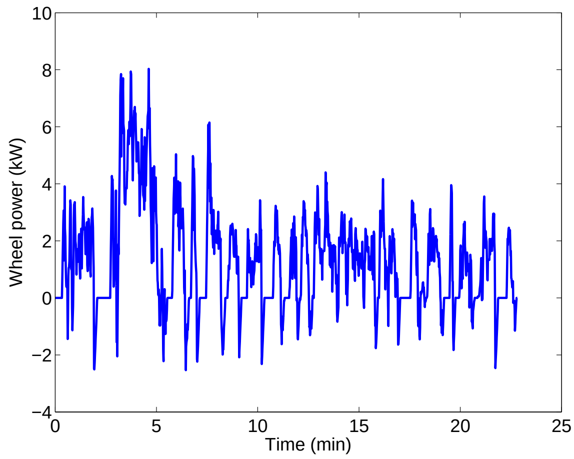
5 Case studies

Two case studies are presented in this section: one during summer and one during winter. The scenario describes below is a 24 hours simulation which starts at 6 AM and finishes the next day at 6 AM. It is assumed the driver goes to work at 8 AM and comes back home at 5 PM, which is the highest probability of departure and arrival (Turker, Bacha, Chatroux & Hably 2012).

The drive cycle which is used in both scenario is the UDDS (Urban Dynamometer Driving Schedule) (Agency 2014) which is shown in Figure 13(a) and its associated power in Figure 13(b). The drive cycle measures 12 km. The simulation starts with 70 % battery SoC.



(a) Drive cycle speed



(b) Drive cycle power

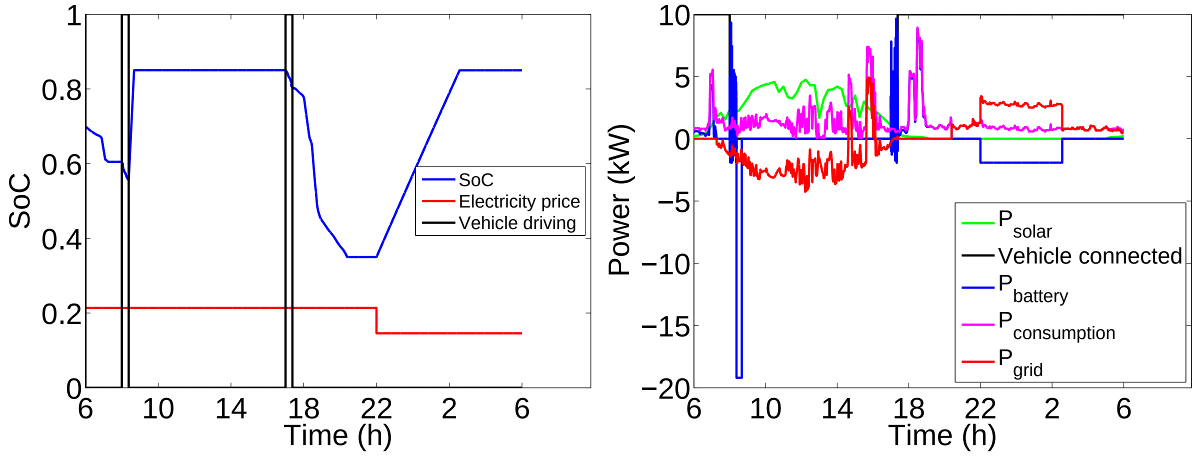
Figure 13: UDDS drive cycle

The consumption and solar production data come from the ÉcoTerra house which was presented in Figure 3(b) and Figure 3(d) for summer and winter solstice respectively. Off peak and on peak system is taken from the French system where the off peak power is between 10 PM and 6 AM. Electricity prices are fixed at $0.146 CAD per kWh during off peak time and $CAD 0.213 per kWh during on peak time. The over production is sold at $CAD 0.175 per kWh. The battery home charging station is a 1.4 kW.

The fuel price is $1.5 CAD per liter whereas the battery work charging is fixed at $0.12 CAD per kWh. The battery charging station at work is a 3.6 kW station.

Summer results

Figure 14 presents summer results where Figure 14(a) is the behavior of the battery SoC. The battery is used in the morning before the driver is going to work, then the vehicle uses the battery energy to propel the vehicle. Once the user reaches the work parking, the driver connects his car and the battery starts to charge. At the end of the day, the battery is used for the return trip, then the battery supplies household loads during on peak time. At the end, the battery is charged at home during night: the off peak time.



(a) SoC (b) Battery, solar, consumption and grid power

Figure 14: Summer results

Using the proposed system, the driver earns $CAD 1.27 for the whole day whereas using a conventional car and its associated system the driver has to pay $CAD 1.12 for the same simulation (Figure 15).

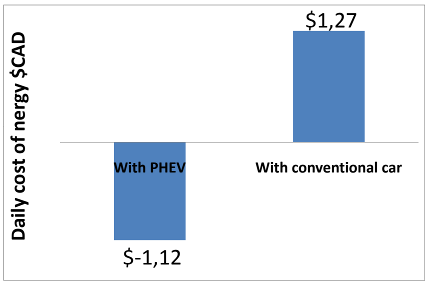


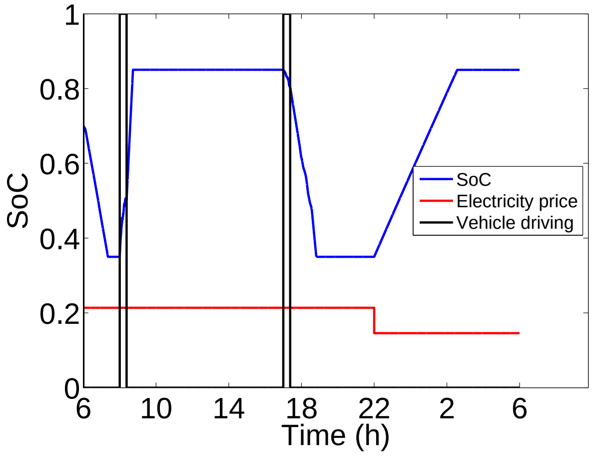
Figure 15: Daily cost summer results

Winter results

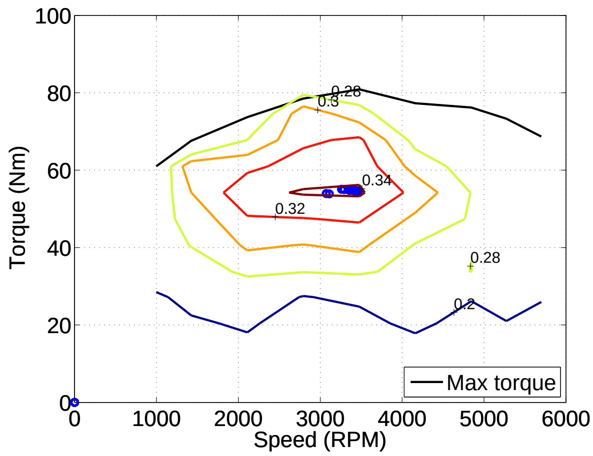
Figure 16 shows winter results where Figure 16(a), Figure 16(b) and Figure 16(c) are the battery SoC, the ICE operations and battery, solar, consumption and grid power, respectively. The battery SoC drops down in the morning before the driver is going to work. The battery charges a little during the trip: home to work. Then charges completely once the battery is connected at workplace. The PHEV comes back home in the all electric range mode. Finally the battery helps to supply the grid during the on peak time and charges during off peak power time. In addition, during the first trip (home to work), the ICE is used and its operations work on its best efficiency : $\eta 34$.

Figure 16(d) focuses on home-work trip. Notice that the battery power is higher than the drive cycle power which is due to the efficiency of the electric motor and its associated converter. In addition the ICE is used to charge the battery and also to propel the vehicle.

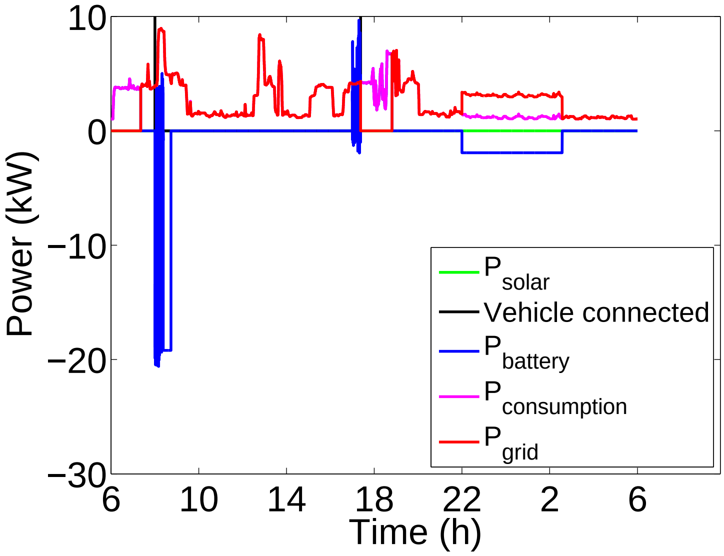
The energy price using a conventional vehicle $CAD 13.00 whereas with the PHEV vehicle the energy price becomes $CAD 11.61 which shows a reduction of 10 % (Figure 17).



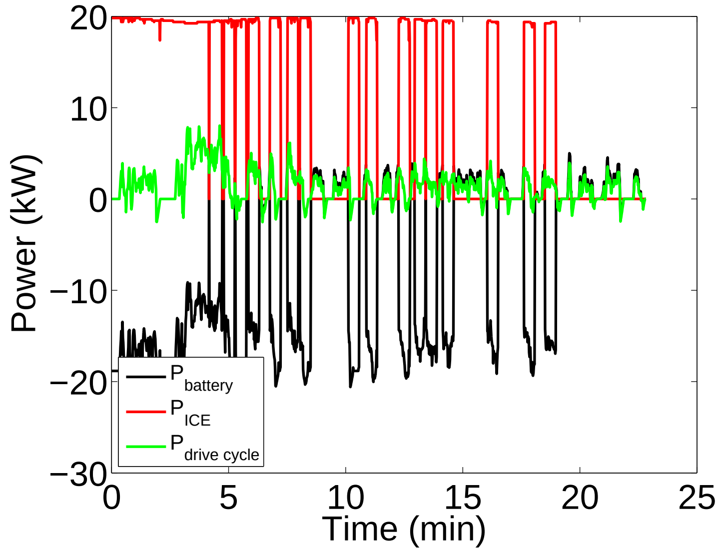
(a) SoC



(b) ICE operation



(c) Battery, solar, consumption and grid power



(d) Focus on the travel home to workplace

Figure 16: Winter results

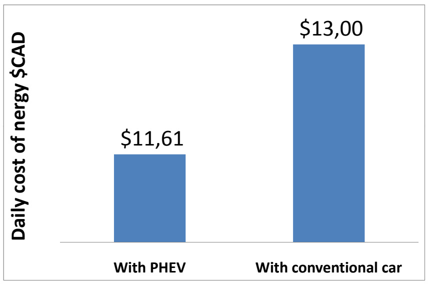


Figure 17: Daily cost winter results

6 Conclusions and future works

This paper has presented a micorgrid composed by a near NZEH named ÉcoTerra with a series PHEV. The home controller is described, providing the rules which decides if the battery helps the grid to supply the household loads or charges it. In addition, the fuzzy logic controller implemented in the series PHEV is presented. The membership functions are limited by the ICE map.

The simulation has shown (Figure 18) the importance of charging the battery during

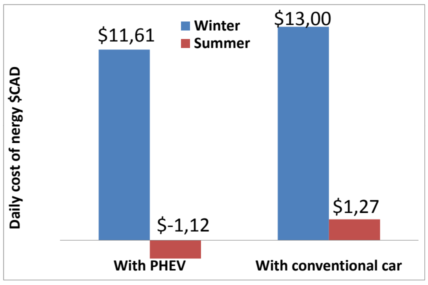


Figure 18: comparison of daily cost

off-peak periods and at the workspace station. Indeed, the study has shown a reduction of energy bill in winter by 10 %. In summer, the system sells more energy than its consumes. In addition, in the winter study case, the PHEV comes back home with the all electric range mode due to the battery charging at workplace.

However, the study has not taken into account the battery state of health. Indeed everyday the battery is charged and discharged which reduces its lifetime.

Moreover, the simulation is limited to one house, to extend it to a neighborhood, the on-peak and off-peak time should be shifted from one house to another one.

7 References

Agency, U. S. E. P. (2014), 'EPA urban dynamometer driving schedule (UDDS) | emission standards reference guide | US EPA'.
URL: *http://www.epa.gov/otaq/standards/light-duty/udds.htm*

An, J., Huang, B., Kang, Q. & Zhou, M. (2013), PSO-based method to find electric vehicle's optimal charging schedule under dynamic electricity price, *in* '2013 10th IEEE International Conference on Networking, Sensing and Control (ICNSC)', pp. 913–918.

Berthold, F., Blunier, B., Bouquain, D., Williamson, S. & Miraoui, A. (2012), Offline and online optimization of plug-in hybrid electric vehicle energy usage (home-to-vehicle and vehicle-to-home), *in* '2012 IEEE Transportation Electrification Conference and Expo (ITEC)', pp. 1 –6.

Bucking, S., Athienitis, A., Zmeureanu, R., O'Brien, W. & Doiron, M. (2010), 'Design optimization methodology for a near net zero energy demonstration home', *Proceedings of the EuroSun 2010* .

Chen, Y., Athienitis, A. K. & Galal, K. (2010), 'Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 1, BIPV/T system and house energy concept', *Solar Energy* **84**(11), 1892–1907.

CMHC, S. (2007), 'Equilibrium maison saine pour un environnement sain'.

Desai, C., Berthold, F. & Williamson, S. S. (2010), Optimal drivetrain component sizing for a plug-in hybrid electric transit bus using multi-objective genetic algorithm, *in* '2010 IEEE Electric Power and Energy Conference (EPEC)', IEEE, pp. 1–5.

Eppstein, M. J., Grover, D. K., Marshall, J. S. & Rizzo, D. M. (2011), 'An agent-based model to study market penetration of plug-in hybrid electric vehicles', *Energy Policy* **39**(6), 3789–3802.

Li, S., Sharkh, S., Walsh, F. & Zhang, C. (2011), 'Energy and battery management of a plug-in series hybrid electric vehicle using fuzzy logic', *IEEE Transactions on Vehicular Technology* **60**(8), 3571–3585.

Noguchi, M., Athienitis, A., Delisle, V., Ayoub, J. & Berneche, B. (2008), Net zero energy homes of the future: A case study of the ÉcoTerraTM house in canada, *in* 'Renewable Energy Congress, Glasgow, Scotland', p. 2008–112.

Ravey, A., Blunier, B. & Miraoui, A. (2012), 'Control strategies for fuel-cell-based hybrid electric vehicles: From offline to online and experimental results', *IEEE Transactions on Vehicular Technology* **61**(6), 2452–2457.

Thomas, W. D. & Duffy, J. J. (2013), 'Energy performance of net-zero and near net-zero energy homes in new england', *Energy and Buildings* **67**, 551–558.

Tie, S. F. & Tan, C. W. (2013), 'A review of energy sources and energy management system in electric vehicles', *Renewable and Sustainable Energy Reviews* **20**, 82–102.

Turker, H., Bacha, S., Chatroux, D. & Hably, A. (2012), Modelling of system components for vehicle-to-grid (V2G) and vehicle-to-home (V2H) applications with plug-in hybrid electric vehicles (PHEVs), *in* 'Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES', pp. 1–8.