# WELL-TO-WHEELS ENERGY EFFICIENCY ANALYSIS OF PLUG-IN ELECTRIC VEHICLES INCLUDING VARYING CHARGING REGIMES

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This is to certify that the thesis prepared

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# ABSTRACT

Well-To-Wheels Energy Efficiency Analysis of Plug-In Electric Vehicles Including Varying Charging Regimes

**Ebrahim Saeidi Dehaghani**

Transition to electric vehicles (EVs) is already under way. EVs were demonstrated to be the most fuel economic and emission free among other propulsion technologies. Electric and plug-in hybrid electric vehicles (EVs/PHEVs) can have a large impact on greenhouse gases (GHGs) reduction, increase in fuel economy and higher fuel efficiency. This thesis seeks to investigate the Well-to-Wheels (WTW) energy efficiency analysis of Electric Vehicles (EVs) in Canada. The main idea behind this research work is to analyze step by step energy efficiency, which is one of the key factors for EVs technology acceptance. Penetration of battery electric and more electric vehicles (BEVs/MEVs) into vehicle fleet, affects load demand as well as electricity market. Smart charging of EVs can remove a lot of stress from electricity grid. Effect of home charging of EVs/PHEVs on electricity demand in the province of Quebec was analyzed. More recently, EVs have been looked at as distributed sources of energy, whereby they could back up the power grid during critical high demand periods. With the help of an on-board battery pack, EVs can act as distributed generators and feedback energy to the AC grid. However, efficiency of energy conversion could become an issue in this power flow. Hence, in this thesis stage-by-stage efficiency of vehicle-to-grid (V2G) power flow was evaluated. In addition, feasibility of using EVs in international islanding to sustain the local grid in the event of an emergency was analyzed.

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# LIST OF ACRONYMS

| | |
|---|---|
| A | Ampere |
| AC | Alternating Current |
| ADVISOR | Advanced Vehicle Simulator |
| AER | All Electric Range |
| AVG | Average |
| Ah | Ampere-Hour |
| BEV | Battery Electric Vehicle |
| Btu/km | British Thermal Unit per Kilometer |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| $CH_4$ | Methane |
| CPM | Charge Point Manager |
| CV | Conventional Vehicle |
| ¢/kWh | Cent per Kilowatt Hour |
| DOD | Depth of Discharge |
| DG | Distributed Generation |
| DSM | Demand Side Management |
| EM | Electric Motor |
| ESS | Energy Storage System |
| EVs | Electric Vehicles |
| FCV | Fuel Cell Vehicle |

| | |
|---|---|
| g/km | Grams per kilometer |
| G2V | Grid-to-Vehicle |
| GB | Great Britain |
| GHGs | Green House Gases |
| GW | Giga Watts |
| HC | Hydrocarbons |
| HEV | Hybrid Electric Vehicle |
| HWFET | Highway Fuel Economy Test |
| ICE | Internal Combustion Engine |
| KJ | Kilo Joules |
| Km/h | Kilometers per hour |
| Km/L | Kilometers per Littre |
| KV | Kilo Volt |
| KVA | Kilo Volt Ampere |
| KW | Kilowatts |
| KWh | Kilowatt Hour |
| L | Littre |
| Li-ion | Lithium-ion |
| LV | Low Voltage |
| M | Meter |
| MM | Millimeter |
| MAX | Maximum |
| MJ | Mega Joules |

| | |
|---|---|
| MJ/kg | Mega Joules per Kilogram |
| MJ/l | Mega Joules per Littre |
| Mt | Mega Tones |
| MV | Medium Voltage |
| MW | Mega Watts |
| L/100 | Liters per gallon |
| $N_2O$ | Nitrous Oxide |
| NM | Newton Meter |
| Ni-MH | Nickel Metal Hydride |
| $NO_X$ | Nitrous Oxide |
| PEM | Proton Exchange Membrane |
| PHEV | Plug-in Hybrid Electric Vehicle |
| RPM | Revolutions per Minute |
| SEC | Second |
| SOC | State of Charge |
| $SO_x$ | Sulphur Oxide |
| STO | Source-to-Outlet |
| SUV | Sport Utility Vehicle |
| TOU | Time of Use |
| TTW | Tank-to-Wheels |
| TWh | Terawatts-Hours |
| UDDS | Urban Dynamometer Driving Schedule |
| UK | United Kingdom |

| | |
|---|---|
| V2G | Vehicle-to-Grid |
| VOC | Volatile Organic Compounds |
| VPP | Virtual Power Plant |
| WTT | Well-to-Tank |
| WTW | Well-to-Wheels |

# List of Principal Symbols

| | |
|---|---|
| cyc_kph_r | Requested Vehicle Speed in Unit of Kilometers per Hour |
| cs_hi_soc | Highest desired battery state of charge |
| ess_soc_hist | State of charge history |
| fc_trq_out_a | Available torque out of the torque coupler |
| kpha | Achieved vehicle speed (kph) |
| mc_trq_out_a | Available motor torque |
| $\eta$ | Efficiency |
| $\eta_{E}$ | Efficiency of stored energy |
| $\eta_{STO}$ | Efficiency of source-to-outlet |
| $\eta_{Charge}$ | Charge efficiency |
| $\eta_{Battery}$ | Battery efficiency |
| $\eta_{Grid}$ | Grid efficiency |
| $\eta_{V2G}$ | Vehicle-to-grid efficiency |
| trip_NEW | New trip |

# CHAPTER 1

# INTRODUCTION

## 1.1 INTRODUCTION

In recent years, air pollution and oil reserves security have become two major global concerns. In one hand, air pollution increased to an alarming level. On the other hand, oil reserves are going to be finished soon. According to Hubert curve, maximum oil production has reached in 2004 [1]. Thus, vehicle industry starts a steady move from oil based fleet to more clean and environmental friendly vehicles. This transition can have a major impact on greenhouse gases (GHGs) reduction as well as less dependency on oil. Electric vehicles (EVs) start to be seen on the roads. Since last decade, several vehicle manufacturers have produced some sort of electrified vehicles. Drivetrain of these vehicles is powered by electricity. A fairly large on-board battery pack must be charged and propel the vehicle. It should not be forgotten, that overall energy conversion efficiency in this vehicles must be carefully analyzed. Input fuel goes through different conversion stages to have actual work at the wheels. Major research studies in this filed must be concentrated in analysis of overall energy efficiency of advanced vehicular systems. The aim of this comprehensive WTW analysis of EVs is to determine how the most promising vehicle of the future can help efficiently reduce dependency on oil and help to reduce GHGs and emission. To compute the WTW energy efficiency of the vehicles, energy substance of fuel source such as oil or natural gas must be analyzed. Then energy conversion steps must be tracked to reach final fuel product such as gasoline or electricity. Second part of the work is to calculate the fuel efficiency of the vehicle to complete the WTW efficiency of the total process [2]. Figure 1-1 shows schematic diagram of different stages in WTW efficiency analysis for different vehicles.

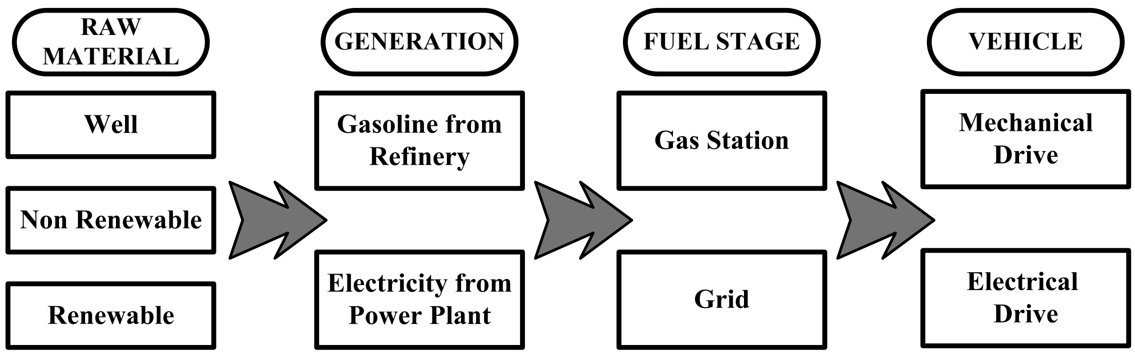



**Fig. 1-1** Schematic diagram of different stages in WTW efficiency analysis

EVs generate significant less GHGs and emissions compare to other types of vehicles with the same weight and power. For EVs which emit nothing during their operation, TTW GHGs and emission will be zero. Therefore, EVs are infinitely cleaner than any other vehicle topologies. But it should be noted that, generation of electricity that is used to propel the vehicle is not a very clean process. GHGs and emissions are generated not only in vehicles, but also by power plants, oil refinery and by distribution of electricity or gasoline. Therefore, it is more appropriate to analyze WTW GHGs and emissions in order to have an accurate comparison between EVs and our present most occupant vehicles as ICE vehicles [3].

## 1.2 BACK-OF-ENVELOPE EFFICIENCY ANALYSIS

Before considering comprehensive WTW efficiency analysis of EVs, it is essential to conduct a basic back-of-envelope TTW efficiency calculation of different vehicles drivetrains, based on theoretical efficiency of individual components of different vehicle’s drive trains. This will give a general overview of the actual work. Also it makes clear, why EVs are selected to have highest chance of being the main technology of future transportation industry.

### 1.2.1 GASOLINE VEHICLES (ICES)

ICE vehicles are very popular in our time. Considering very low efficient engine and other losses in drive train component of conventional vehicles, average theoretical efficiency of these vehicles is between 10 - 30%. In this type of vehicle, chemical energy must transform to heat and then to mechanical energy and that goes through transmission system to propel the vehicle. All of these transformations create losses that make this vehicle very low efficient. Figure 1-2 shows schematic diagram of gasoline vehicle drivetrain.

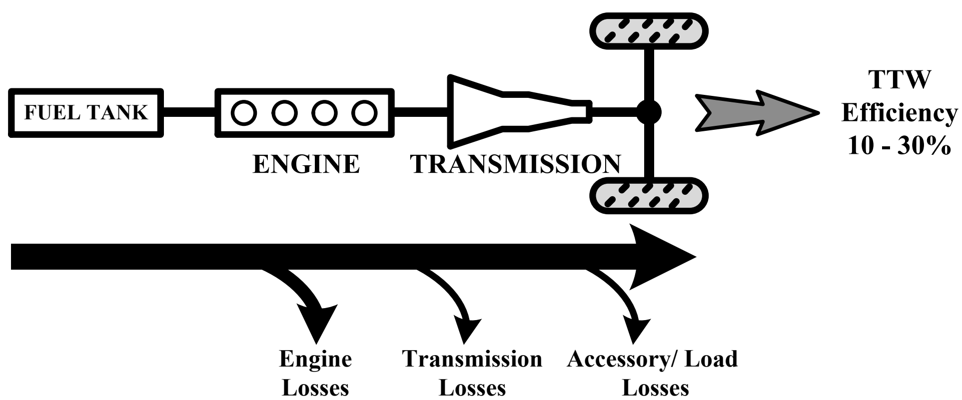



**Fig. 1-2** Schematic diagram of gasoline vehicle drivetrain

### 1.2.2 HYBRID ELECTRIC VEHICLES (HEVS)

HEVs have more than one internal energy source. These sources can propel the vehicle separately or simultaneously. But, battery can be charged by using an energy that is generated by IC engine. Based on drive train configuration, different HEV operating scenario can be introduced.

In series drive train, mechanical drive train delivers power to electric drive train and the electric drive train propels the vehicle. One significant issue with series HEVs is that the engine is overworked, in order to maintain battery charge. In parallel HEV, both the IC engine and the electric traction motor are connected to the transmission, which in turn, drives the wheels. Such an arrangement improves the system efficiency significantly. In series-parallel drive train, system combines the series and parallel hybrid systems, to maximize the benefits of both systems. Similar to the series HEV, the combined HEV configuration makes use of 2 electric machines (traction motor and generator/alternator). Depending on the driving conditions, the combined HEV configuration uses only the electric motor or the driving power from both, the electric motor and the IC engine. Since, IC engine must operate to charge battery pack; the TTW efficiency of these drive trains can't be very high. From efficiency and emission point of view, HEVs can be named as more efficient gasoline vehicle and average theoretical efficiency of these vehicles are between 25 - 40%. Figure 1-3 shows the schematic diagram of hybrid electric vehicle drivetrain.

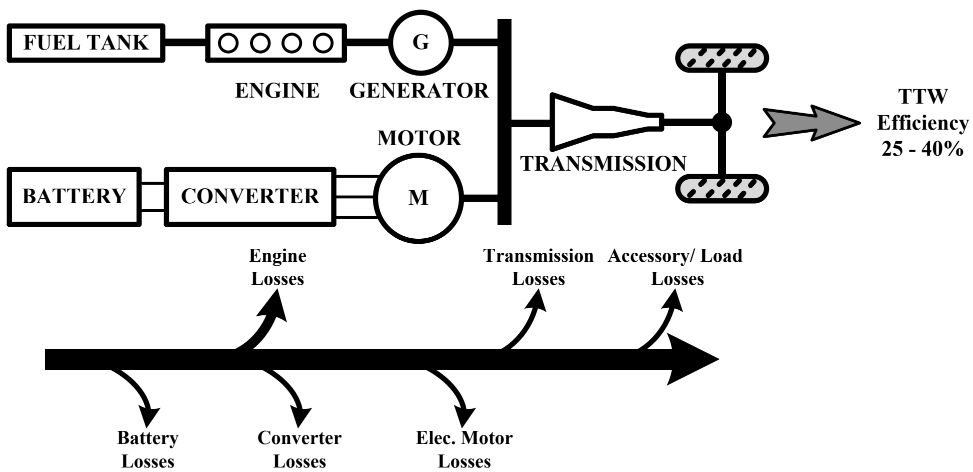



**Fig. 1-3** Schematic diagram of parallel hybrid electric vehicle drivetrain

### 1.2.3 FUEL CELL VEHICLES (FCVS)

In the past few years, there are many research have been done to analyze, whether or not, FCVs can be a viable technology in the future vehicle industry. In fuel cell vehicles, the primary source of energy is from a source of fuel, mainly hydrogen. Due to extremely expensive high-pressure hydrogen tank as well as safety issues of carrying pure hydrogen, hydrogen will be provided on board through a fuel reforming process. Hydrogen usually extracted from hydrocarbons in fuel reformer and then stored in fuel stack. In vehicular applications, proton exchange membrane (PEM) fuels cell is usually used. FCV promoters claimed that, FCVs has high efficiency that can reach to 60 – 70%. But, when overall losses of the system and sub systems taking into consideration, the overall TTW efficiency dropped from 60 – 70% in the order of a mere 30% or lower [4-5]. Figure 1-4 shows the schematic diagram of fuel cell vehicle drivetrain.

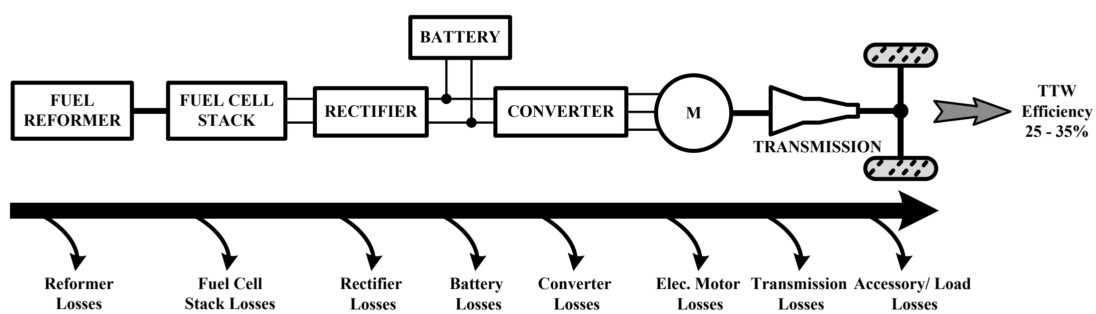



**Fig. 1-4** Schematic diagram of fuel cell vehicle drivetrain

### 1.2.4 PLUG-IN HYBRID ELECTRIC VEHICLES (PHEVS)

PHEV is an HEV, with sufficient rechargeable on-board battery, which is allowed to employ either: Series topology; Parallel topology or Series-parallel combined topology. PHEV has multiple energy sources on-board that can propel the vehicle separately or simultaneously. In PHEVs, fuel consumption is reduced by charging larger battery pack than HEV, from grid. A reasonable PHEV covers at least the first 50-70 kilometers in all-electric driving mode, which is the most efficient driving mode with zero emission at tailpipe. In low speed driving, it will be very efficient to drive vehicle in electric mode because, IC engine will be very low efficient in this mode of driving.

It is not easy to calculate a theoretical TTW efficiency for PHEV. In one hand two drive train, one electric and one mechanical can operate separate or simultaneously to propel the vehicle. On the other hand, two energy sources are on-board that can affect the total TTW efficiency of the vehicle [6]. TTW efficiencies can range between 50-70%. Higher number can be depend on electric drive train component efficiencies, size of battery pack and by employing electric drive train more than mechanical drive train. Figure 1-5 shows schematic diagram of plug-in hybrid electric vehicle drivetrain.

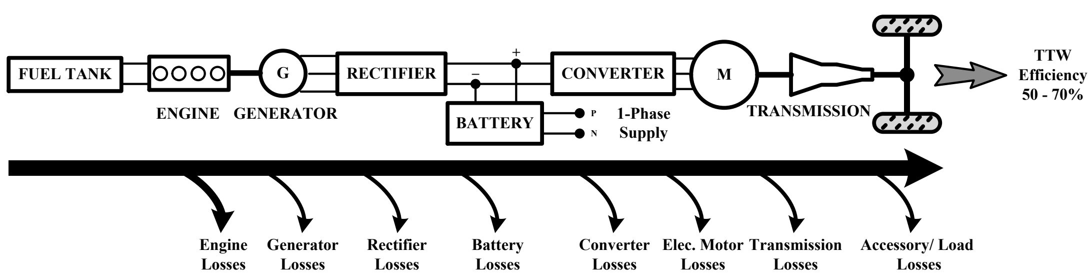



**Fig. 1-5** Schematic diagram of series plug-in hybrid electric vehicle drivetrain

### 1.2.5 ELECTRIC VEHICLES (EVS)

EVs can be named, the most efficient and cleanest vehicle ever introduced. However, EVs with zero emission tailpipe did not have the same support and enthusiasm as plug-in hybrid and hybrid electric vehicles (PHEV/HEV). The main reason is that, by entering these vehicles into the fleet, gasoline industry sales will be bypassed. EVs purely driven by electricity supplied from grid. Fairly large on-board battery pack is charged and can have a drive range of up to 400 km [7].

This vehicle sometimes called “emission elsewhere” vehicle and this is because, electricity is generated in power plant that produce emissions. But in comparison with ICE vehicle and other alternatives, we must consider how much pollution an EV can produce per kilometer. Though, emission that is produced, starting from raw material where fuel extracted from oil or mine to electricity consumed in vehicle’s motor is still far less than gasoline based vehicles.

High TTW efficiency of EVs is impacted by high efficient drive train components. The efficiency of the modern components such as battery pack, electric motor and converters used in EV drive train are efficient enough to put the TTW efficiency of EVs in the range of 60 – 90%. Higher efficiency is also possible, considering energy recovered from regenerative braking. This energy recovery cannot reflect a true TTW efficiency, but it can perform an accurate comparison with ICE vehicles. Figure 1-6 shows schematic diagram of electric vehicle drivetrain.

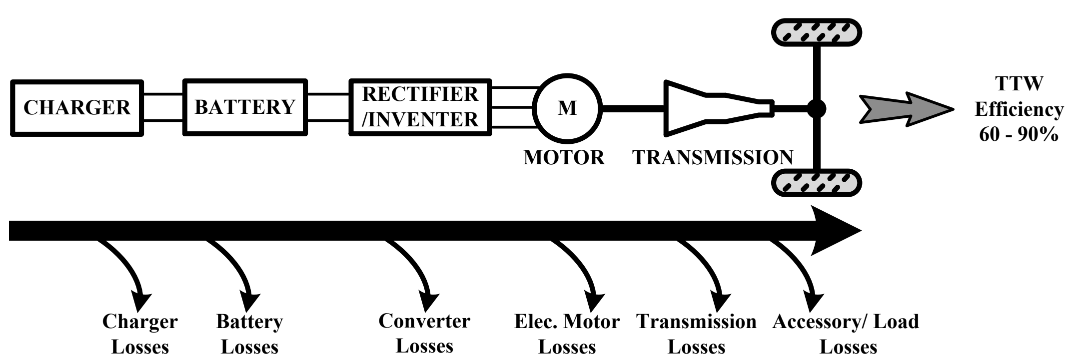



**Fig. 1-6** Schematic diagram of electric vehicle drivetrain

Theoretical Back-of-Envelope TTW efficiency of different drivetrains is shown in Figure 1-7. In chapter 2, WTW analysis will perform and comparison study will focus on electric vehicle and internal combustion engine vehicle to evaluate the advantages of EVs over ICE vehicles in Canada.

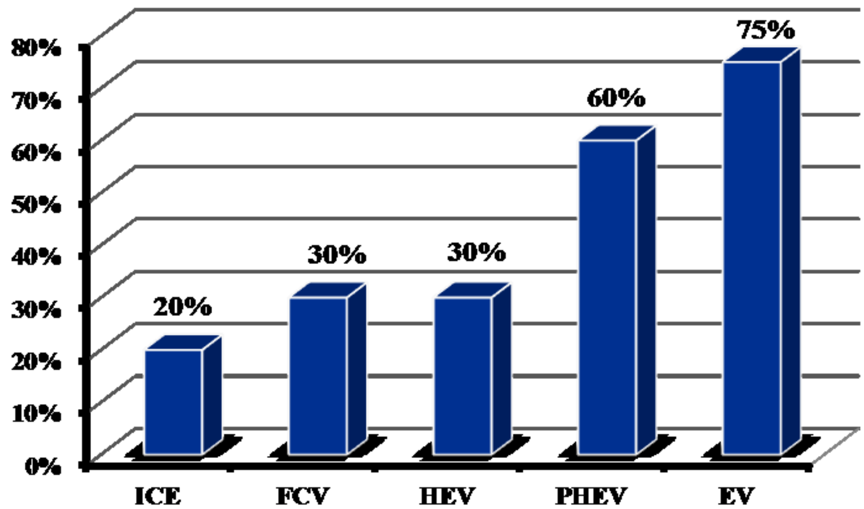



**Fig. 1-7** Average theoretical Back-of-Envelope TTW efficiency of different drivetrains

## 1.3 CONTRIBUTION OF THE THESIS

The major contributions of this thesis include,

(a) Define and investigate the Well-to-Wheels (WTW) energy efficiency analysis of Electric Vehicles (EVs) in Canada. The main idea behind this work is to analyze step by step energy efficiency, which is one of the key factors for EVs technology acceptance.

(b) One of the major reasons of moving towards EV industry is to help on greenhouse gases (GHGs) reduction. Considering this fact, WTW GHGs emission will be analyzed to investigate how EV penetration into the vehicle fleet will affect GHGs reduction.

(c) GHGs WTW efficiency comparison study will perform to investigate EVs parameters against internal combustion engine (ICE) Vehicles.

(d) Modeling, simulation and analyze of the effect of home charging of EVs/PHEVs on electricity demand in the province of Quebec. Case study is developed to assess the effect of different charging regimes and EV penetration level on total load demand of Quebec in 2030.

(e) Analyze operation condition for V2G power flow and detail loss (or efficiency) analysis to prove inefficiency of V2G based on energy flow.

(f) Analysis on effect of battery degradation as a result of V2G on WTW efficiency of EV.

(g) Offer different suggestions to eliminate V2G power flow inefficiency; perform demand side management (DSM) using Virtual Power Plan (VPP).

(h) Review and analyze the feasibility and effectiveness of using EV battery as DG on the distribution grid.

(i) Review and analyze issues concerning international islanding for medium term future.

(j) Modeling and simulation of existence of enough micro-generation and EVs penetration to support radial line in grid for remote or isolated communities in the event of international islanding.

## 1.4 THESIS OUTLINE

The contents of the thesis are organized into 6 chapters. Chapter 1 (this chapter) provided a brief introduction to the research work as well as general introduction of different vehicle’s drivetrain configuration and their Back-of-Envelope efficiency. This brief analysis shows why EVs have the highest chance to replace ICE vehicles.

Chapter 2 will look into the Well-to-Wheels (WTW) energy efficiency of EVs as well as ICE vehicles. WTW efficiency analysis will divide into 2 parts as Well-to-Tank (WTT) and Tank-to-Wheels (TTW) efficiency analysis. Product of these 2 parts will give an accurate assessment of the overall EVs efficiency analysis.

Chapter 3 identifies the effect of EVs home charging in 2 different charging strategies in province of Quebec in 2030. Effect of different characteristics such as the number of vehicles, charging time frame as well as length of charge on Quebec load demand will be analyzed. Comparison study is performed between Quebec case and UK to verify the accuracy of the work.

Chapter 4 will focus on Vehicle-to-Grid (V2G) concept. Efficiency of energy conversion in different stages of this power flow will be analyzed to evaluate practical feasibility. Issues regarding reverse power flow from vehicle into the grid and inefficiencies of the idea will be discussed. Research directions will be offered for near future in order to make V2G a practical idea.

Chapter 5 will review the use of EVs to support international islanding. This can be an opportunity for improving reliability of grid support to customers during major disasters such as floods or storms may arise. Existence of enough micro-generation and EVs within distribution will be evaluated.

Chapter 6 summarizes the research study and concludes the thesis work. Based on this conclusion and recognizing the advantages and concerns of EVs penetration into the fleet, appropriate suggestion will be offered for future research direction.

# CHAPTER 2

# WELL-TO-WHEELS ENERGY EFFICIENCY OF ELECTRIC VEHICLES IN CANADA

## 2.1 INTRODUCTION

This chapter seeks to investigate the Well-to-Wheels (WTW) energy efficiency analysis of Electric Vehicles (EVs) in Canada. The main idea behind this research work is to analyze step by step energy efficiency, which is one of the key factors for EVs technology acceptance. For ease of calculation, this calculation will divide in two stages as Well-to-Tank (WTT) and Tank-to-Wheels (TTW) to present critical points with regards to the efficiency analysis of the most permissible technology of current and future in vehicle industry. Product of these two stages will give an accurate assessment of the overall efficiency of EVs. The WTT cycle includes the raw material production, electricity generation, transmission and distribution, and TTW will analyze the vehicle operation stage.

One of the major reasons of moving towards EV industry is to help on greenhouse gases (GHGs) reduction. Considering this fact, WTW GHGs emission will be analyzed. Also, comparison study will be done to investigate EVs parameters against internal combustion engine (ICE) Vehicles.

## 2.2 WELL-TO-WHEELS EFFICIENCY ANALYSIS OF VEHICLES UNDR STUDY

Each and every alternative fuel vehicles other than EVs, has some sort of dependency to oil, which makes them not a very reliable and clean vehicle of future.

Sooner or later, research and development on vehicle technology must completely switch to EVs. For this reason, WTW efficiency will present on the assessment of ICE and electric vehicles, to have an accurate and proper comparison of, how our future generation can safely survive from lack of enough oil and gas in lower GHGs in their daily commute. There are many constrains to accurately calculate the WTW efficiency value of different vehicles. For this reason, WTW efficiency analysis is not a simple task. This calculation is much harder for electricity generation as renewable sources are connected to the grid.

In part A, WTT analysis will focus on energy content of the source fuels such as oil, natural gas, renewable and non-renewable energy sources. Then, conversion steps will follow to reach the final product that can be gasoline or electricity. Greenhouse Gases Regulated Emissions and Energy Use in Transportation (GREET) model is used from Argonne National Laboratory, to analyze vehicle fuel cycle for current and future fuel/vehicle systems. GREET receive user's energy data as input and uses in simulation on energy use and emissions associated with production, transportation and distribution of different fuels that is used for transportation purpose [8].

In part B, TTW analysis will focus on the drivetrain efficiency analysis of ICE and electric vehicles. ADVISOR (ADvanced VehIcle SimulatOR), developed by US National Renewable Energy Laboratory's (NREL) Center for Transportation Technologies and Systems is used for simulation in this section. ADVISOR is a flexible modeling tool that rapidly assesses the performance and fuel economy of conventional, electric, hybrid, and fuel cell vehicles [9].

### 2.2.1 WTT Simulation Model

WTT efficiency analysis is focused on ICE and electric vehicles, separately. Considering Canadian different source of fuels in 2012 and 2030, will give better understanding of WTT efficiency for gasoline and electricity generation. WTT efficiency analysis using GREET model will perform in following sections for the vehicles under study.

#### 2.2.1.1 WTT Simulation Results for ICE Vehicle

Two different WTT simulations are performed using GREET model for 2012 and 2030 energy consumption in fuel pathway of gasoline production. Crude oil recovery efficiency as well as gasoline refining efficiency is used to attain the WTT values for gasoline. Results shown that WTT efficiency of gasoline production, transportation and distribution at the pump is 81.6% for 2012 and 83.9% for 2030. Energy content of gasoline is 46.6 MJ/kg or 35 MJ/l [10]. Based on the 2012 WTT simulation for gasoline, production, transportation and distribution of gasoline to gas station is on average 81.6% efficient. It means 18.4% of fuel is lost in the production, transportation and distribution. Hence,

$$[35 \text{ MJ/l}] \times [1/81.6\%] = 42.9 \text{ MJ} \quad (2\text{-}1)$$

of oil is needed to give one litter of gasoline at the gas station. The 2030 WTT simulation had shown efficiency of production, transportation and distribution of gasoline to gas station is on an average 83.9% efficient. Therefore,

$$[35 \text{ MJ/l}] \times [1/83.9\%] = 41.72 \text{ MJ} \quad (2\text{-}2)$$

of crude oil will make one litter of gasoline at the gas station.

#### 2.2.1.2 WTT SIMULATION RESULTS FOR EVs

Total installed generation capacity in Canada was 133 GW in 2010. It is projected to increase from 133 GW to 170 GW by 2035. Canadian fuel sources data extracted from national energy board data base. Simulation in GREET model is also performed for electricity generation path, for 2012 and 2030 in order to analyze the improvements in fuel production efficiency and emission reduction.

Figure 2-1 has shown the Canadian generation mix in 2010 and 2035 as reference cases. Annual increase rate for Canadian electricity generation is 1.0%. But, as it shown in generation mix pies, generation mix percentages had not very significant changes for the period of 2010 to 2035. Therefore, the 2010 and 2035 generation mixes are considered in the simulations data needed for 2012 and 2035 generation pathway [11].

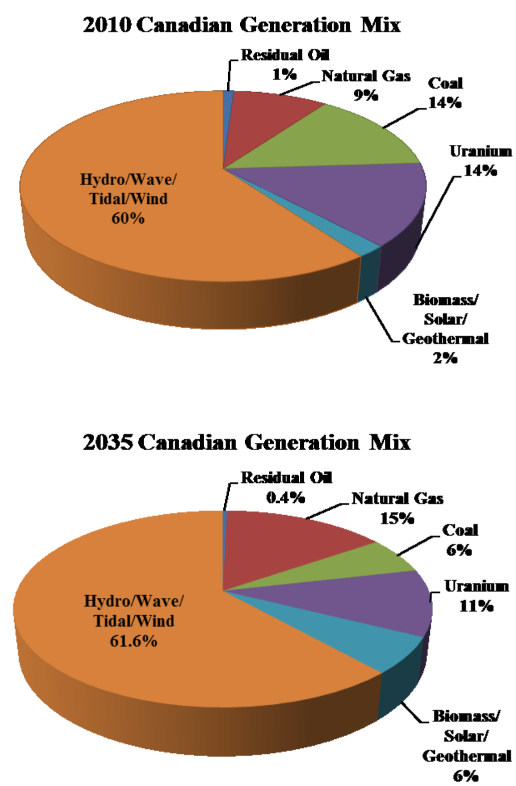



**Fig. 2-1** 2010 and 2035 Canadian generation mix

Generation mix in Canada is a combination of generation from different power plants. Even though, Canada has the largest hydro power plants in the world, coal plants are also running to generate electricity. As it shown in above pies, there is a positive move towards independency from energy sources such as residual oil and coal. Also, hydro, natural gas, biomass and solar power generations are going to be increased by 2035. By applying energy sources data into the GREET model and considering efficiencies in different power plants and transmission losses, WTT efficiency of electricity generation pathway are calculated as 62.1% for 2012 and 66.6 % for 2030.

Table 2-1 and 2-2, shows the results of GREET simulation on WTT efficiency analysis.

**Table 2-1** 2012 WTT fuel pathway efficiency results for gasoline vehicle

| **Year: 2012** | **Btu/km – Gasoline Vehicle** | | | |
|---|---|---|---|---|
| **Item** | **Feedstock** | **Fuel** | **Vehicle Operation** | **Total** |
| **Total Energy** | 186.16 | 482.71 | 2974.63 | 3643.5 |
| **Fossil Fuels** | 175.21 | 412.09 | 2905.25 | 3492.55 |
| **Coal** | 8.98.0 | 10.40 | 0 | 19.38 |
| **Natural Gas** | 125.71 | 228.19 | 0 | 353.9 |
| **Petroleum** | 40.51 | 173.49 | 2905.25 | 3119.25 |

**Table 2-2** 2012 WTT fuel pathway efficiency results for electric vehicle

| **Year: 2012** | **Btu/km – Electric Vehicle** | | | | **% Change Relative to ICE Vehicle** |
|---|---|---|---|---|---|
| **Item** | **Feedstock** | **Fuel** | **Vehicle Operation** | **Total** | |
| **Total Energy** | 34.33 | 498.91 | 874.89 | 1408.1 | -61.4% |
| **Fossil Fuels** | 31.50 | 204.45 | 387.13 | 623.08 | -82.2% |
| **Coal** | 1.66 | 142.64 | 236.75 | 381.05 | 1966.2% |
| **Natural Gas** | 20.41 | 56.87 | 126.77 | 204.05 | -42.3% |
| **Petroleum** | 9.43 | 4.94 | 23.59 | 37.96 | -98.8% |

2012 results shows, that EV fuel pathway has less dependency to fossil fuel, natural gas and petroleum. But, coal usage drastically increases, because of coal power plants operation.

**Table 2-3** 2030 WTT fuel pathway efficiency results for gasoline vehicle

| Year: 2030 | Btu/km – Gasoline Vehicle | | | |
|---|---|---|---|---|
| **Item** | **Feedstock** | **Fuel** | **Vehicle Operation** | **Total** |
| **Total Energy** | 185.00 | 311.61 | 2595.29 | 3091.9 |
| **Fossil Fuels** | 175.08 | 222.99 | 2486.15 | 2884.22 |
| **Coal** | 5.91 | 5.54 | 0 | 11.45 |
| **Natural Gas** | 135.22 | 131.04 | 0 | 266.26 |
| **Petroleum** | 33.94 | 86.414 | 2486.15 | 2606.50 |

**Table 2-4** 2030 WTT fuel pathway efficiency results for electric vehicle

| Year: 2030 | Btu/km – Electric Vehicle | | | | % Change Relative to ICE Vehicle |
|---|---|---|---|---|---|
| **Item** | **Feedstock** | **Fuel** | **Vehicle Operation** | **Total** | |
| **Total Energy** | 29.11 | 331.64 | 720.91 | 1081.66 | -65.0% |
| **Fossil Fuels** | 27.63 | 95.12 | 245.31 | 368.06 | -87.2% |
| **Coal** | 0.35 | 40.08 | 80.79 | 121.22 | 1058.7% |
| **Natural Gas** | 20.99 | 56.30 | 154.46 | 231.75 | -12.9% |
| **Petroleum** | 6.30 | 1.26 | 10.069 | 15.109 | -99.4% |

Table 2-3 and 2-4 also shows less dependency to fossil fuel, natural gas and petroleum in EV fuel pathway. In 2030, coal usage in electricity generation projected to increase. But, percentage is dropped in comparison with 2012 generation.

Generation mix pies shows that coal usage will dropped by 8% in electricity generation and replaced by, natural gas and renewable power plants. Also, it must be noted that natural gas, biomass and solar electricity generation had increased in 2030.

In fact WTT electricity generation can increase by involving more renewable energy sources and natural gas in the path. This will result improvement in total WTW energy efficiency of electric vehicles.

### 2.2.2 TTW Simulation Model

ADVISOR software is used in this section, to analyze performance and fuel economy of ICE and electric vehicles. ADVISOR combines forward/backward modeling, which allows monitoring of different component performances with fairly accurate dynamic solutions [12-13]. The vehicle chosen for this study was a typical 4 door mid-size sedan vehicle, which was simulated under combined city and highway drive cycles. It is assumed, that driver will drive the vehicle in the city, then goes to highway to go to work, in the morning. In the afternoon, driver will drive beck home. First, drive in to the highway and then after, reach to the city and drives home.

Urban dynamometer driving schedule (UDDS) drive cycle is picked for the city driving simulation. Highway fuel economy test (HWFET) drive cycle is also chosen to simulate highway driving simulation.

In Canada, average distance travelled by light vehicles is around 42 kilometers per day [14]. In this study, travel distance is considered to be 57 km, to be above average driving as worth case scenario and also to be matched with combined drive cycle for more accuracy in the analysis. Simulated drive cycle, time percentage over speed pattern and specification of driving schedule are shown in Figures 2-2, 2-3 and Table 2-5.

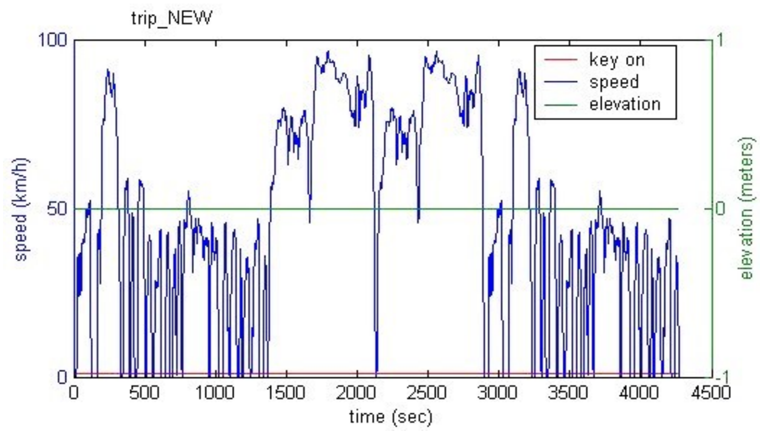



**Fig. 2-2** Simulated multiple drive cycle

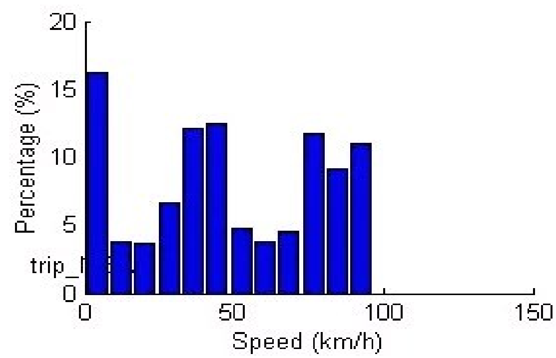



**Fig. 2-3** Time percentage over Speed pattern for vehicles under study

**Table 2-5** Summary of tested driving schedule

| **Item** | **Trip Specification** | |
|---|---|---|
| | **Value** | **Unit** |
| **Time** | 4271 | s |
| **Distance** | 57 | km |
| **Max. Speed** | 96.4 | km/h |
| **Avg. Speed** | 48.03 | km/h |
| **Max. Acceleration** | 1.48 | $m/s^2$ |
| **Max. Deceleration** | - 1.48 | $m/s^2$ |
| **Avg. Acceleration** | 0.39 | $m/s^2$ |
| **Avg. Deceleration** | - 0.44 | $m/s^2$ |
| **Idle Time** | 530 | S |
| **No. of Stops** | 36 | - |

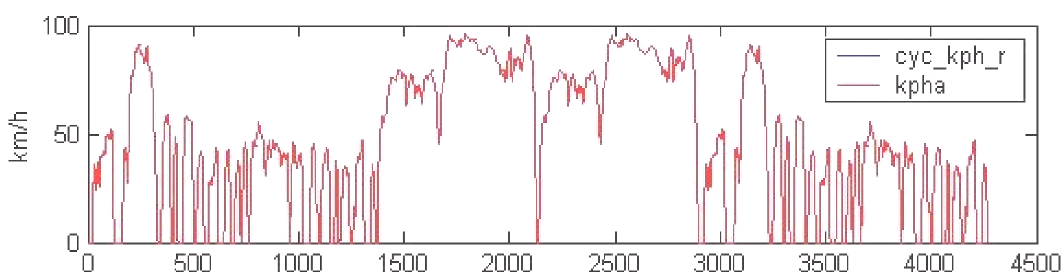
A brief summary of parametric physical specification of the vehicle considered for the simulation purposes, are shown in Table 2-6. Chassis is selected as a 4 door sedan for ICE and electric vehicles.

**Table 2-6** Physical specification of the representative 4 door sedan vehicle

| Parameters | ICE Vehicle | Electric Vehicle |
|---|---|---|
| **Max. Power** | 1.9 L Engine (95 kw) | 85 kw – AC Induction Motor |
| **Fuel Cycle** | Gasoline | Electricity |
| **Energy Storage** | - | 24 KWh – Li-ion |
| **Parameters** | **Characteristics** | |
| **Description** | 4 door mid-size sedan vehicle | |
| **Frontal Area** | 2.4 m² | |
| **Coefficient of Drag** | 0.33 | |
| **Total Mass** | 1580 kg | 1400 kg |

### 2.2.2.1 TTW Simulation Results for ICE Vehicle

The ICE vehicle under study was run through the combined city and highway driving schedule. Upon running the simulation for the scheduled trip, achieved TTW efficiency is 21.9 %, as well as fuel economy of 15.4 kilometers per litter of gasoline (15.4 km/L).



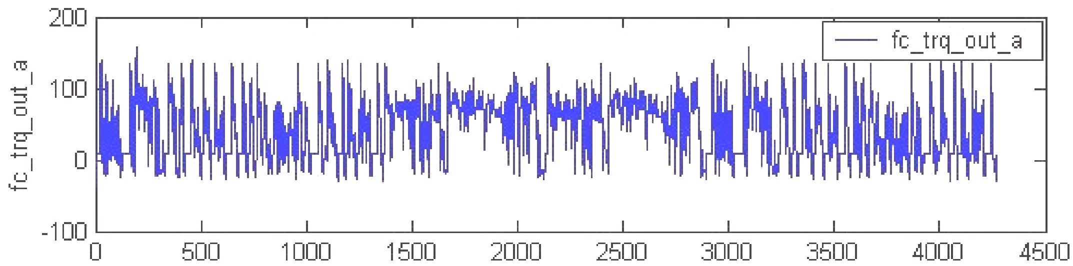



**Fig. 2-4** above: time-aligned vehicle driving speed. Below: engine torque delivery

Figure 2-4 gives the IC engine torque achieved through the driving cycle, aligned with delivered speed. It is clear that, the highest achieved torque demands are associated with acceleration.

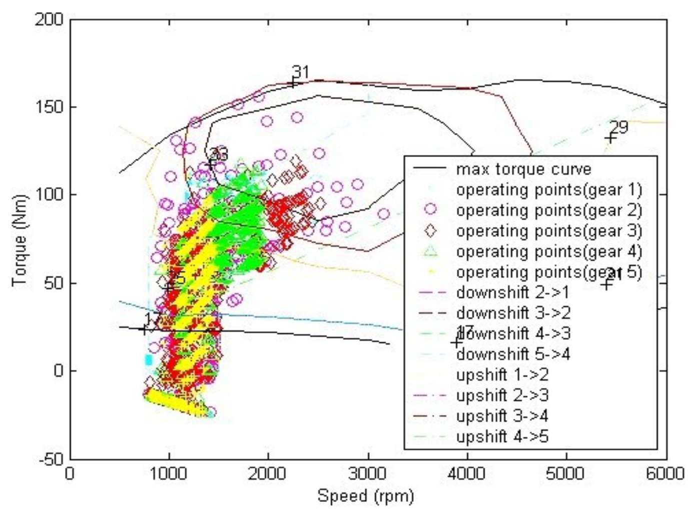



**Fig. 2-5** ICE operating points

Figure 2-5 shows the engine operating points of the vehicle under scheduled drive cycle. In low-speed, engine works at lower efficiency. In fact, higher efficiency achieved, in higher speed and high gear. Though, optimal engine efficiency achieved at gear 4.

The course of IC engine efficiency along driving time is shown in Figure 2-6. It is clearly indicate the well-known fact, which IC engines are not working efficiently under part-load. In particular, lowest efficiency achieved in lower gear level.

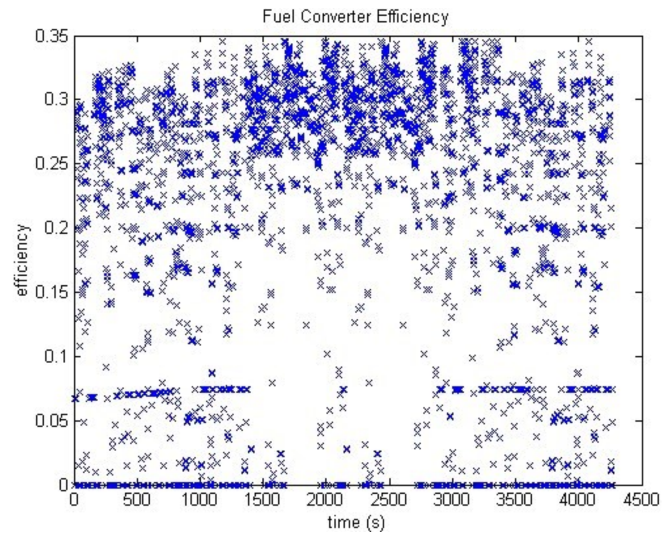



**Fig. 2-6** ICE conversion efficiency during driving schedule

Figure 2-7 gives a survey over devices lose distribution on driving mode over drive cycle. This is another proof of inefficiency in the fuel converter, which makes this vehicle, low efficient.

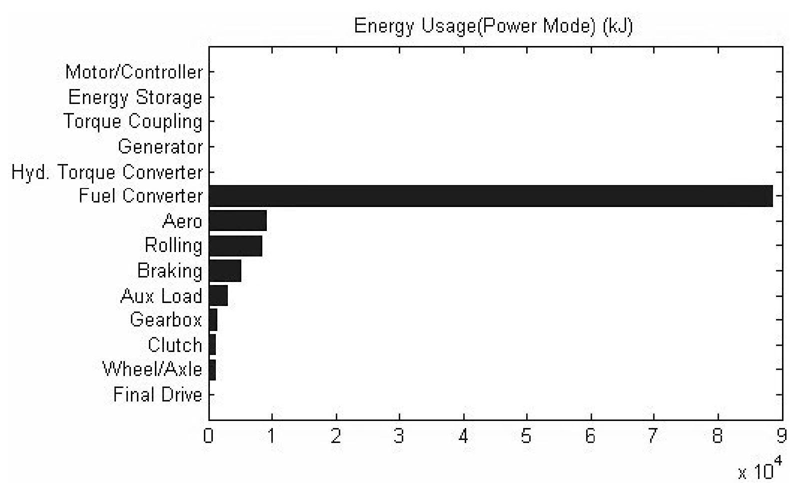



**Fig. 2-7** ICE vehicle total loss distribution (powering mode) over drive cycle

### 2.2.2.2 TTW SIMULATION RESULTS FOR EVS

The electric vehicle under study was also run through the combined city and highway driving cycles. Charge depleting control strategy is used for the simulated vehicle. The charge depleting control strategy sets a large state of charge (SOC) window between the maximum and minimum SOC levels. In this condition, battery can discharge to minimum SOC of 20%, making sure of good use of stored energy in the battery and keep up battery life. Upon running the simulation for the driving schedule, TTW efficiency of 71 % is achieved for simulated EV drive train.

Figures 2-8b and 2-8c are shown the simulated performance of the EV for a trip through the scheduled drive cycle. Figure 2-8b shows that electric motor is capable of delivering higher torque than IC engine of Figure 2-3, whenever is required. Figure 2-8c shows, that 28% of the state of battery charge is used during the drive cycle.

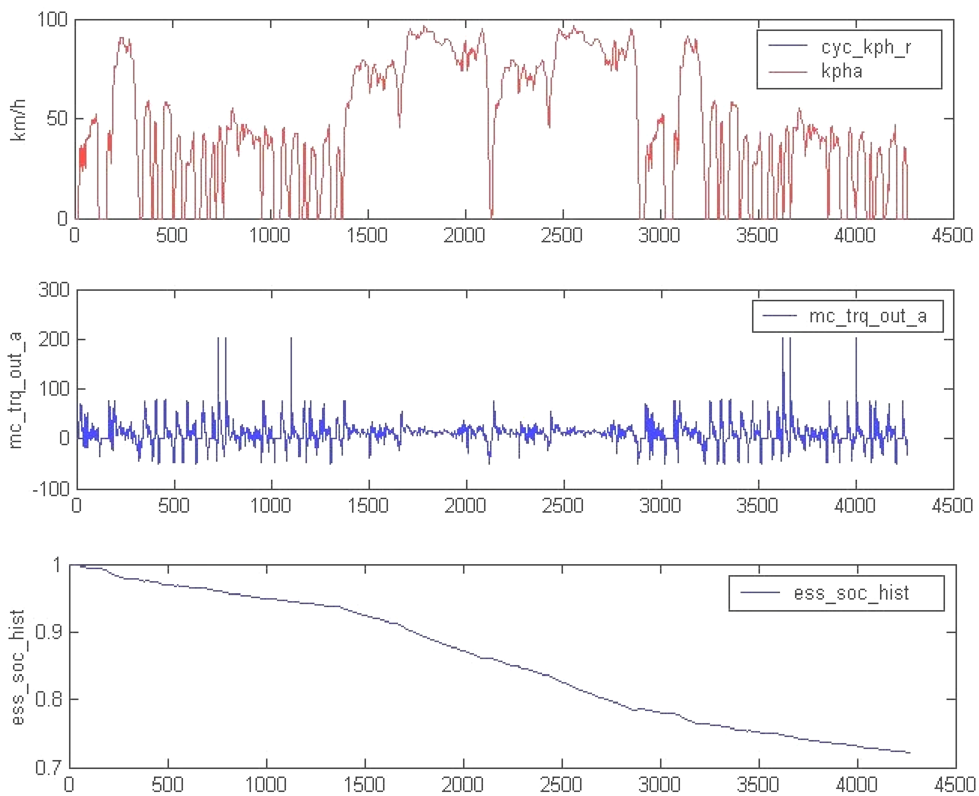



**Fig. 2-8** a. above: drive cycle, b. middle: EV simulated torque delivered by motor over drive cycle (negative during regenerative braking), c. below: state of Li-ion battery charge history during drive cycle

In Figure 2-9, the traction motor operating points of the simulated EV is presented. As it is shown, traction motor is used more in low-speed and high-torque region, resulting operation of low efficiency. In powering mode, the motor operating points of electric vehicle are concentrated in the extended high-speed and high-efficiency region. Regenerative braking also takes place in low efficiency to high efficiency region and helps to increase SOC of the battery pack.

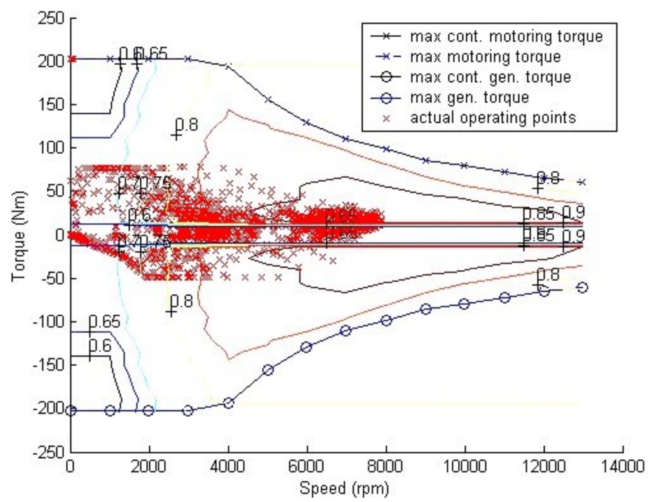



**Fig. 2-9** Traction motor operating points

Achieved traction motor efficiency over diving time for motoring mode is shown in Figure 2-10. In this simulation average efficiency of 85% is achieved for traction motor, which is relatively high in comparison to the engine in ICE vehicle.

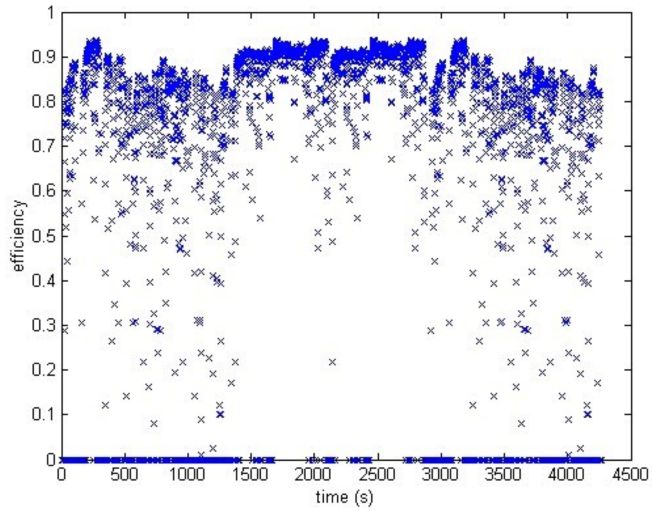



**Fig. 2-10** Motor controller efficiency (motoring mode) during driving schedule

Figure 2-11 gives a survey of devices lose distribution on motoring mode over drive cycle. Aerodynamic resistance as well as rolling resistance of tires has the highest energy losses in EV.

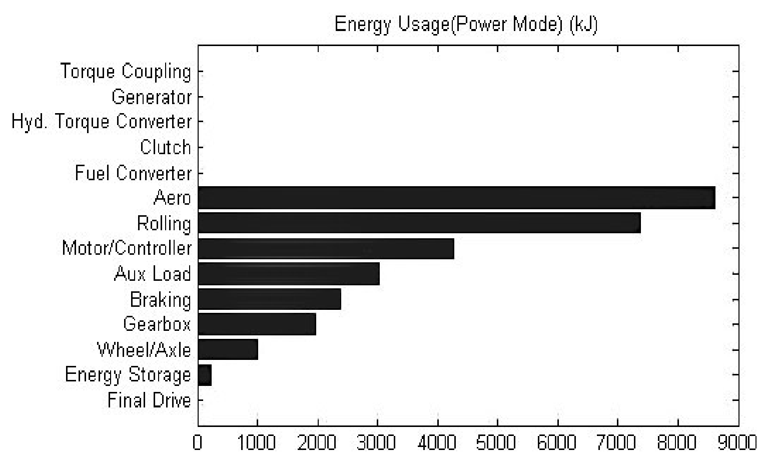



**Fig. 2-11** EV total loss distribution (motoring mode) over driving cycle

In fact, all components of any passenger vehicle that may influence efficiency must be made as energy efficient as possible. Advanced low-weight but high-strength materials and design the vehicle with smallest rolling resistance effect and less aerodynamic resistance can be far below the cost of vehicle power system equipment.

## 2.3 COMPARISON OF SIMULATIONS

The first step to calculate the WTW efficiency of any vehicle is to determine the total energy supplied at fuel source. In 2.2.1 by employing GREET model, WTT efficiency of gasoline and electricity production and distribution obtained. Also, 2012 and estimated 2030 fuel pathways are presented to give an overview of positive changes in energy sources consumption. Based on calculated TTW efficiency of ICE and electric vehicles in 2.2.2, it is possible to determine the actual WTW efficiencies for ICE and EV drive trains. WTW efficiency is then expressed by multiplying WTT to TTW efficiency values.

Table 2-7 shows the WTT and TTW efficiency values for different drive train configurations. Figure 2-12 shows the overall WTW efficiency of ICE, EV as well as other more electric vehicles. In Table 2-7 and Figure 2-12, WTW of other types of drivetrains are also presented from different studies to have a better comparison of advanced vehicular technologies [15-17].

**Table 2-7** Overall efficiency of different drivetrains

| | **WTT%** | **TTW%** | **Overall WTW%** |
|---|---|---|---|
| **ICE** | 81.6% | 21.9% | 17.73% |
| **FCV** | 46% | 26.9% | 12.37% |
| **HEV** | 81.6% | 36.4% | 29.70% |
| **PHEV** | 75% | 56.6% | 42.45% |
| **EV** | 62.1% | 71% | 44.09% |

It is a growing need, that today`s vehicle fleet must be replace with more efficient vehicles. It is a fact, which EVs continue to be the most efficient vehicle of today and future. With using more renewable energy sources, EVs can improve more in WTW efficiency and GHG reduction.

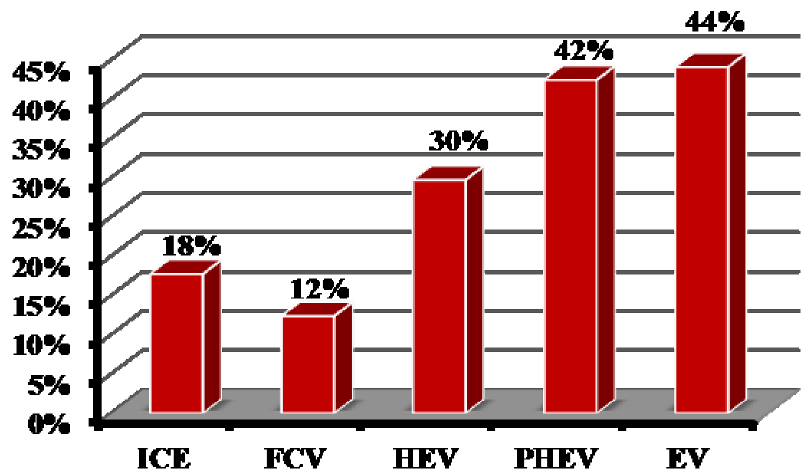



**Fig. 2-12** WTW efficiency of different drivetrains

## 2.4 COMPARISON OF WTW GHGS AND EMISSIONS

Burning fuel produce a variety of emissions in the form of gas and liquid. These emissions includes, carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), volatile organic compounds (VOC), carbon monoxide (CO), sulphur oxides ($SO_x$), greenhouse gas emission (GHGs) and water.

In order to have a clear vision of emissions and GHGs reduction, WTW efficiency simulation were performed in GREET model in addition to performance WTW efficiency. Overall WTW GHGs and emissions analysis presented, for 2012 and expected 2030 technologies. The GHG emissions (g/km) for 2012 and 2030 are summarized in tables 6 and 7. Emission percentage changes in EVs fuel pathway, relative to gasoline vehicle simulated in GREET model, shows a positive emission reduction in both years 2012 and projected for 2030.

$SO_x$ are mainly formed from combustion of fuel containing sulphur. Although, there is a positive increase shows in $SO_x$ generation. But, by comparing $SO_x$ values in Tables 2-8 to 2-11, there is a projected clear trend towards reduce $SO_x$ emissions in 2030.

Although, produced $SO_x$ in EV fuel pathway is not created by EV itself. This is another good reason to use more renewable energy sources to eliminate $SO_x$ from fuel pathway.

**Table 2-8** 2012 WTW GHG emission analysis for ICE vehicle

| Year: 2012 | gr/km – ICE Vehicle | | | |
|---|---|---|---|---|
| **Item** | **Feedstock** | **Fuel** | **Vehicle Operation** | **Total** |
| **$CO_2$** | 9.6940 | 33.3912 | 228.5938 | 271.6790 |
| **$CH_4$** | 0.2988 | 0.1197 | 0.0080 | 0.4266 |
| **$N_2O$** | 0.0002 | 0.0037 | 0.0074 | 0.0445 |
| **VOC** | 0.0103 | 0.0708 | 0.1050 | 0.0812 |
| **CO** | 0.0167 | 0.0194 | 2.2643 | 2.3006 |
| **$SO_x$** | 0.0303 | 0.0355 | 0.0037 | 0.0695 |
| **GHGs** | 17.2284 | 37.5128 | 231.0178 | 281.7591 |

**Table 2-9** 2012 WTW GHG emission analysis for electric vehicle

| Year: 2012 | gr/km – Electric Vehicle | | | | % Changes Relative to ICE Vehicle |
|---|---|---|---|---|---|
| **Item** | **Feedstock** | **Fuel** | **Vehicle Operation** | **Total** | |
| **$CO_2$** | 2.1579 | 56.4226 | 0 | 58.5805 | -78.4% |
| **$CH_4$** | 0.1461 | 0.0035 | 23.5863 | 23.7360 | -64.9% |
| **$N_2O$** | 0.0004 | 0.0010 | 0 | 0.0014 | -86.9% |
| **VOC** | 0.0042 | 0.0013 | 0 | 0.0056 | -97.0% |
| **CO** | 0.0032 | 0.0311 | 0 | 0.0344 | -98.5% |
| **$SO_x$** | 0.0057 | 0.1530 | 0 | 0.1587 | 128.1% |
| **GHGs** | 5.9432 | 56.8267 | 0 | 62.7699 | -78.0% |

**Table 2-10** 2030 WTW GHG emission analysis for ICE vehicle

| Year: 2030 | gr/km – Gasoline Vehicle | | | |
|---|---|---|---|---|
| **Item** | **Feedstock** | **Fuel** | **Vehicle Operation** | **Total** |
| **$CO_2$** | 5.8186 | 18.2000 | 199.4773 | 223.4959 |
| **$CH_4$** | 0.2535 | 0.0660 | 0.0062 | 0.3257 |
| **$N_2O$** | 0.0002 | 0.0048 | 0.0074 | 0.0124 |
| **VOC** | 0.0088 | 0.0591 | 0.0938 | 0.1617 |
| **CO** | 0.0141 | 0.0116 | 2.1637 | 2.1894 |
| **$SO_x$** | 0.0146 | 0.0157 | 0.0032 | 0.0335 |
| **GHGs** | 12.2197 | 21.3098 | 201.8548 | 235.3843 |

**Table 2-11** 2030 WTW GHG emission analysis for electric vehicle

| Year: 2030 | gr/km – Electric Vehicle | | | | % Changes Relative to ICE Vehicle |
|---|---|---|---|---|---|
| **Item** | **Feedstock** | **Fuel** | **Vehicle Operation** | **Total** | |
| **$CO_2$** | 1.7689 | 30.7858 | 0 | 32.5547 | -86.2% |
| **$CH_4$** | 0.1137 | 0.0071 | 0 | 0.1208 | -67.0% |
| **$N_2O$** | 0.0007 | 0.0012 | 0 | 0.0019 | -84.8% |
| **VOC** | 0.0023 | 0.0019 | 0 | 0.0042 | -97.4% |
| **CO** | 0.0025 | 0.0620 | 0 | 0.0645 | -97.1% |
| **$SO_x$** | 0.0034 | 0.0536 | 0 | 0.0570 | 33.0% |
| **GHGs** | 4.8235 | 31.3311 | 0 | 36.1546 | -85.4% |

In fact, since EVs has driving range limited by battery capacity, their use will be limited to drive in city or suburban area for a daily trip up to 100 km. These trips will require only small to mid-size vehicles. These types of vehicles are intrinsically less energy consuming and they will be even cleaner and more fuel efficient.

Figure 2-13 is generated to give a visual sense of anticipated GHGs and emission reduction by 2030.

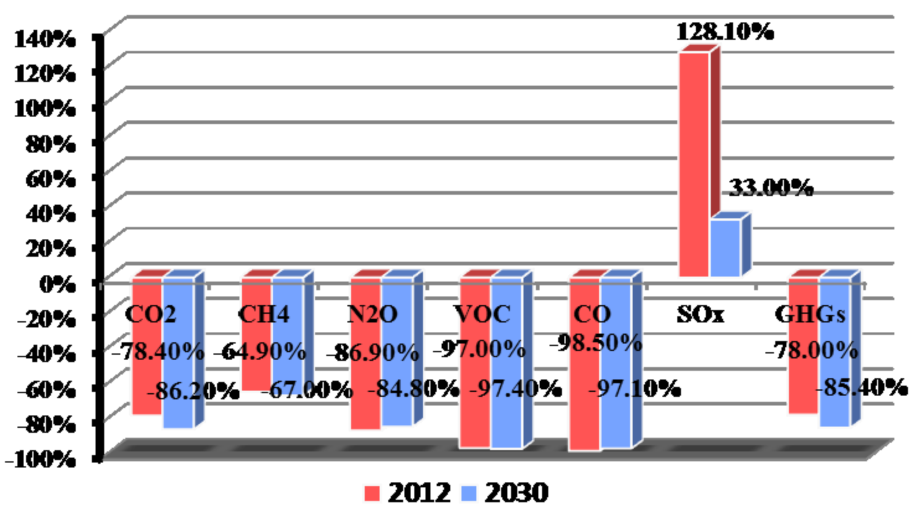



**Fig. 2-13** Comparison of emission reduction between 2012 and 2030

## 2.5 SUMMARY

Aside from clear emission reduction by using EVs in vehicle fleet, there is another way that EVs can immensely smash ICE vehicle. ICE delivers a very little torque at low speed which can provide only reasonable horsepower in a narrow speed range. But in EVs, high torque can be delivered at zero rpm. It means EVs can get to maximum speed in a very short time without any change in the drive train. But in ICE vehicle providing this performance need a bigger engine which makes extra weight and cost in the drive train.

Overall, electric vehicles have higher efficiency and lower emission rate than most efficient vehicles. As it is shown in this chapter, TTW efficiency of EV easily scores over its counterparts. But, as it is addressed, calculation of TTW efficiency alone is not enough to evaluate the overall efficiency. For this reason, WTW efficiency analysis needs to be performed to give more reliable results. There is a worldwide desire need to reduce emissions, mainly carbon footprint of the vehicle fleet. This study showed, EVs are the most promising solution to tackle this need.

The initial section of this chapter focused on developing an understanding of different power train technologies. Then after, theoretical efficiency analysis of these drive trains analyzed. WTW efficiency analysis introduced and two major parts of this analysis which include WTT and TTW are explained. For WTT efficiency, analyses performed by using GREET model for 2012 and estimated analysis of 2030 for different fuel pathways. Analysis showed that, gasoline production pathway is more efficient than electricity generation, transmission and distribution by 17–19%. Although, gasoline production is more efficient than electricity, but electricity pathway consumed much less energy. Coal consumption is drastically increased for electricity generation, but this consumption can be eliminated by focusing on renewable electricity generation.

TTW efficiency analysis showed EVs can be the most promising and clean technology for current and future vehicle fleet. Through the simulation, using ADVISOR software, it is clear that, even current EV technology is about 15% more efficient compare to its closest competitive counterpart, PHEV. EVs are mechanically much simpler than other vehicles under this study. There is no engine, no clutch, no spark plugs, no fuel reformer in drive train and transmission is also much simpler.

WTW GHGs and emissions analysis also confirmed that EV technology is the most viable technology of the future. Analysis, using GREET model showed, GHGs can be reduced by 85.4% followed by $CO_2$ reduction for 86.2% in 2030, if ICE vehicle fleet replaced by EVs.

To the end, it was found to be advantageous for EVs to penetrate to the vehicle fleet as rapidly as possible. Meanwhile, until required infrastructure established and EVs gets popular and affordable for consumers, it is a good idea to move towards more electric vehicles such as PHEVs to make this transform more smooth and acceptable.

# CHAPTER 3

# IMPACT OF DIFFERENT DOMESTIC ELECTRIC VEHICLE CHARGING REGIMES ON QUEBEC'S LOAD DEMAND – PREDICTION FOR 2030

## 3.1 INTRODUCTION

Electric and plug-in hybrid electric vehicles (EVs/PHEVs) can have a large impact on greenhouse gases (GHGs) reduction, increase in fuel economy and higher fuel efficiency. EVs are propelled by the energy from electric power source, whereas PHEVs propelled by two energy sources as electricity and gasoline. The market penetration of battery electric and more electric vehicles (BEVs/MEVs) into a country's vehicle fleet is anticipated to increase the load demand at a national level. The severity of the charging impact on load demand will depend on charging regimes, EV uptake and owner's behavior. Therefore, smart charging of EVs may remove a lot of stress from electricity grid. This paper assesses the effect of home charging of EVs/PHEVs on electricity demand in the province of Quebec in Canada. A number of case studies are developed to assess, how different charging regime and EV uptakes can change total load demand of Quebec in 2030. The number of light-duty vehicles and prediction of EVs/PHEVs penetration into vehicle fleet is drawn from different Canadian studies. Canada traffic distribution is developed from data acquired from INRIX Traffic Scorecard. The load demand for the year 2011 is used as a base load from Hydro Quebec and typical planning load estimates are used to project the load demand for the year 2030. It is shown that an uncontrolled charging regime would increase the load demand up to 12%, whereas controlled charging of EV batteries using TOU tariffs would lead to a have a tinny increase of up to 5% on load demand in summer time.

## 3.2 Related Works

Air quality and emissions will remain the major concern in our decade among different nations. In 2010, Canada generated a total of 692 Mt of GHGs, where it has a narrow change of 0.25% increase from 2009. This means, that Canada's emissions remained relatively steady, in spite of an economic growth of 3.2% [18]. Approximately 80% of the total bulk greenhouses gas emissions ($CO_2$, $CH_4$, and $N_2O$) are accounted to the energy sector in Canada. These emissions mostly come from the use of transportation fuels and Canada's fossil fuel industry [19]. Transportation including passenger, freight and off-road vehicles sector is the largest contributor of GHGs emission in Canada, representing 24% of total GHGs in 2010 [18]. The Government of Canada has a target of total GHGs emission reduction by 17% between 2005 and 2020. A fine progress is shown towards this target through a sector by sector approach. Federal approaches as well as action which was taken by different provinces shows that Canada is at present half way towards the 2020 target [20].

The market penetration of BEVs/MEVs may contribute to the federal approaches' 2020 GHG emissions reduction target. These vehicles plug into the power system to charge their battery packs. BEVs are purely powered by electricity, while PHEVs using a combination of gasoline and electricity to propel the vehicle. A number of the new models of these vehicles from major automakers can be seen on the roads in Canada. It is obvious that, penetration of EVs/PHEVs and with help of smart grid, fossil fuel sources of energy can be displaced by electricity where dramatically reduce GHGs emissions.

Provinces like Quebec and British Columbia use a large amount of clean electricity with a major fraction being from hydro. The clean electricity production will increase in 2014 with further new installations of renewable generation plants and closure of coal plants [4]. A study in University of Waterloo [21] shows that, EVs/PHEVs charging will not affect the load demand in the electricity grid, immediately.

The authors support that the system planners have 3-5 years' time to evaluate new vehicles penetration in Ontario's streets. It is likely that the adoption of EVs/PHEVs will be firstly realized in urban areas which will impose congestions on the distribution grids assets loading and affect distribution feeders' voltage profiles. Considering EVs/PHEVs charging level and timing, a load equivalent to a new house can be added to the distribution system [22]. The implementation of smart EV battery charging methods which will target charging during lower off-peak prices and encourage EV/PHEV owners to charge overnight out of peak hours, may help maintain the operation of distribution networks within their operating limits. The purpose of this study is to identify the impact of different domestic EV battery charging regimes on Quebec's load demand. It is anticipated that load demand can be affected by various characteristics such as: the number of EVs/PHEVs, the time frame and length of EVs/PHEVs battery charging and the power rating of the battery chargers. To ensure the accuracy of this research work, studies and methods of different sources are firstly reviewed and evaluated. A valley filling approach for EV battery charging was addressed in [23]. In this study, it is considered that 40% of distances are travels on EV mode with an average consumption 0.21 kWh/km. The findings of this study show that an increase of 18 to 40% in minimum load is anticipated with EV battery charging depending on different charging regimes.

A study from U.S. Oak Ridge National Laboratory [24] investigated the effect of

EV utilization on the grid demand for different US regions in 2020 and 2030. The study focused on evening and night charging where in evening charging, half of the vehicles plugged in 5 pm, and the other half start to charge at 6 pm. Night charging is also divided in 2 groups as half of the vehicle start to charge at 10 pm, while the other half start charging at 11 pm. Three different charging levels of 1.4, 2 and 6 kW were considered. The results of the study show, that no additional generation would be necessary using the night charging regime, whereas in the case of evening charging regime at 6 kW rate, additional generation would be necessary to cover the EVs/PHEVs battery pack charging. A major European project called Mobile Energy Resources in Grid of Electricity (MERGE) investigated the effect of domestic EV charging on the national grid of six different European countries [25]. Dumb charging, where EV owners would charge their EVs charge as soon as they arrive home after their last trip and smart charging where EV battery charging would be controlled to minimize the impact on demand peaks using a valley filling control, was considered. The results of the study show that a dumb charging approach would increase the peak demand of all six countries under the study between 6 to 12%. The smart charging control would not increase the daily peak demand of any of the six European countries under the study.

The review of the above studies reveals the importance of considering the following factors in studying the effect of domestic battery charging on electricity demand at a national level: i) EVs/PHEVs uptake level, ii) battery charging occurrence and duration . The contribution of the present study is the assessment of the effect of EV/PHEV penetration in Quebec's load demand is forecasted through various penetration levels such as mild and aggressive uptakes. Firstly, the EV uptake for the year 2030 is estimated using governmental and international projections and then electric vehicle battery charging regimes are developed using data from a national survey. The term EV/PHEV or EV are used throughout this paper to point at electric vehicles and plug-in hybrid electric vehicles, as both of them are treated in the same way from a power systems viewpoint.

## 3.3 VEHICLES ON THE ROADS IN CANADA AND QUEBEC

Natural Resources Canada (NRCan) published the latest Canadian Vehicle Survey in 2009 [26]. This is a quarterly survey of activities in the area of vehicle transportation. The 2009 report deals with road vehicle activities of the vehicles registered in Canada and provide the characteristics of the Canadian vehicle fleet and their fuel consumption as well as a comparison between the number of vehicles in 2000 and 2009. According to the study, Ontario and Quebec had 58.7% of the total Canadian fleet in 2009, with 7.4 million vehicles in Ontario and 4.7 million vehicles in Quebec. It is also reported that in 2009, 96.3% of 20,511,161 vehicles in Canada were light vehicles. Medium and heavy trucks accounted for 2.1% and 1.5% respectively. For this reason, focus in this study is on the light vehicle sector in general.

Tables 3-1 and 3-2 provide results from the survey. Assumption on compound annual growth rate prediction for 2030 is taken based on light vehicle growth rate between year 2000 and 2009 and translated to 2030. Table 3-1 shows the total number of vehicles in Canada and Quebec. Table 3-2 shows the total number of light vehicles in Canada and Quebec. In this study, light vehicles assumed to be as light cars, SUVs and station wagons.

**Table 3-1** Number of cars in Canada and Quebec

| Region | No. Of Cars: 2000 | No. of Cars: 2009 | Compound Annual Growth Rate | Estimated No. Of Cars: 2030 |
|---|---|---|---|---|
| CANADA | 17,217,143 | 20,511,161 | 1.9% | 28,695,114 |
| QUEBEC | 3,856,820 | 4,679,516 | | 6,546,642 |

**Table 3-2** Number of light vehicles in Canada and Quebec

| Region | No. Of Veh.: 2000 | No. of Veh.: 2009 | Compound Annual Growth Rate | Estimated No. Of Veh.: 2030 |
|---|---|---|---|---|
| CANADA | 12,034,782 | 14,706,502 | 1.9% | 20,574,396 |
| QUEBEC | 2,695,917 | 3,355,213 | | 4,693,925 |

The Canadian Vehicle Survey reports that:

- There was an average of 0.8% increase in light vehicle kilometers between 2000 and 2009.
- The growth of light vehicles between 2000 and 2009 was 1.9% on average.
- Light vehicles were driven 17000 kilometers in 2000, whereas in 2009 total kilometers drop to 15,336.
- In the period of the study vehicle ownership increased from 1.43 in 2000 to 1.47 in 2009 per household. This means that even though the number of vehicles increased, compared to the year 2000, Canadians travelled fewer kilometers in each vehicle [26].

## 3.4 QUEBEC ACTION PLAN AND EV MARKET SHARE

In 2011, the Government of Quebec published the Electric Vehicles: 2011-2020 Quebec Action Plan [27]. In this plan, it is reported that private EV use is anticipated to contribute by 6% towards Quebec's target of GHG reduction in 2020 and 20% reduction on petroleum product use in which will reduce Quebec total energy consumption from

38-32% in 2020. The government's target, as reported in this plan, is to have 25% of new light vehicles as plug-in or all electric vehicle by 2020. In 2020, 118000 new EVs will be sold.

Assuming that EVs which have been sold in earlier years;

- In 2020, it is anticipated that 300,000 EV operating in Quebec roads. The outcome of this uptake in terms of GHG emissions will be 900,000 tons reduction.
- In 2030, it is estimated that Quebec will have 1.2 million EVs by 2030 with a total saving of 305 million tons of GHGs reduction and 1.5 billion litter of petroleum [28].

The fraction of BEVs/PHEVs has been drawn based on results from the survey [29]:

- 35% of US owners and prospective buyers of personal vehicles preferred to buy BEVs,
- 65% preferred to buy PHEVs.

Since the Quebec Action Plan did not distinguish between BEVs and PHEVs, this fraction is used in the present study. In study [30], the business as usual scenario introduces two different EV penetration level as low and high uptakes. 7.07% is introduce as low uptake or mild penetration and 48.56% is represents the EV high uptake or aggressive penetration range in 2030. These two uptake levels will assumed to be low and high EV uptake in this study. Table 3-3 shows the two predicted uptakes relevant to the study for 2030 vehicle fleet in Quebec.

**Table 3-3** EVs uptake prediction in 2030 by type of vehicle

| Description | QUEBEC (Projected) | | |
|---|---|---|---|
| Vehicle fleet of 2030 | 4,693,925 | | |
| EV fleet of 2030 | EV Fleet | BEVs | PHEVs |
| Low uptake | 328,575 | 115,000 | 213,575 |
| High uptake | 2,276,554 | 796,794 | 1,479,760 |

## 3.5 STUDY ANALYSIS AND ASSUMPTIONS

According to the 2011-2020 Quebec Action Plan, charging station must be located in places that vehicle parked long enough to charge their battery pack. These places can be home, work or shopping malls and restaurants. It is estimated that around 80% of charging load will be in either home or work place where vehicle parked in a long time during the day. EVs will most likely be used and developed first in urban areas. So, the best place to charge these vehicles are at residential parking and garages. A survey [31] that has been done by Hydro-Quebec in 2009 shows, that 94% of Quebecers who own or intending to buy a vehicle already have a parking space in their homes. 89% of these people have access to Level-1 charging point in their parking. Although with quick technology development, fast charging stations can be seen soon in strategic location.

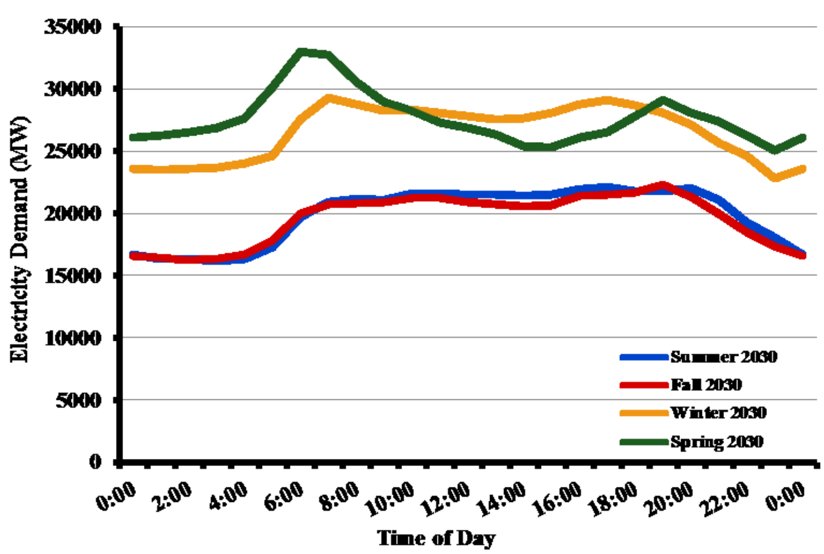
This study will consider, 1-phase, 120V, 15A connection will be the main domestic charge rating of Quebec in 2030. The Depth of discharge (DOD) considered in this study is 80%. So, it is assumed that batteries are initially at 20% state of charge (SOC), and then they are being fully charged.

**Table 3-4** Main assumptions of the study

| Assumptions | | References |
|---|---|---|
| EV charger efficiency | 87 | 21 |
| EV battery charging efficiency | 85 | 24 |
| EV charger rated power (KW) | 1.8 | 32 |
| Average battery capacities (kWh) | | |
| BEV | 24 | 33 |
| PHEV | 4 | 33 |
| Usable battery capacity | 80% on nominal rate | 24 |

The load demand for the year 2011 and the expected annual growth have been provided by Hydro-Quebec. The load profiles of 15th day of the first month of each season are used in this study for analysis of typical days. In “état d'avancement 2011, du plan d'approvisionnement 2011-2020” [34], Quebec annual electricity demand for 2011 indicated as 184.5 TWh. Plan also predicted annual electricity growth rate is 0.7% for 2011-2020. By calculating this rate for 2011-2020 period and transpose it to 2021-2030 period, estimated annual electricity demand of Quebec in 2030 will be 209 TWh.

Figure 3-1 shows the electricity demand of the assumed typical days of 2011 and 2030 for Quebec.



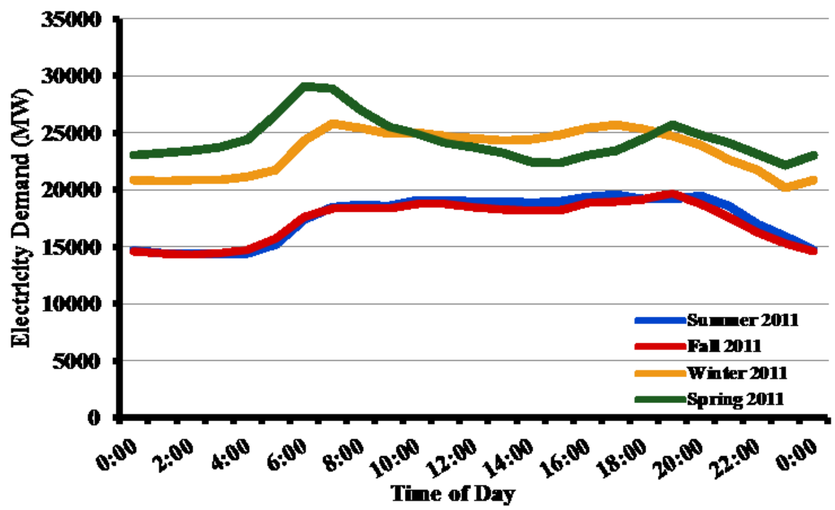



**Fig. 3-1** Quebec electricity demand in four different seasons. Figure above 2011 (actual) and figure below 2030 (projected)

## 3.6 EV CHARGING REGIMES IN QUEBEC

The impact of EVs/PHEVs on load demand from the model, considers different variables such as: Quebec population, vehicle growth, electricity price forecast and EV/PHEV efficiency through development of the technology. The model will consider the number of EVs/PHEVs and their energy consumption rate.

The EV/PHEV load demand forecast is not a certain procedure. Changes in any of major variables and assumptions will affect new technology adoption and may lead to modify the prediction especially in the next 10 years. The new technology acceptance will depend on many factors such as: technology improvement especially in battery production, consumer acceptance and charge station infrastructure.

EV/PHEV charging is developed using two major charging regimes. Uncontrolled as well as dual tariff (price driven and smart charging base) regimes are considered for this study. The additional load demand from EV/PHEV charging on Quebec load demand is incorporated for electricity grid preparation and safe electricity production margin purposes.

### 3.6.1 UNCONTROLLED CHARGING REGIME

In this regime, EV owners start charging their vehicle as soon as they arrive home. The charging periods of EVs depend on the daily traffic pattern of the region. The daily traffic pattern of Canada is used for Quebec, which is acquired from INRIX Traffic Scorecard [35].

A study on assessing vehicle mobility behavior shows, that vehicles are parked at home in about 23 hours on average per day [36]. So, the total driving time will be one hour per day.

According to a study that presents traffic statistics for Canada [37], Canadian commuters took an average of 30 minutes with all modes of transportation to go to work in metropolitan areas that have population of more than one million. 30 minutes travel time is used in this study as reference of an average time for a daily trip with car; it is considered that every trip that occurs within specific hour, commuters can start charging in the following hour. Figure 3-2 shows the traffic pattern of Quebec in 24 hours.

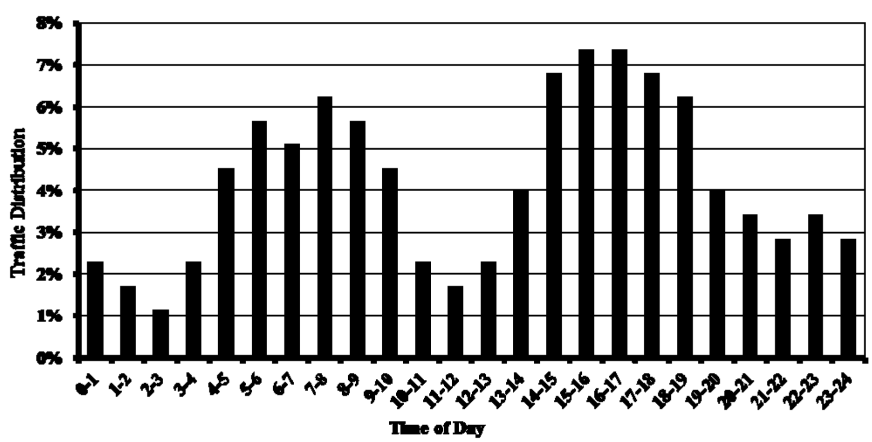



**Fig. 3-2** Quebec's traffic distribution in 24 hours

EVs/PHEVs are different than dispatchable loads, such as pump storage stations in their primary function. These loads can be named as flexible loads used as vehicle that has own simplicity and constrains. The required daily energy is directly proportional to total daily trip distance.

$$E_d = N \times d \times f \quad (3\text{-}1)$$

Here:

$E_d$ : Total daily vehicles energy requirement,
$N$: Number of vehicles,
$d$: Average travelled distance by vehicle and
$f$: Average energy consumption KWh/km.

Number of vehicles for mild penetration is 328,575 and 2,276,554 for aggressive penetration. Average distance travelled by light vehicles is around 45 kilometers per day [26] and average energy consumption is 0.2 KWh/km [38]. Therefore, the average daily vehicles energy consumption for EV low uptake is 2.9 GWh and for EV high uptake is 20.4 GWh.

In Quebec, with Level-1 charging facility, PHEV batteries would become fully charged from fully discharge level, in an average of 7 hours and EV batteries charging time can be 12 hours in an average.

Quebec EV charge distribution is also shown in Figure 3 for mild (above figure) and aggressive EV penetration. Note that in this study, 4 PM considered starting time to charge EVs.

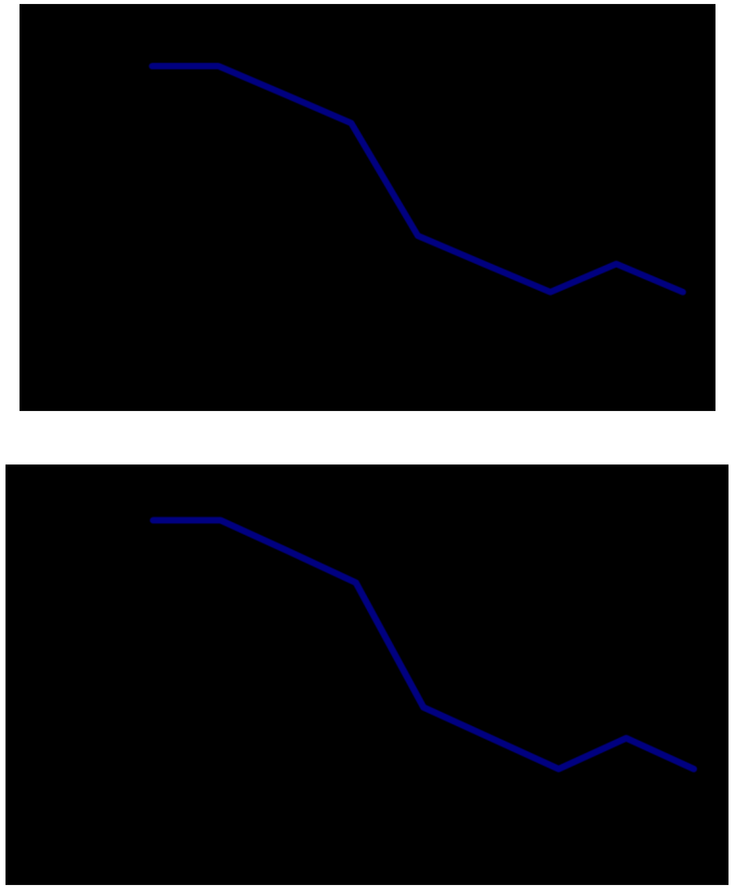


**Fig. 3-3** Quebec's EV charge distribution for EV low uptake (above figure) and EV high uptake (below figure) for uncontrolled scenario

### 3.6.2 CONTROLLED CHARGING REGIME

Quebec's electricity tariff is based on the amount of consumption in 24 hrs. 5.32 ¢/kWh is the price for the first 30 kWh of consumption and 7.51 ¢/kWh will be charged for the remaining energy usage. Target in dual tariff regime is to move EV charge to overnight. In the 2006-2015 Quebec Energy Strategy, government wants Hydro-Quebec employ new rates model based on season and time of use for residential customers [39].

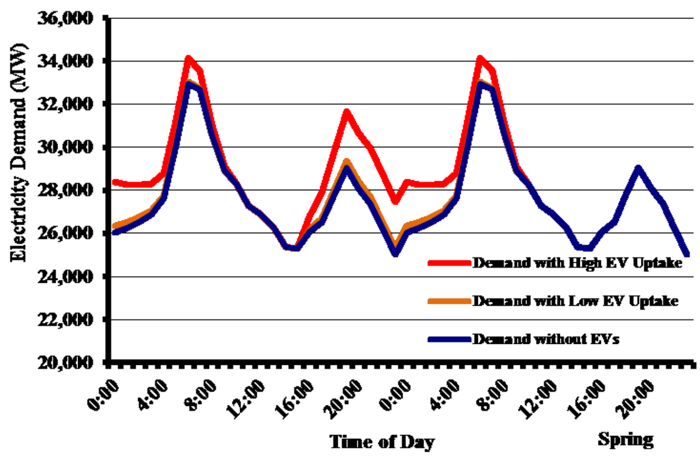
"Time it right" rate project was run in 2010 in four cities in Quebec [40]. Target in this project was to set a new rate structure, which could help customers to manage their electricity bill better. In this project, off peak period starts at 10 pm and finish at 6 am of the next morning. By changing in rate structure and with using smart meters, dual tariff regime can be applied to Quebec EV charging. It is assumed that, EV owners who arrived home before 10 pm start to change their vehicle at 10 pm, and those who arrived home between 10 pm and 11 pm start charge their vehicles at 11 pm.

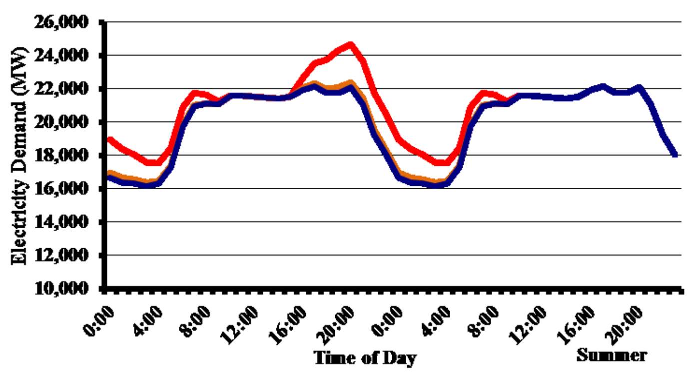
To have an assessment on the impact of dual tariff regime on EV charging, hourly electricity price that Hydro-Quebec used in its electricity transmission to neighboring provinces in Canada and US, is considered in this study. Since, there is no dual tariff on Quebec electricity tariffs; electricity transmission price to out of province customers is used as a tool to evaluate the impact of this EV charging regime on load demand.

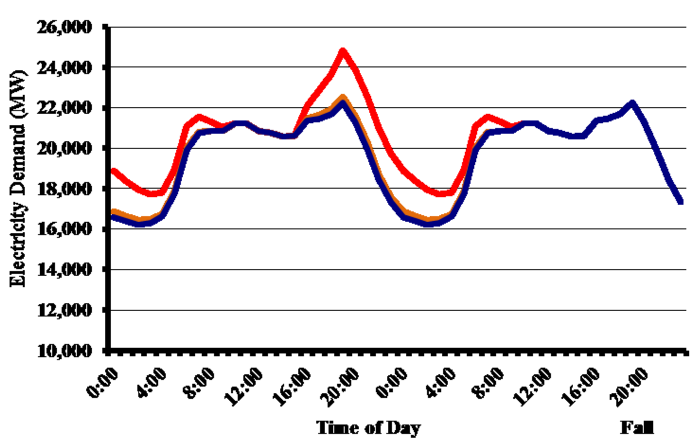
EV charging regime could have a major role on load demand. Penetration of EVs can have benefits if specific vehicle charging implemented. In general, by employing controlled regime, utilization of the existing power system can be maximized. By implementing a particular charging method, and move EV charging to overnight, thermal generation can be minimized and inflexible generation such as renewable energies in particular wind energy can be facilitated. With this smart strategy, emission and total system cost are also reduced. But, with uncontrolled charging regime these benefits may not arise and load demand, total system cost and emission will increase [38].

## 3.7 STUDY RESULTS AND EFFECTS OF CHARGING PATTERNS

The effect of EV market penetration on Quebec's load demand is assessed using four different seasonal load profiles for both uncontrolled and controlled charging regimes. Figure 3-4 shows projection of two days duration load demand for each season in uncontrolled charging regime for year 2030. The peak load is found to increase in all seasons for low and high EV uptakes. The time that commuters would return home coincides with the peak demand. However, it is interesting to observe that new peak demand times occur for summer and winter. Figure 3-4 also shows projected peak increase is relevant to the time that commuters arrive home and start charging vehicles. In result, increase in peak demand, peak demand time shift for different seasons and times.



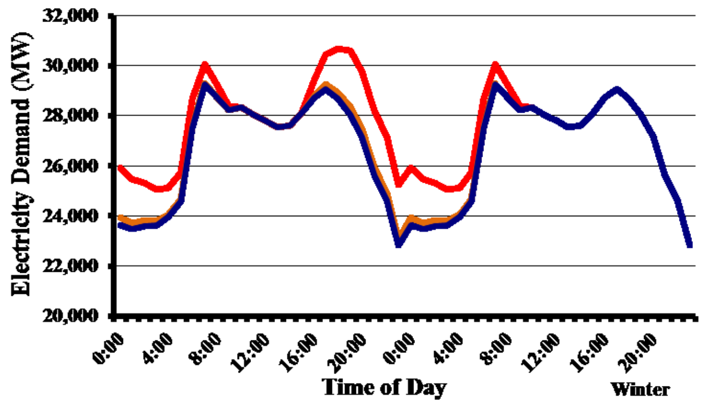



**Fig. 3-4** Quebec's predicted energy demand in 2030 for uncontrolled scenario

Table 3-5 shows the peak demand without EVs, the peak demand with a low EV uptake and the peak demand with a high EV uptake using an uncontrolled charging regime. The percentage in peak increase and new peak time in uncontrolled charging regime for different seasons of year 2030 are also provided.

**Table 3-5** Peak increase and new peak time as a result of EV penetration in uncontrolled scenario

| Season | Demand without EV | Peak Time | Demand with Low EV Uptake | New Demand Peak Time | Peak Increase (%) |
|---|---|---|---|---|---|
| Spring | 32970.30 | 6:00-7:00 | 33052.46 | 6:00-7:00 | 0.25 |
| Summer | 22137.69 | 17:00-18:00 | 22382.55 | 20:00-21:00 | 1.11 |
| Fall | 22250.99 | 19:00-20:00 | 22560.67 | 19:00-20:00 | 1.39 |
| Winter | 29272.19 | 7:00-8:00 | 29313.27 | 18:00-19:00 | 0.14 |

| Season | Demand without EV | Peak Time | Demand with High EV Uptake | New Demand Peak Time | Peak Increase (%) |
|---|---|---|---|---|---|
| Spring | 32970.30 | 6:00-7:00 | 34124.05 | 6:00-7:00 | 3.50 |
| Summer | 22137.69 | 17:00-18:00 | 24670.23 | 20:00-21:00 | 11.44 |
| Fall | 22250.99 | 19:00-20:00 | 24825.24 | 19:00-20:00 | 11.57 |
| Winter | 29272.19 | 7:00-8:00 | 30665.79 | 18:00-19:00 | 4.76 |

Figure 3-4 and Table 3-5 show that using an uncontrolled charging regime in Quebec for 2030:

- For a low EV uptake, the peak demand is increased up to 1.4%. The demand peak time is shifted in summer and winter seasons into the evening.
- For a high EV uptake, the peak demand is increased up to 11.57%. The demand peak time is shifted in summer and winter seasons into the evening.

Figure 3-5 shows projection of two days duration load demand for each season using a controlled charging regime for year 2030. The peak load is found to increase in all seasons for low and high EV uptakes. But, scenario is considerable in high EV uptake. Demand peak increased in all seasons with more stress in summer and fall. Peak is also shifted from afternoon and morning to evening in summer and fall.

Load demand profile is also developed for controlled charging regime. For this charging regime, an algorithm is used that allow vehicle arrived home before 10 PM, start charging at 10 PM. Vehicles arrives home between 10 PM to 11 PM must wait until 11 PM. So, their charge will start at 11 PM. In this regime charge profile is developed with regular rate for after 10 PM charging.

Using this controlled charging regime, it is found that the major fraction of EV battery charging would occur overnight. Giving this charging strategy with off-peak energy use by delaying of home charging after 10 PM can optimize the use of low cost energy at off-peak period. With use of this strategy, renewable energy generation can be fit into the generation market and can be consumed directly with the help of overnight EV charging.

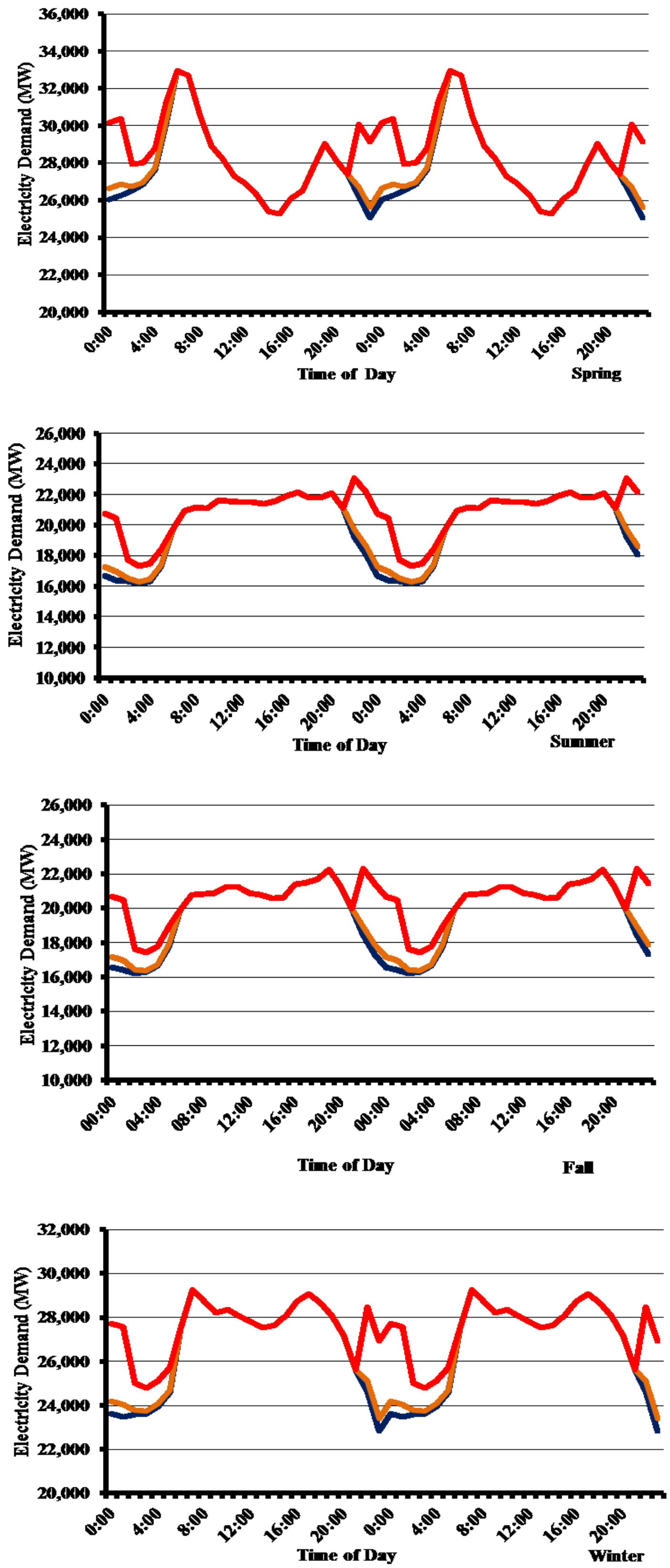



**Fig. 3-5** Quebec's predicted energy demand in 2030 for controlled scenario

Table 3-6 shows peak demand without EVs, peak demand with a low EV uptake and the peak demand with a high EV uptake using a controlled charging regime. The percentage in peak increase and new peak time in uncontrolled charging regime for different seasons of year 2030 are also provided.

**Table 3-6** Peak increase and new peak time as a result of EV penetration in controlled scenario

| Season | Demand without EV | Peak Time | Demand with Low EV Uptake | New Demand Peak Time | Peak Increase (%) |
|---|---|---|---|---|---|
| Spring | 32970.30 | 6:00-7:00 | 32970.30 | 6:00-7:00 | 0 |
| Summer | 22137.69 | 17:00-18:00 | 22137.69 | 17:00-18:00 | 0 |
| Fall | 22250.99 | 19:00-20:00 | 22250.99 | 19:00-20:00 | 0 |
| Winter | 29272.19 | 7:00-8:00 | 29272.19 | 7:00-8:00 | 0 |

| Season | Demand without EV | Peak Time | Demand with High EV Uptake | New Demand Peak Time | Peak Increase (%) |
|---|---|---|---|---|---|
| Spring | 32970.30 | 6:00-7:00 | 32970.30 | 6:00-7:00 | 0 |
| Summer | 22137.69 | 17:00-18:00 | 23068.93 | 00:00-1:00 | 4.21 |
| Fall | 22250.99 | 19:00-20:00 | 22295.09 | 19:00-20:00 | 0.20 |
| Winter | 29272.19 | 7:00-8:00 | 29272.19 | 18:00-19:00 | 0 |

Figure 3-5 and Table 3-6 show that using a controlled charging regime in Quebec for 2030:

- For a low EV uptake, the peak demand is maintained in both figure and time.
- For a high EV uptake, the peak demand is increased up to 4.21%. The demand peak time is shifted only for the summer season into the evening.

The advantage of this controlled charging regime over the uncontrolled charging regime is the application of valley filling. The ability of the controlled charging regime to mitigate the impact on peak demand increase and time shift has been demonstrated.

## 3.8 $CO_2$ EMISSION ANALYSIS

As mentioned previously, transportation sector is the largest contributor of GHGs emission in Canada. One of the main reasons of transportation electrification is to reduce $CO_2$ emission from tailpipes. This $CO_2$ reduction must be closely monitored. Penetration of EVs into the transportation sector may shift emission production to electricity generation sector.

The carbon footprint from the operation of EVs in the scenarios developed in this paper is assessed. In general, the carbon footprint is related to the type of fuel source. The total $CO_2$ emissions can be calculated as [21]:

$$Total\ CO2 = Total\ CO2\ (From\ Power\ Plants) + Total\ CO2\ (From\ Non\ EVs) + Total\ CO2\ (From\ EVs) \tag{3-2}$$

$$Total\ CO2\ (From\ Power\ Plants) = \sum M_P \times CE_P \tag{3-3}$$

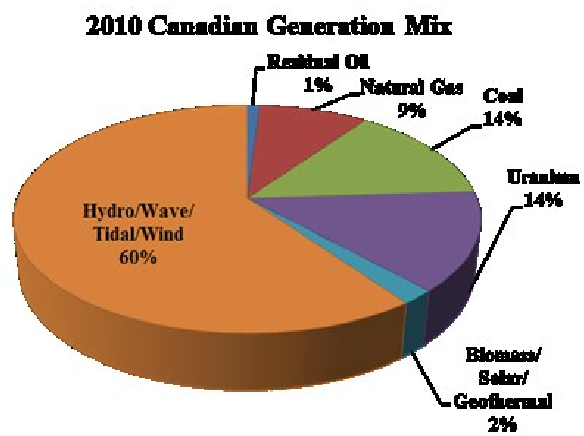
$$Total\ CO2\ (From\ Vehicle, non\ EVs) = \sum AD_y \times CE_V \times N \tag{3-4}$$

Whereas:
$CE_P$ : $CO_2$ emission$(t/MWh)$,
$CE_V$ : $CO_2$ emission$(t/km)$,
$P$: Type of power plant,
$V$: Type of EVs/PHEVs,
$AD_y$ : Average community distance per year and
$N$: Number of EVs/PHEVs.

The total $CO_2$ emission from the operation lifecycle of BEV is assumed to be zero. According to 2009 vehicle survey, the daily average community distance traveled in Canada is 42 kilometers [26]. It is assumed, that PHEVs are driven on their electric mover for the first 40 kilometers and then use their IC engine. For simplicity it is assumed that $CO_2$ emissions from PHEVs operational lifecycle are zero.

One of the strong reasons to adopt EVs is the environmental benefits of this new technology. Penetration of EVs in transportation sector can greatly reduce emissions of $CO_2$ and other emissions from tailpipe. But it should be noted, that this emission reduction, has direct relation with how electricity used in EVs, is produced. Electricity generation with natural gas can reduce net $CO_2$ emission from tailpipe more than 50 %. While, generation from renewable sources such as, hydro, wind, solar and nuclear can reduce total emission to zero [32].

Government and industry in Canada puts lots of effort to limit GHG emission as a result of energy generation. All generation options such as, provincial energy strategies, utility expansion plans are taken into consideration. As a result, electricity generation in Canada become cleaner. Figure 3-6, shows the Canadian generation mix for the period of 2010 to 2035 according to [41]. As it is shown in the pie charts, the share of renewable generation sources such as, hydro, wind and other renewable sources are increased from 76% in 2010 to 79% in 2035. Specifically, renewable-based generation sources increases from 62% in 2010 to 68% in 2035 [41].



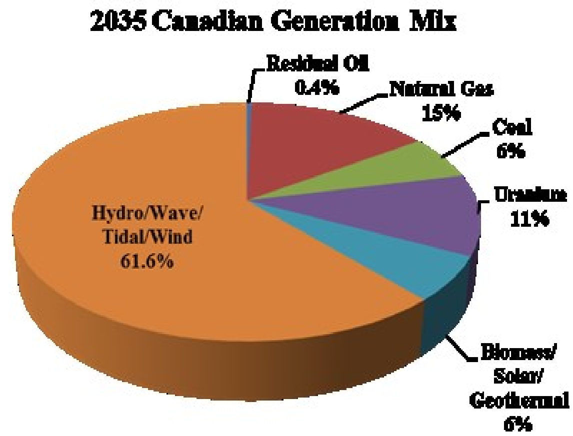



**Fig. 3-6** 2010 and 2035 Canadian generation mix

Regardless of generation mix, EVs can have environmental benefits in the location where they are used. Also, the high efficiency in fuel converting to motion in comparison with IC engine vehicles makes EVs emission-free.

## 3.9 COMPARISON WITH GB STUDY

This study have been compared with the results from a UK project, which analyzes the impacts that EV domestic charging may create on the national electricity demand of Great Britain (GB) [42]. The purpose of the study was also to identify the impact of different home charging regimes on GB load demand. The GB study considered 13A single phase 240V connection as the main domestic charging rate in GB in 2030 [43].

In this study, the batteries of BEVs and PHEVs considered to become fully charged from full discharge in 15h and 4h respectively. Figure 3-7 shows the impact of EV domestic charging for three seasons and for different uptake levels in uncontrolled scenario.

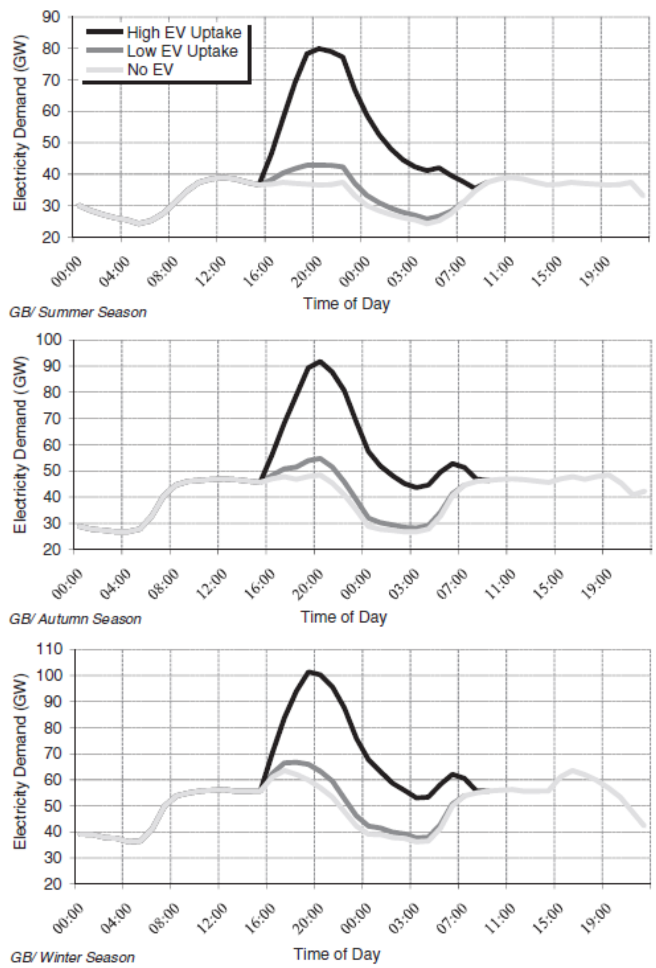



**Fig. 3-7** British predicted energy demand for uncontrolled charging in 2030

In the dual tariff regime, the EVs assumed to start the charging process at night. There are different price rates and off peak times in GB, according to each energy supplier. For this study, it was assumed that the British off peak charges start at 23:00 and finish at 07:00 of the next day [44]. This period is also considered the British off peak time in 2030. EVs that return before 23:00 will wait until this time then start the charging process. EVs arrive between 23:00 and 24:00; will begin charging the batteries at 24:00.The British predicted load demand for the dual tariff regime is presented in Figure 3-8.

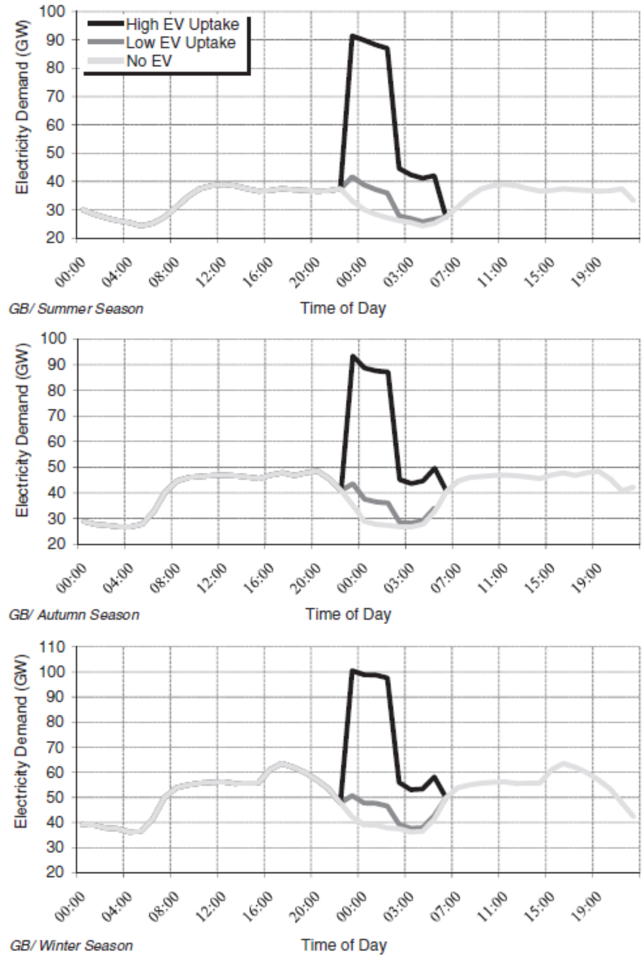



**Fig. 3-8** British predicted energy demand for dual tariff charging in 2030

The peak increase and time displacements by season for the low EV uptake case are illustrated in Table 3-7 for both uncontrolled and dual tariff charging regime.

**Table 3-7** Peak increase and time displacement by season for uncontrolled and dual tariff regimes as a result of EV charging and low uptake

| | | Uncontrolled charging | | Dual Tariff charging | |
|---|---|---|---|---|---|
| | Actual Peak Time (2008) | Peak increase GW | Projected peak time (2030) | Peak increase GW | Projected peak time (2030) |
| Spring | 18:00-19:00 | 5.770 (11.4%) | 19:00-20:00 | 0 | 18:00-19:00 |
| Summer | 12:00-13:00 | 3.94 (10.1%) | 20:00-21:00 | 2.653 (6.8%) | 23:00-24:00 |
| Autumn | 20:00-21:00 | 6.315 (13%) | 20:00-21:00 | 0 | 20:00-21:00 |
| Winter | 17:00-18:00 | 3.160 (5%) | 18:00-19:00 | 0 | 17:00-18:00 |

It was found that even the low EV uptake level, will increase the peak of the electricity demand in 2030. The uncontrolled EV charging was found to increase the winter day peak demand by 3.2 GW (5%). However, with a dual tariff control strategy, the winter day peak demand will not change.

In conclusion, it was found that the peak day demand will increase slightly with low EV uptake, in uncontrolled scenario. However, in dual tariff regime peak increase can successfully eliminate for the most cases. For the high uptake scenario, it was found that more smart control algorithms must be applied to manage the EV charging requests without increasing future electricity demand in GB. Tables 3-8 and 3-9 are shown summary of comparison between QC and GB cases.

**Table 3-8** Comparison in peak increase and new peak time between QC and GB in uncontrolled scenario

| Season | QC Peak Time | QC Peak Increase (%) | QC New Demand Peak Time | GB Peak Time | GB Peak Increase (%) | GB New Demand Peak Time |
|---|---|---|---|---|---|---|
| Spring | 6:00-7:00 | 3.50% | 6:00-7:00 | 18:00-19:00 | 11.4% | 19:00-20:00 |
| Summer | 17:00-18:00 | 11.44% | 20:00-21:00 | 12:00-13:00 | 10.1% | 20:00-21:00 |
| Fall | 19:00-20:00 | 11.57% | 19:00-20:00 | 20:00-21:00 | 13% | 20:00-21:00 |
| Winter | 7:00-8:00 | 4.76% | 18:00-19:00 | 17:00-18:00 | 5% | 18:00-19:00 |

**Table 3-9** Comparison in peak increase and new peak time between QC and GB in controlled scenario

| Season | QC Peak Time | QC Peak Increase (%) | QC New Demand Peak Time | GB Peak Time | GB Peak Increase (%) | GB New Demand Peak Time |
|---|---|---|---|---|---|---|
| Spring | 6:00-7:00 | 0 | 6:00-7:00 | 18:00-19:00 | 0 | 18:00-19:00 |
| Summer | 17:00-18:00 | 4.21% | 20:00-21:00 | 12:00-13:00 | 6.8% | 23:00-24:00 |
| Fall | 19:00-20:00 | 0.20% | 19:00-20:00 | 20:00-21:00 | 0 | 20:00-21:00 |
| Winter | 7:00-8:00 | 0 | 18:00-19:00 | 17:00-18:00 | 0 | 17:00-18:00 |

## 3.10 SUMMARY

In this study, the effect of EVs/PHEVs home charging on Quebec's load demand was examined. Number of vehicles in 2030 was estimated based on Natural Resources Canada information. Quebec Action Plan for electric vehicles mentioned, that 25% of Quebec vehicles will be PHEV until 2020 and 1.2 million will be EVs by 2030. As a result 900,000 tons of GHG reduction by 2020, and 305 million tons of GHG reduction by 2030 are anticipated to be reached.

Two EV home charging strategy are developed, as uncontrolled and controlled (dual tariff) regimes. In uncontrolled scenario, there is no time limit on EV charging. Charging starts as soon as vehicle gets home. Fig. 3-4 and 3-7 showed demand peak is increased in four seasons for mild and aggressive EV penetration in Quebec and GB. The maximum increase is in fall with 11.57% between 19:00 – 20:00 for Quebec. In GB case, 13% is the maximum increase occurred between 20:00 – 21:00. Table 3-8 showed the results of comparison between two studies in uncontrolled scenario. In Quebec, peak time is shifted to evening for summer, fall and winter. This peak shift is not in interest of distribution companies, as it will but extra stress on the network. Therefore, expensive electricity must generate to supply the extra load. In GB case, all load shifts are in the afternoon and evening with more stress between 20:00 to 21:00 in fall season.

In controlled scenario, certain limitations are applied to EV charging. Vehicles are not allowed to start charging at any time they want. Results showed that in both cases, there is no extra load in spring and winter. Less than 0.5% increase for Quebec in fall and less than 7% increase for both cases in summer, which is shifted to late evening for both cases. Table 3-9 showed the results of comparison between two studies in controlled scenario.

The results of both study shows that, neither in Quebec nor in GB, uncontrolled charge scenario would be an adequate solution for EV home charging. These increases in electricity demand will affect the cost of generation in high peak time. Therefore, electricity market price will be affected and consumers must pay more for their consumption. As a result, controlled charging seems to be a smart solution for EV home charging in the future.

# CHAPTER 4

# VEHICLE-TO-GRID (V2G) POWER FLOW: INEFFICIENCIES, POTENTIAL BARRIERS AND POSSIBLE RESEARCH DIRECTION

## 4.1 INTRODUCTION

Transition to electric vehicles (EVs) is already under way. EVs are equipped with a drivetrain that is completely electric powered, with a fairly large on-board battery pack. More recently, apart from charging applications, it has been proposed that EVs could also provide back-up power to grid during critical high demand periods, using the on-board battery, in the form of vehicle-to-grid (V2G) power flow [45]-[49]. With the help of an on-board battery pack, EVs can act as distributed generators and feedback energy to the AC grid. V2G connection has acquired much attention and interest amongst power system engineers and numerous business models have been proposed. While interconnecting EVs with the grid for reverse V2G power flow seems to be a lucrative business model, the question to be raised from a pure electrical engineering standpoint is, that how efficient (or inefficient) is the process of interconnecting the EV to the grid. Power electronic converters need to take care of energy conversion stages. This raises some critical conversion efficiency issues as well as protection and security concerns.

Modeling of operating condition for V2G power flow and detailed loss (or efficiency) will be proposed in this chapter, in order to depict realistic system efficiency. Possible solutions through interconnecting renewable energy systems, advanced power conversion designs, and virtual power plant concepts will be discussed. Furthermore, possible research topics in the areas of advanced power electronic conversion for V2G applications will be highlighted. Thus, this chapter will point out the myths and concrete realities of connecting future EVs to the existing grid or homes.

## 4.2 POWER DEMAND AND VEHICLE-TO-GRID OVERVIEW

Load demand on the grid is high in certain seasons. In summer, there are appliances that can put up more stress in electricity grid. An example can be air conditioners that can be used in different sectors. On the other hand, electricity demand is not constant throughout a typical day. Figure 4-1 shows a typical 24 hour load profile during a day for commercial, industrial, and residential loads [46].

Several models have been described to reduce stress from grid in high demand times. Vehicle-to-Grid (V2G) is considered as a possible solution to stabilize the power network and to smoothen the load curve. It is claimed that EVs can be considered as load and distributed storage [50]. Future V2G connection of EVs or PHEVs is considered as a lucrative solution to stabilize the existing AC grid.

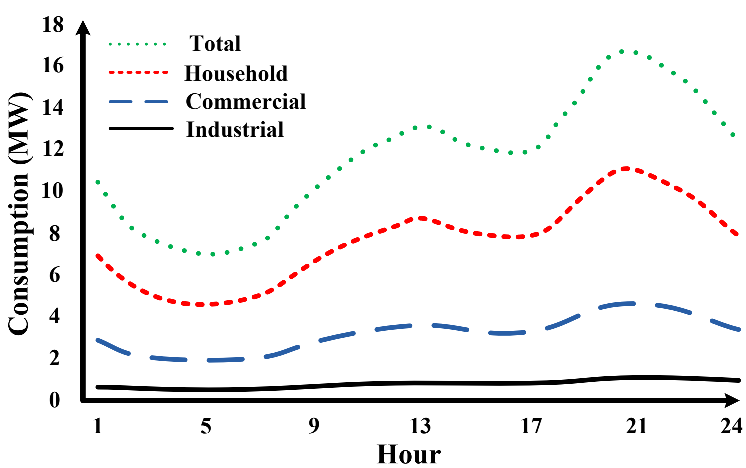



**Fig. 4-1** Typical 24 hour load profile

In addition, V2G proposes smoothening out stressful load demands within the grid, especially in time slots when grid power is expensive, and to provide ancillary service. V2G power flow will be established when a connection is made, such that the energy is transferred from the vehicle to electricity grid. Figure 4-2 shows a schematic diagram of V2G connection.

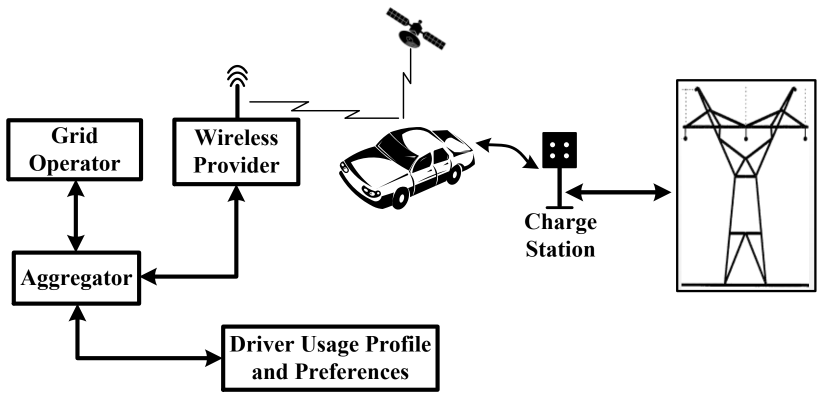



**Fig. 4-2** Schematic diagram of V2G connection

Following are the imperative elements to implement V2G successfully: 1) multiple power electronic converter stages, so that energy can flow from EV to grid, 2) bi-directional charging unit that can either be on-board or off-board, 3) accurate, certified metering, on-board the vehicle, to track energy flow, and 4) means of communication between grid and EV. Based on the vehicle type, there are three main V2G systems proposed.

### 4.2.1 BATTERY ELECTERIC VEHICLES (BEVS)

Drive train in BEVs is completely electrified and battery is the main source of energy to drive the vehicle. The battery pack will plug-in and charge, whenever needed from the grid, and when there is a shortage power in electricity grid, the process will be reversed, and the EV discharges its stored energy to the grid.

### 4.2.2 Plug-in Hybrid Electric Vehicles (PHEVs)

The battery pack is used only for short or medium distances in PHEVs. The ICE is on-board, to provide additional power through a generator, for driving beyond the battery range [6]. For V2G applications, either the battery or the engine as motor-generator, can supply power to the grid. The battery pack in PHEVs is designed for traveling short distances and cannot feedback much energy to the grid. Hence, powering the grid from a PHEV will rely on the ICE, which can be used as an alternator.

### 4.2.3 Plug-in Fuel Cell Hybrid Electric Vehicles (PFC-HEVs)

These vehicles are powered using recyclable hydrogen. The hydrogen may be sourced from water (electrolysis) or reformed from hydrocarbons. In addition to using hydrogen as a fuel, these vehicles have the capacity to plug-in to the grid and charge its battery (and regenerate hydrogen on-board). The stored energy in the battery pack can be used for propulsion or for V2G applications.

## 4.3 Major V2G Difficulties and Issues

Vehicle fleet integration with the power grid has two critical technical areas. Grid-to-vehicle (G2V) capability is already proven and PHEVs as well as EVs can be now charged from the grid. EVs/PHEVs act as new loads to the grid. Thus, restructured load curves must be reconsidered. Vehicle-to-grid (V2G) is a perception that is being proposed vehemently by power system researchers, claiming that it could stabilize the power grid. V2G claims to provide benefits for the power grid, the vehicle owners, the government, as well as the environment.

Since an EV would be parked for about 22 hours per day on an average [51], there exists an opportunity to feedback power to the grid with a large number of battery EVs.

Surely, this seems a very lucrative proposal. Basically, the proposal claims that the EVs can be charged during low power demand and reverse energy flow can be achieved during high load demand. Unfortunately, the proposed idea suffers from fundamental energy conversion problems, which makes it unlikely for viable processing on a large scale; at least, in the near future. The following sub-sections highlight the concerns that make the V2G concept questionable.

### 4.3.1 BATTERY DEGRADATION AND PROTECTION AGAINST POWER SYSTEM FAULT DAMAGE

Using rechargeable batteries to power the grid will increase its number of charge and discharge cycles, which will unquestionably end up in probably having to replace the EV battery sooner than usual (compared to only using the battery pack for driving purposes and charging it when idle). As is well known in EV energy storage literature, the number of charge/discharge cycles contributes heavily towards the lifetime of rechargeable lithium-ion (Li-ion) and nickel-metal hydride (Ni-MH) batteries [51], [52]. The lifetime of batteries is not unlimited; this is the major concern with EV commercialization. Using an EV battery pack to perform long term V2G will decrease the battery capacity (or drastic change in SOC) over its lifetime [51]-[53]. Studies show that V2G is a technically feasible option to balance electricity load with the generation in the future. The energy that can be fed back to the grid per vehicle can be calculated as [51]:

$$W = (E_S \times \text{DOD} - (d_1 + d_2) \times R_{el} \times E_{km}) \times \eta_{con} \quad (4\text{-}1)$$

DOD: Depth of discharge;
$E_S$: Battery capacity;
$d_1$: Number of kilometers that car was driven during a day;
$d_2$: Extended drive range to not limit flexibility of drive;
$E_{km}$: Per kilometer energy consumption;

$\eta_{con}$: Charge/discharge efficiency;
$R_{el}$: Electricity driving share of vehicle.

Studies show that EV owners can benefit from V2G from few hundred to several hundred dollars per month. However, a study in the German market shows positive control and feeding back electricity are not going to be a trusted option, due to the not-so-cost-effective degradation of battery packs. Battery degradation must be considered in order to estimate decreasing battery lifespan as a result of powering grid with V2G. $DOD_{V2G}$ is the depth-of-discharge (DOD) as a result of V2G [51]. With the assumption that the battery pack is completely charged before each dispatch, $DOD_{V2G}$ can be calculated as:

$$DOD_{V2G} = \frac{P_{veh} \times min\{ t_{Disp}; 24 . R_{d-c}\}}{E_S} \quad (4\text{-}2)$$

$t_{Disp}$: Dispatch time;
$R_{d-c}$: Dispatch probability (%).

The other important parameter is the number of charge/discharge cycles over the entire battery lifespan ($C_{life}$):

$$C_{life} = 1331 \times DOD^{-1.8248} \quad (4\text{-}3)$$

It should be noted that battery life will be reduced disproportionally to the depth of discharge [51], [52]. A greater rate of energy delivery can be obtained when depth of discharge is shallow in a cycle, compared to a deep discharge over the lifespan of the battery. This means that at the end of the day's driving, if the battery is at 55% DOD, it is better to plug it in and charge it, rather than discharge the remaining capacity to the grid. Also, another study claimed that, in order to assure the mobility of the vehicle, the EV can participate in V2G service only if the SOC is higher than 60%. With this assumption, there is not much energy that can be fed back to the grid from the on-board battery pack. To back up these statements, a mutual relationship between battery DOD and total number of cycles over a lifespan is shown in Figure 4-3 [51].

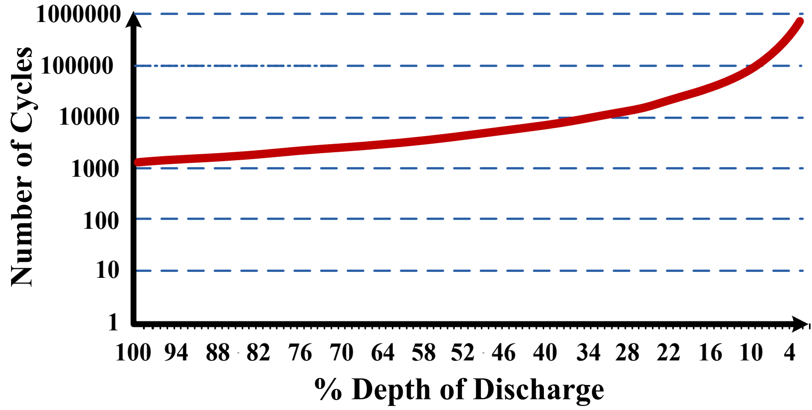



**Fig. 4-3** Mutual relationship between DOD and cycle lifespan

In addition, it should be noted that the environmental benefits of V2G are also not promising. By using the vehicle as a distributed generator (DG), the battery pack will lose its lifespan and will need to be replaced more frequently. Again, as is well documented in EV literature, it is well-known that the overall process of battery manufacturing is a not an efficient process. Apart from that fact, recycling of old or completely exploited batteries is a major environmental concern, which needs to be seriously considered before practicing V2G services.

Another problem while considering EV battery pack connection to grid is battery protection circuitry. It is obvious that grid operators cannot support protection of millions of EV battery packs coming online at the same time. The utility companies cannot guarantee the occurrence of a fault. Hence, they obviously cannot guarantee the safety of the EV owners' battery packs. Hence, this issue cannot be ignored, before practicing V2G.

### 4.3.2 Grid Control Issues

During V2G, every EV acts as a generator, and in the mass market, millions of tiny generators will be connected to the power grid. Controlling these small EV distributed generators independently is another problem that needs to be addressed. It should be noted that by using ordinary EV-grid interface devices cannot resolve issues arising as a result of integration of EVs to the distribution grid. The grid operator needs to know the status, availability, and willingness of these EV generators at all times, as to which one is suitable for drawing energy from a specific battery pack. Issues such as voltage drop, as a result of EV charging, decrease the charging rate locally. Voltage drop control methods could be used to manage and control these interfaces [53]. However, this would not be acceptable, when it comes to higher level control, such as control and management of congestion in the branches or participating EVs to electricity market sharing.

### 4.3.3 Energy Conversion Losses; Efficiency Issues Related to Well-to-Grid, Grid-to-Vehicle, and Reverse Power Flow

It is obvious that there exist losses each time, energy is stored, converted, or transmitted. In a PHEV, the amount of losses vary, which can be very large, such as losses in the ICE, or smaller losses, such as those in power electronic devices and electric drives. In a PHEV-grid or EV-grid interconnection, it is obvious that, when energy goes through the various stages of storage, conversion, regulation, and transmission, each stage contributes to losses. Thus, the end result is that the actual energy available for work is considerably low. Figure 4-4 shows losses in the process of energy transmission and conversion, specifically for V2G practice. Using a theoretical (back-of-envelope) efficiency analysis, it is clear that efficiency of the process of generating and transmitting electricity (source-to-electric outlet; STO efficiency) is about 50-52% [54]. For EV charging, this energy must go through a charger, which has approximate efficiency of about 94%. This energy has to be stored in the EV battery, which has an efficiency of approximately 80% [54], [55]. Thus, the efficiency of stored energy ($\eta_E$) is calculated as:

$$\eta_E = \eta_{STO} \times \eta_{Charge} \times \eta_{Batt} \tag{4-4}$$

Thus, $\eta_E = (0.52) \times (0.94) \times (0.8) \cong 0.39$

Approximately 60% of energy is lost in different stages of generation, transmission, and conversion to charge an EV battery pack. Furthermore, V2G process claims that energy flow can be reversed, and stored energy can be fed back to the grid. The proposed V2G idea is to use the distribution grid, which has an approximate efficiency of 92% [54]. Thus, the theoretical back-of-envelope efficiency of V2G can be calculated as:

$$\eta_{V2G} = \eta_E \times \eta_{Charge} \times \eta_{Grid} \tag{4-5}$$

Therefore,

$$\eta_{V2G} = (0.39) \times (0.94) \times (0.92) \cong 0.34$$

This is relatively low. This efficiency number certainly cannot be considered appropriate to back up the power grid using EVs and PHEVs.

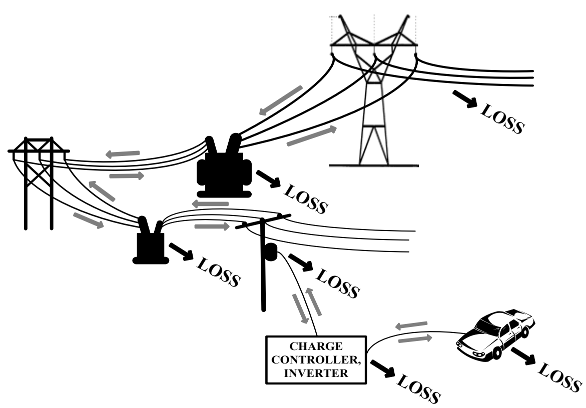



**Fig. 4-4** Energy transmission and conversion losses

### 4.3.4 V2G Reliability and EV Owner Behaviour

The V2G concept assumes that the EV is a reliable and available source of energy that can be available as reserve during peak load shaving. Hence, it should be noted that mobile behavior of EV owners can seriously affect the reliability of these EV distributed generators. Assuming that the power demand is high and there exists a sufficient number of EVs connected to the grid. Also, let us assume that there is enough energy to feed back into the grid. However, depending on driving behavior, EV battery charge availability varies during distinctive times and days of the week. In fact, mobility behavior of owners is obviously different on weekdays compared to weekends. If a large number of EVs are not able to feed energy or if owners simply do not intended to feed the grid, it could cause an unexpected shortage to the grid. From a pure efficiency standpoint, not only the number of connected EVs to the grid is important, but also the location of their connection. Even though these EVs act as DGs, if a group of EVs are connected at some point in the system, and demand is high on another side of the system, energy must be transmitted to the critical demand side, and transmission losses needs to be accounted for.

It is obvious that, from an owner's perspective, driving is the primary purpose of the EV; not V2G. Furthermore, because of the aforementioned reasons, the EV cannot be treated as a reliable source to deliver the exact amount of energy demanded by the grid in real time. Thus, to begin with, using V2G seems like using an unrestricted and cheap resource to help the grid overcome high demands. However, the fact is that, by using V2G, both the grid as well as the EV requires an enormous amount of upgrades to be built into their respective systems. Even then, such a restructuring of the grid and EV/PHEV charge/discharge system would prove to be an exceptionally uneconomical task.

## 4.4 V2G Efficiency Solutions and Potential Research Dririection

In the electricity grid, generation capacity is grouped in different categories. The four main categories are: 1) peak power, 2) spinning reserve, 3) regulation services, and4) renewable sources and energy storage systems. Spinning reserve and regulation services are assumed as ancillary services to support the grid. Renewable energy will have a prodigious positive impact on the electricity network. One main concern about renewable energy sources, such as photovoltaic and wind is that, there is no guarantee to acquire energy whenever required. The volatility as a result of renewable energy resources to the grid must be compensated with reinforcement of the power grid, virtual power plant structure, demand control management, energy management, and energy storage systems.

One of the main candidates to help the reliability of the power grid is a virtual power plant (VPP). VPP structure is an accumulation of DGs, energy storage systems, as well as loads that can be controlled locally. The entire system can be controlled by a central control entity; it works as a unique power plant. VPP not only deals with the supply side, but it also helps manage the demand and ensure grid reliability through demand response in real time. Figure 4-5 shows a virtual power plant structure.

The control aspect of VPP can be divided into three different categories: direct, hierarchical, and distributed system. Decision-making in direct control concept is centralized control, whereas distributed control concept is based completely on decentralized decision making. The hierarchical control lies between the other two methods that have some level of distributed decision-making. Responsibility of the control center in VPP is to coordinate between available resources in an optimal way and present them to the market as a single entity. Information and communication technology solutions enable the control center of VPP to manage resources within the system to near real time. Operation of a group of individual resources can be managed by some entities. EV charging facilities may be represented by charge point managers (CPM), within the framework of VPPs. Number of connected EVs to the grid, their power consumption at each time, state of charge of their individual battery packs, and controlling the charging period can be done by VPP control center, based on reviewing the aggregation of all gathered information.

Furthermore, power generation and load profiling can be forecasted in VPP. Power generation and consumption can be scheduled in the VPP control center. Any error in this forecasted schedule can be corrected in real-time operation. By means of a metering system, data can be provided to VPP control center, to monitor the behavior of power generation and load consumption. It is obvious that by a demand side management (DSM) system, the charging period of EVs can be easily shifted to low-demand times. Also, if EV owners insist on charging their vehicles during high load demand period, multiple price bidding can be scheduled. In VPP, different sources of power generation are available. Renewable energy can be one of the important resources in VPP. Since the power production of renewable energy resources cannot be forecasted, it can be considered as ancillary services to the power generation market.

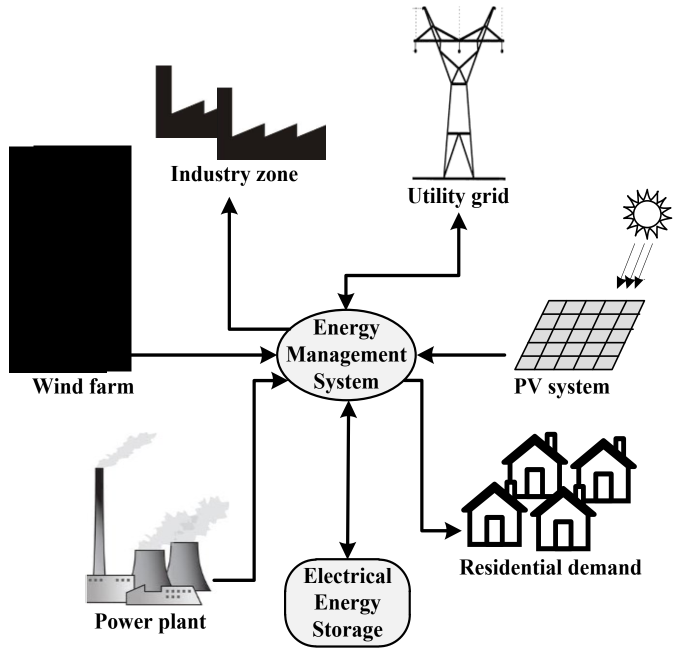



**Fig. 4-5** Virtual power plant structure

So, a means of reliable storage system is required to store the energy, and inject it into the grid, whenever required. Local scale battery systems offer very high efficiency and reliable energy for short durations, and can be used as distribution generation in virtual power plants. Energy will be stored during high power production and can be used during high demand, without having complex and overwhelming control systems [56].

## 4.5 SUMMARY

This chapter discussed the important issue of V2G inefficiency, from a well-to-wheels efficiency standpoint. Most critically, the energy conversion efficiency suffers, due to the multiple conversion stages, when attempting to connect an EV to the electricity grid. Efficiency of energy conversion is a major issue in reverse power flow, while discharging an EV battery to the grid (vehicle-to-grid). Hence, vehicle-to-grid (V2G) power flow requires a detailed stage-by-stage efficiency analysis, to evaluate practical feasibility. This chapter introduced the critical issues in connecting battery-powered EVs to the electricity grid. The chapter highlighted the important inefficiencies of V2G connection, especially from the point of view of power electronics converter energy conversion stages, and suggested some research directions for the near future, in order to possibly make V2G a practical reality. In chapter 5, V2G behavior will be assessed with a case study to analyze, whether or not, V2G can be a trusted candidate to back up grid in emergency situation.

More specifically, the chapter highlighted the grid control issues, battery degradation issues, and the critical problem of V2G inefficiency with regards to power electronic conversion stages. Hence, the virtual power plant (VPP) is suggested as a possible and likely solution solely for EV charging purposes. EV charging can be performed most efficiently by matching available battery energy with load demand. By shifting EV charging loads to low demand times, the load peak as a result of EV charging can be shaved. Individual regulation needs to be adapted instead of asking EV owners to feed energy back to the grid. This way the owner can charge their EVs during a suitable low demand time, in order not to put any stress on the grid. With these regulations, utilities can make sure owners' charging behavior will not add up consumption to the grid during high demand times.

# CHAPTER 5

# FEASIBILITY ANALYSIS OF EVS SUPPORT FOR GRID ISOLATED SYSTEMS (INTERNATIONAL ISLANDING)

## 5.1 INTRODUCTION

As it is discussed in chapter 4, V2G draws attention of researchers. Apart from charging applications of EVs, different proposal made those EVs battery can help to sustain the local grid in the event of, either high demand period or local grid interruption of supply, in the form of vehicle-to-grid (V2G) power flow. V2G connection has acquired much attention and interest amongst power system engineers and numerous business models have been proposed. It is mentioned in previous chapter, that application of EVs to sustain grid in high demand time will not be a smart idea of the field. But, helping local distribution grid in the event of power outage in an emergency situation such as floods or storms to improve security and reliability of the grid, may use as a lucrative idea.

This chapter aims at modeling and simulating operating conditions for bidirectional power flow of EVs to sustain islanded mode of distribution grid in the event of grid emergencies. Comparison study will performed between EVs and static battery storages to analyze the fast response devices, short term and long term operation as well as reliability of support in the event of islanded mode of grid. Furthermore, possible research topics in the areas of advanced power electronic conversion for sustaining grid isolated application of EVs will be discussed. Thus, this paper will end up pointing out the popular myths and actual realities of connecting future EVs to the existing grid.

The new EV fleet will have an impact on distribution grid in the form of extra loads. Proper charging strategies must be set to avoid any stress on grid as result of EVs battery charging. While EVs are going to be extra loads to the grid, they may act as backup of the islanded mode of operation in distribution grid. However, following questions will arise to verify the efficiency of EVs support of grid sustainability.

- Is use of EVs battery best solution to sustain islanded grid?
- Can EVs be a proper source for grid security?
- In terms of reliability and economic benefits, how EVs can beat static battery storage systems for local grid support?

In this case, smart micro grid control system for network emergencies must be connected into the grid. Load variation must be responded in micro grid autonomously. This strategy must apply to the system in a way, that voltage control and frequency regulation can be achieved. In order to obtain grid sustainability, control center needs to have information of loads, backup generators, battery storage units, electric vehicles as well as micro and mini sources as it is presented in Figure 5-1. To analyze behavior of EVs in the event of a short term international islanding:

- Number of vehicles for the year of study must be examined,
- EVs penetration prediction into the fleet needs to be predicted,
- Number of household and amount of necessary power for each of them must be estimated and,
- Behavior of EVs for reverse power flow in an emergency condition needs to be verified.

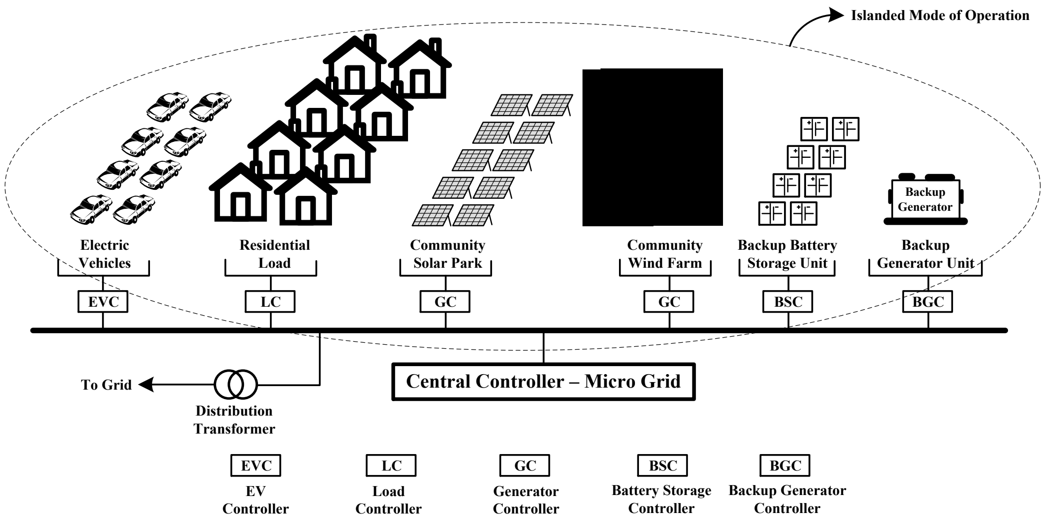



**Fig. 5-1** Future smart microgrid configuration and islanded mode of operation

## 5.2 GENERIC NETWORK UNDER STUDY

In order to obtain a 2030 prediction of EVs support for international islanding, a case study in LV distribution network in city of Isfahan – Iran is picked, where energy system modeling is used to find out, how far EVs can help in grid sustainability in the event of short term international islanding. This network and relevant data was acquired from local grid Distribution Company and represented as typical radial lines in residential districts.

The total power generation and electricity consumption of the country are extracted and analyzed from relevant sources [57]. Household load analysis is performed and power consumption per household is calculated for two different scenarios as normal and emergency loads. Prediction on power generation and consumption has been made for year 2030 in the area under study. Figure 5-2 shows the three live feeders of the local distribution system.


**Fig. 5-2** Lines 1 (top left), 3 (top right) and 4 (bottom) of the system under study

The area under study is within city of Esfahan - Iran, that is powered from a 20/0.4KV, 400 KVA, YY0 distribution transformer under Esfahan Province Electric Distribution Company. Three low voltage outgoing radial feeders are serving 342 single phase customers. This study will consider, 1-phase, 240V, 15A connection will be the main domestic rating of Isfahan in 2030. Feeders are modeled in detail, and Figure 5-3 represents the schematic diagram of the case.

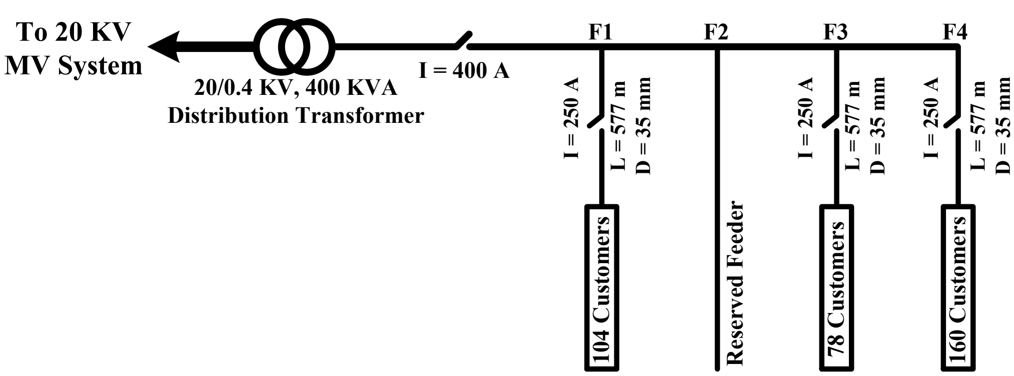



**Fig. 5-3** Single line diagram of the system under study

### 5.2.1 Power Generation and Energy Consumption Analysis

For power generation modeling, data are used from 2011 energy balancing strategy [58]. In this document it is indicated that in 2009, total generation capacity was 52971.6 MW that has 7.2% increases compare to 2008. Document is also states that generation increase for the period of 2008 to 2020 is going to be 7% per year. This increase rate is also used in this study. It is also assumed that 7% increase rate remains for period of 2020 to 2030. Figure 5-4 shows the average power generation and consumption prediction of 2030 for the country.

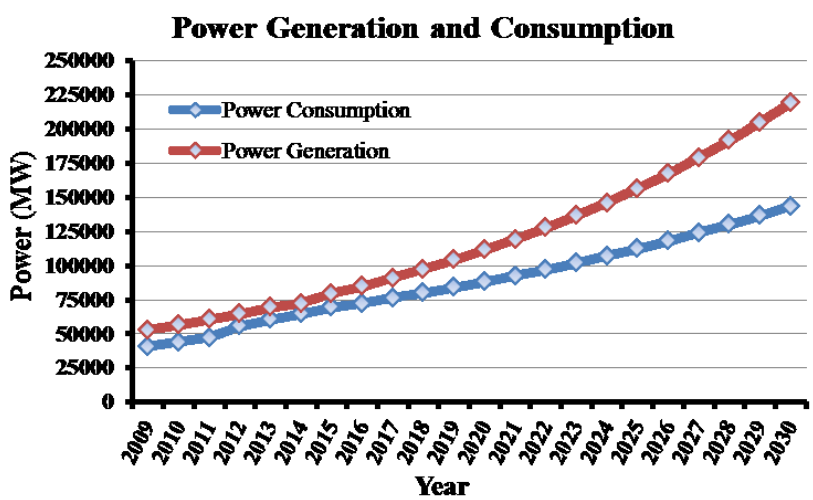



**Fig. 5-4** Power generation and consumption - Prediction for 2030

In recent years, due to increase in population, urban development, increase in living standard and welfare, energy consumption is increased. So, regardless of the amount of consumption, energy management can make a big role in normal and critical situations. Energy management has two key elements as: a) optimal consumption, b) move unnecessary loads to off peak period.

The average residential energy consumption of the area under study is also extracted from [58] that has shown yearly increase rate of 1.6% from 2000 to 2011.

Since, this is the most updated document; we will also consider this increase rate for this study and transpose it to 2030. Considering 1.6% yearly increase in residential energy consumption, Figure 5-5 shows 2030 household energy consumption prediction.

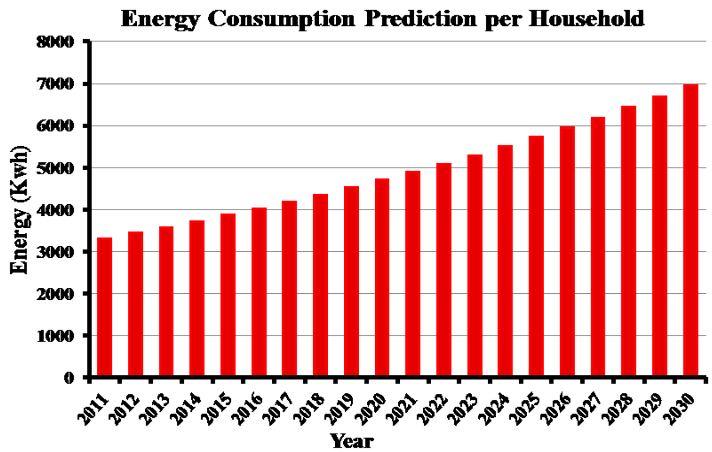



**Fig. 5-5** Household energy consumption - Prediction for 2030

### 5.2.2 POPULATION AND VEHICLE PREDICTION

The population and availability of EVs must be examined for the years under study. Population of the country is increasing by 1.2 to 1.3% from 2002 to 2012 and it is estimated to have increase around this average until 2030. While population is increasing, average number of people in household is decreased from 5.02 to 3.6 people for the past 35 years. Although for the province under study, household population dropped to 3.4 people [59]. But, with it is estimated that household population remains stable for future years, because of social security incentive packages. So, 3.4 people in a household are considered for the study as increase rate in household growth. According to [60] since 1995, annual growth rate of residential energy consumers is increased between 4.7 to 4.8%. 4.8% is also picked and applied to 2030 residential electricity consumers' prediction in the area under study. Figure 5-6 shows increase in number of inhabitants as well as increases in number of consumers.

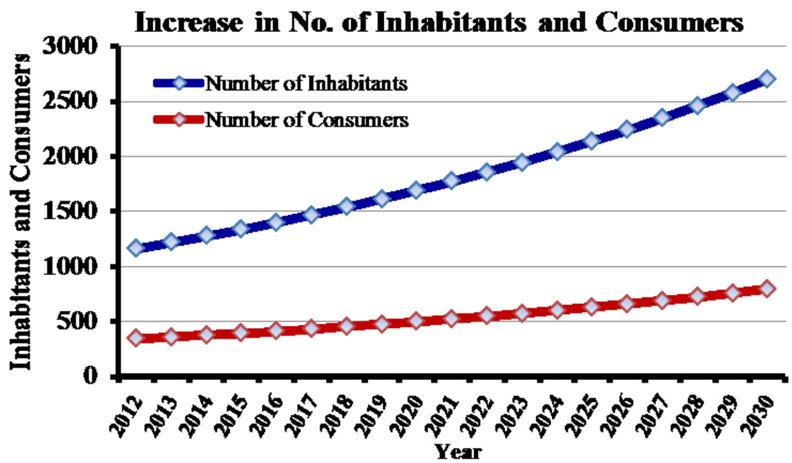



**Fig. 5-6** Increase in inhabitants and consumers - Prediction for 2030

Total vehicles on the roads in the country are about 17 million. 48% of them are private cars as light duty vehicles and remaining 52% are buses, trucks, vans and motorcycles. To calculate the number of private cars, population of each region is being used. According to statistics, there are 200 cars are available in Iran per every 1000 inhabitants. It is also mentioned by end of 2021; the total number of vehicles will be doubled that has shown an average 10% increase per year [59]. In this study it is assumed that this increase rate will remain steady from 2021 to 2030. Figure 5-7 shows the vehicle increase rate for islanded area as well as per capita vehicle increase.

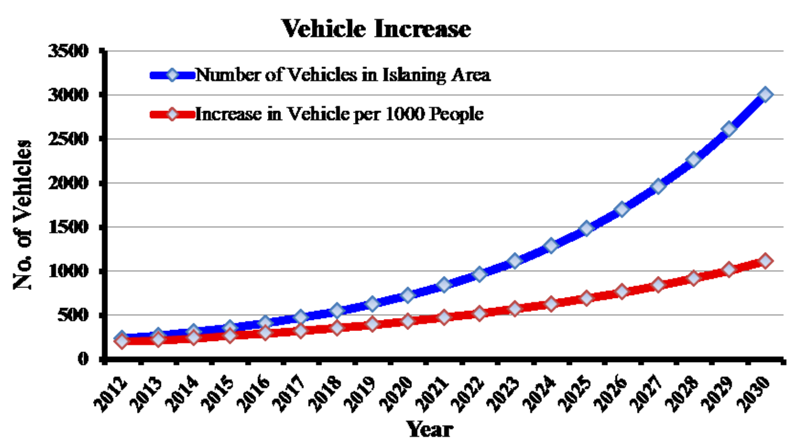



**Fig. 5-7** Vehicle increase per 1000 inhabitant and area under study - Prediction for 2030

### 5.2.3 DOMESTIC LOAD AND EVS PREDICTION

Household electricity consumption usually comes from lighting, home appliances and air conditioners. At first, the electrical appliances available at home are itemized with their power ratings and time of operation during the day. So, normal consumption and consumption at emergency situation can be obtained. In this study, emergency load consumption assumed to be 10% of total load at normal situation. These loads can be few lights, fridge, phone and TV. Heating is not considered in total load as heating system is running on natural gas.

In 5.2.2 total vehicles across the country is calculated, and transposed to 2030 prediction for the area under study. Business as usual scenario for EV penetration level of 7.07% as low and48.56% as high uptakes selected in 2030. These two EV uptakes are selected as low and high EV penetration for the households of islanded area.

These two levels of EVs uptake applied to the predicted vehicle grow in 2030 and it is shown in Figure 5-8.

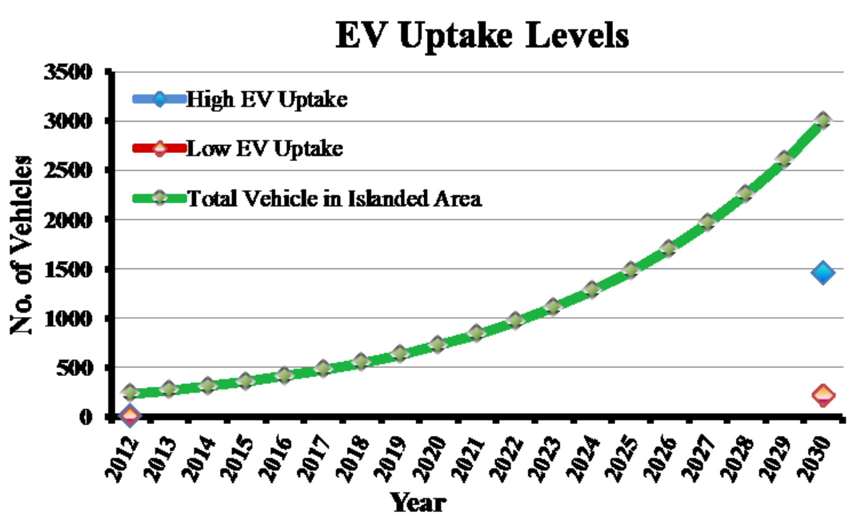



**Fig. 5-8** EVs uptake levels - Prediction for 2030

EVs/PHEVs assumptions are taken based on Table 3-4. The Depth of discharge

(DOD) considered in this study is 80%. Based on these assumptions, availability of EVs to sustain the islanded distribution grid is simulated. The fraction of BEVs/PHEVs has not been shown in any document for the area under study in 2030. For this reason, average battery charge availability from EVs and PHEVs considered as 20 KWh.

These vehicles must be controlled by a central control entity; it works as a unique distributed generation. VPP is a control solution. VPP structure is an accumulation of DGs, energy storage systems, EVs, as well as loads that can be controlled locally. VPP not only deals with the supply side, but it also helps manage the demand and ensure grid reliability through demand response in real time.

Control strategy in VPP is discussed in Chapter 4. Responsibility of the control center in VPP is to coordinate between available resources in an optimal way and present them to the islanded area as a single entity. Information and communication technology solutions enable the control center of VPP to manage resources within the system to near real time. Operation of a group of individual resources can be managed by some entities.

## 5.3 SIMULATION RESULTS

The proposed EVs support solution for islanded area is based on the idea of connecting EVs after distribution grid connection failure. These EVs will connect to the grid not in a common point, but also spread all around the islanded area and replacing the role of grid. A common controller is applied to EVs to make all these micro generators as a unique distributed generation, as it is presented in figure 5-1. The EVs in this model assumed to work in the microgrid and absorb energy whenever it is available in conventional grid, and reverse the power flow in the event of failure in conventional grid support [61]. The study has been done on the low voltage side of the grid with four radial feeders that has 3 live feeders and one in reserve with the total of 342 consumers. In this study, best case scenario is considered. All EVs in the islanded area are ready to support local grid with full energy reverse power flow. This assumption is too optimistic, but the reason to pick this, is to evaluate, if EVs would be able to stand and play the role of back up to the microgrid in islanding mode of operation. Emergency loads are calculated, and 2 different reverse power flows that come from high and low uptakes of EVs are modeled. Figure 5-9 shows simulation results.

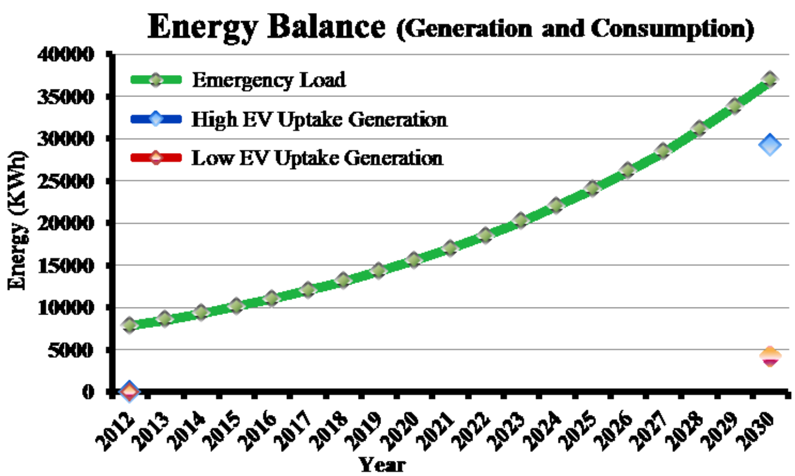



**Fig. 5-9** Energy balance between emergency load and EVs generation in islanded area

As it is shown in the graph, in 2030 with low EVs uptake, 11.5% of total load can be covered, whereas with high EVs uptake 79.1% of emergency load can be covered.

**Table 5-1** Total emergency load and covered load by different EV uptakes

| Year: 2030 | Total Emergency Load (KWh) | EV Uptake | | Emergency Load Covered (KWh) | Emergency Load Covered (%) |
|---|---|---|---|---|---|
| | 36866.8 | Low | 212 | 4246.3 | 11.5 |
| | | High | 1458 | 29165.5 | 79.1 |

Results shows that even with a very optimistic assumption which will not usually happen, EVs can’t support islanded grid as a standalone storage system. It is obvious that in real case, neither all vehicles nor 100% EVs battery SOC are available to support islanded area.

## 5.4 SUMMARY

The international islanded can be important in the future smart grid. In this chapter, the opportunity of utilizing of available EVs to support islanded grid is examined and evaluated. A case study for 2030 was examined in a location were the penetration of EVs are likely more viable. Required data are extracted from different valid and accurate sources for population increase, number of vehicles as well as two different levels for EV uptake. It is found that in 2030 it is likely that between 212 to 1458 electrified vehicles are available in the area under study. In an ideal scenario that all vehicles are available for V2G with 100% available SOC, these EVs can give from 4246.3 to 29165.5 KWh energy to the islanded area. But, even with this high level of certainty, EVs can support up to 79.1% of required energy to grid. So, in real case EVs may provide a set of ancillary service to the islanded mode of grid. But, this service can't be as standalone system.

The other problem with application of EVs is that EVs can't cope with grid simultaneously, can't be fast balanced and a gap will be seen between failure of grid and EVs support for islanded mode of grid operation. For this reason it is more viable to have more stationary storage system and the generator in the conventional grid. The role of these stationary storages is to absorb excess energy renewable energies such as wind or solar and supply it to the grid either in high peak demand of in the islanded mode of grid operation. Portable generators can be a means of back up for grid in emergency mode of operation where permanent generators can't provide enough amount of energy and also enough stationary battery storage is not exist. Even in the situation where not enough source of power is ready to cover the load in islanded area, EVs can't be a reliable source of energy to support the grid.

Problems such as grid control issues of EVs, reliability of these mini storages, availability of them when they are needed and available battery SOC will remain the major concerns for V2G reverse power flow even in the event of international islanding.

# CHAPTER 7

# CONCLUSIONS AND FUTURE WORK

## 7.1 SUMMARY

Electric vehicle (EV) Well-to-Wheels efficiency analysis is a wide range and multidisciplinary research topic among universities and research and development (R&D) centers across world. In one hand, optimization of EV's drivetrain efficiency, and on the other hand working on different fuel sources to have high efficient and clean electricity generation became as an important research topic. Moreover, impact of EVs penetration into the fleet and effects of battery charging based on different charging strategies needs to be evaluated. In this case grid performance constrains also have to be satisfied. Different charging regimes have been discussed. Both of methods repeat simulations multiple times, with different constraint values, to obtain multiple trade-off solutions.

In addition, these charging regimes require assumption to achieve the objective function which is high efficient EV not only in TTW, but also in WTW. Traffic pattern and availability of home charging after work can be specified. Although, this is a pre define method and can be assumed as suboptimal solution if updated data are not considered in real time simulation. Development of charging strategy for EVs is not a simple task. Sets of fundamental consideration needs to apply in the process of charging to prevent from any distribution grid uncertainty as well as gets benefits from renewable energies in Grid-to-Vehicle power flow. Importance and issues related to reverse power flow are considered. Most critically, energy conversion efficiency suffers, due to the multiple conversion stages, when EVs are attempting to connect to electricity grid for reverse power flow. Behavior of EVs in the situation is analyzed and evaluated. Different constraints for V2G topology are assessed, but at the same time willingness of EVs to support in the event of international islanding are also analyzed and evaluated.

In this research work, definitions of WTW efficiency of EVs in Canada have been proposed. Efficiency of EV's different drivetrain steps are analyzed and coupled with different stages of raw material, generation and fuel stages efficiency of the source fuel. Specific case study has been developed for Canada fleet to find predicted WTW efficiency of future EV on the road. One of the major expectations of EVs penetration into the fleet is air pollution reduction. For this reason, comprehensive WTW GHGs emission analysis performed. Simulations are approved that EV fleet can have a huge effect on GHGs reduction, if electricity can be provided from clean sources.

In this study effect of home charging of EVs/PHEVs on electricity demand in the province of Quebec is analyzed. A number of case studies are developed to assess, how different charging regime and EV uptakes can change total load demand of Quebec in 2030. Different EV characteristics, EVs/PHEVs penetration prediction, charge pattern and optimal charging time are simulated and analyzed for two different charging regimes. Uncontrolled charging showed that load increase up to 12% can occur, if no limitation puts on charge time. As a results, reserve generators which is usually generate expensive electricity needs to help grid. Another issue with this charging strategy is that peak load is also shifted to even worse time. But, by applying a controlled strategy on charging procedure, peak increase and peak shifting are limited and also can be eliminated with the help of smart grid application.

This study was also focused on detail efficiency analysis in use of EVs as a remote distribution generator in local grid. It has been proposed that EVs can help grid in critical peak time in the form of reverse power flow to act as ancillary service to shave peak in high demand time. Stage by stage efficiency analysis performed in total power flow cycle from Grid-to-Vehicle (G2V) and Vehicle-to-Grid (W2G). Analysis showed that the idea suffers from major deficits such as battery degradation, grid control issues, energy conversion losses and reliability which make it not a viable solution for grid back up in the future. Different suggestion such as demand side management and using virtual power plant structure have been proposed to give a chance to V2G to be practical in the future.

Also, application of EVs to support islanded area of grid in occurrence of international islanding is simulated and results are analyzed. Results shows that even in an emergency case where 10% of loads are in, V2G can't be a standalone and reliable support for islanded grid. Study considered best case scenario in the favour of EVs to get proper level of reliability of using EVs as full back up to the grid in emergency cases such as flood or storms. Again, V2G is failed to support grid even with 10% load in the grid. Result shows that in the proposed scenario, only around 80% of emergency load can be supplied. It means another source of power is required to keep grid live in an emergency situation.

## 7.2 POTENTIAL FUTURE WORK

Presently, existing study on WTW efficiency analysis of EVs are limited to certain level of accuracy. Number of analysis is performed that shows a very high WTW efficiency, but based on very optimistic and sometimes even non real assumptions. It is obvious that EVs drivetrain has higher efficiency and zero emission rates compare to the most efficient vehicles in the market. But as it is addressed into this study, increase in overall WTW efficiency and GHGs reduction must be the target of research in this field.

Efficiency of the process of electricity generation is still questionable. If electricity cannot be provided from clean and environmental sources, then chances of EVs to compete with other vehicle technologies will be decreased. So, using clean and renewable energy to charge vehicles needs to be expanded and make it accessible to vehicle charge. ADVISOR was used in this efficiency analysis. The same vehicle can goes through another vehicle modeling package and may provide with different results. This is because of different simulation approach and relevant data.

In terms of different charging topologies, smart charging topology must be applied. It is easy to get home at any time and start to charge, but it is not a practical and efficient charging solution. However, due to current limitation on electricity billing in Quebec, controlled charging is a fine option to prevent demand peak increase. Other than controlled or dual tariff charging regime, dynamic price regime as well as mixed charging regime are also options that can eliminates negative effect of EVs home charging on distribution grid.

Real time modeling of V2G application can provide with more realistic system efficiency. Even if total efficiency of reverse power flow increases, demand side management (DSM) and virtual power plants (VPP) must apply to the system. In such a case grid control issues can be decreased and V2G reliability can increase in long term application.

It is obvious that in international islanding application and with uncertainties such as EVs availability and accessible SOC level, EVs cannot be a standalone support for islanded communities. But it can be assumed, in presence of stationary battery storages and portable generators, EVs can play role of ancillary service into these backup systems.

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