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CO2 and Fuel Consumption Reduction Potential of a Photovoltaic Battery Recharging System

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***Abstract*—Environmental concerns, sustainability and energy security demand new and alternative forms of transportation. Plug-in hybrid electric vehicles (PHEVs) are getting more and more attention due to their rechargeable aspect and ability to utilize alternative sources of energy. If the energy used to charge the batteries of a PHEV is obtained from clean and renewable sources, these vehicles will emit less CO_2 emissions and consume less fuel. In this study, solar energy is used as clean and renewable energy source to charge PHEV batteries. The scope of this study is to design a photovoltaic battery charging system to propel a PHEV for 32 km per day on pure electric mode and achieve the goal of reducing daily fuel consumption by 50%. The proposed solar energy system is envisaged to be installed on the roof of a house. The daily measurements of stored energy via solar panels show the viability of this approach and the potential of traveling on renewable sources of energy without burning fossil fuels.**

Keywords-plug-in hybrid electric vehicles; battery charging; solar energy

I. INTRODUCTION

Land, sea and air transportation depends mainly on oil derived fuels. Transportation sector consumed 2.16 10^9 tons of oil in 2007 alone [1]. CO_2 emissions from burning fuels derived from oil result in global warming and climate change. Also, oil reserves are not evenly distributed around the world which brings up sustainability and energy security issues. CO_2 emissions are closely related to fuel consumption. In order to reduce the fuel consumption, efforts have been directed towards improving internal combustion engine technology and efficiency, implementing advanced propulsion systems and utilizing alternative sources of energy. Although internal combustion engines will continue to play a major role in transportation sector, plug-in hybrid electric vehicles (PHEV) will find more and more application and acceptance in relatively short term. A PHEV is defined as: “a hybrid vehicle with the ability to store and use off-board electrical energy in the rechargeable energy storage system” [2]. Another definition of PHEV is a vehicle that draws motive power from a battery with a capacity of at least 4 kilowatt hours [3]. These definitions distinguish PHEVs from regular hybrid cars which do not use any electricity from the grid. PHEVs also have internal combustion engines, however they are much smaller than those used in typical hybrid vehicles and only used to charge the vehicle's battery when battery power is below a threshold value. Due to their rechargeable aspects and ability to utilize alternative energy sources instead of oil derived fuels, PHEVs are considered to be a major candidate for transportation technology of the future. The expected outcomes of driving PHEVs are reduced emissions and fuel consumption and increased energy diversification. PHEVs allow the utilization of alternative energy sources in propelling vehicles. If energy used to charge the batteries of PHEVs is obtained from clean and renewable sources, then these vehicles will emit no CO_2 emissions and consume no fuel during battery powered driving mode.

How people use their vehicles has a great influence on PHEV design strategies. About 78% of people who use their vehicles for commuting between home and work stay within the daily 64 km range (Fig. 1) [4]. Cumulative frequency is defined as the percentage of the total driving time during which the daily driving distances are less than or equal to the said distance on the horizontal axis [5]. PHEVs take advantage of the fact depicted in Fig. 1 that the typical (78% of the total) daily driving distance is less than 64 km. If most of this distance could be driven on electricity, an appreciable reduction in fuel consumption of the vehicle could be realized. In cases where the daily travel distance is beyond 64 km range, a large amount of the petroleum fuel can be saved by utilizing electric mode driving which takes up a large portion of the total daily travel. Even if the pure

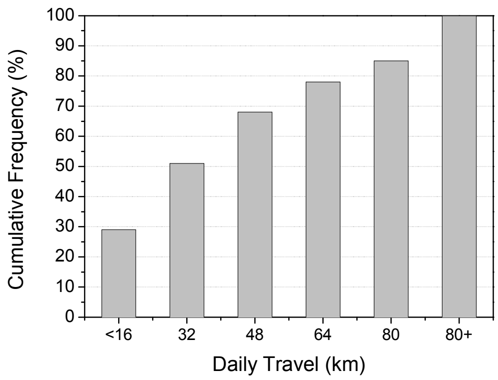

Figure 1. Cumulative frequency of daily vehicle travel.

electric range is less than 64 km, the available pure electric range will still save a large amount of petroleum that normally would be used during normal daily driving. If a vehicle and its battery recharging infrastructure are designed to have 32 km of pure electric range, as is the case in this study, that vehicle will cover half of its total daily driving distance in pure electric mode. Therefore, it is important in PHEV design to know how much energy is required to drive a vehicle and how much energy could be harnessed and stored in the batteries of a PHEV. Energy consumption by the driven wheels for a mid-size sedan in FTP75 driving cycle is given in Fig.2 [6]. As seen in Figure 2, the energy consumption on the wheels is about 7.5 kWh for a driving distance of 64 km, which corresponds to 0.117 kWh/km. Fuel consumption data of mid-size sedans also confirm this value. If a vehicle with a gasoline consumption of 7.5 liter/100 km and overall tank-to-wheel efficiency of 0.18 is considered, the energy required in the wheels is calculated as 0.130 kWh/km. In this study, although energy consumption may vary depending on the road and vehicle conditions and how the vehicle is driven, it is assumed that 0.130 kW of energy should be supplied to the driven wheels

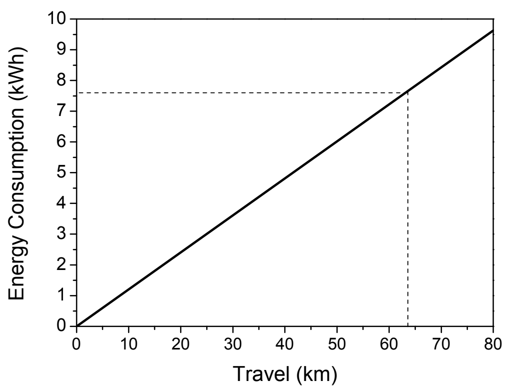

Figure 2. Energy consumption of a mid-size sedan in FTP75 cycle.

for every 1 km of distance travelled. Design of a photovoltaic battery charging system presented in this study is based on this value.

While 0.130 kWh/km represents the required energy in the wheels to propel the vehicle, the energy storage in the battery should be higher because of the losses in the electric motor and the power electronics. Assuming that the efficiencies of the motor and power electronics are 0.85 and 0.95 respectively; then the amount of energy needed to store in the battery is 0.161 kWh for each km of vehicle travel. Therefore, for a daily travel of 32 km, 50% of the total daily travel, 5.152 kWh energy should be stored in the battery of a PHEV. In the extreme case, 11.04 kWh energy storage is needed to supply total daily energy requirement of a vehicle to travel 64 km.

The scope of this study is to design a solar energy storage system to propel a PHEV for 32 km daily on pure electric mode and therefore achieve the goal of reducing daily fuel consumption by 50%.

II. PHOTOVOLTAIC BATTERY CHARGING SYSTEM

For the near future, the place where PHEVs are most likely to be charged is the vehicle owner's garage or parking lots. In this study, it is envisaged that every house will have a solar panel on the roof top for charging during day time. In order to investigate the feasibility of this idea, an experimental battery charging system is installed in Kocaeli region in Turkey. The layout of the system is given in Fig. 3. The energy produced via the solar panel is stored in batteries. The amount of energy transferred to and stored in the batteries is measured via a charge controller. As seen in Fig.3, a wind turbine with a rated power of 600 W is also included in the system to aid battery charging under cloudy and windy conditions in which sunshine and solar radiation are not availiable or sufficient. However, due to the

Figure 3. View of photovoltaic battery charging system .

location of the charging system, the energy produced via wind turbine was found to be negligible and therefore only solar energy is used and measured to charge the batteries.

The rated power of monocrystal solar panel is 190 W with a surface area of $1m^2$. The power rating is chosen low because the proposed system is intended for domestic utilization of harnessing renewable energies, one solar panel system per household. For this reason the scale of the system should be suitable to be installed on or near a house to minimize any discomfort to residents and neighbours. A larger wind turbine would also have produced effective amount of energy but would have violated the stated requirement that the system should be easily installed in a residential or work area. Fig.4 shows charge controller, netbook used as data recorder and deep cycle batteries that store the energy transferred via solar panel.

In order to minimize daily and seasonal variations as much as possible, the measurements were taken for a duration of 5 months, which is considered sufficient to find the solar energy availability and the potential of the charging system. The experimental layout is constructed to form a basic solar battery recharging system design such that having obtained the amount of solar energy that can be transferred and stored in the batteries, any amount of energy could be stored just by increasing the surface area of the solar panels. The results of this study will lay the foundation of a subsequent project of installing a solar charging station in the region to charge batteries of PHEVs and electric vehicles as well.

Energy harnessed via solar panels could be transferred to vehicle battery in two ways: 1-By using on-board or off-board chargers through which solar energy is directly fed to the vehicle batteries, 2-Battery swapping, in other words utilizing exchangeable batteries.

Figure 4. Charge controller, data recorder and deep cycle batteries.

If on-board or off-board charging is used, solar energy available only where the vehicle is parked could be harnessed. All of the solar energy will be supplied while the car is parked. In this case, solar battery charging system should be installed at parking lot or wherever the vehicle is parked during day time.

If battery swapping is used, the batteries are charged at home and a home-based solar battery charging system is applied, which fits perfectly with the scope of this study. In this case, the vehicle will use in its daily routine the solar energy stored in the previous day. Battery swapping would allow the utilization of wind energy harnessed during night time also. In battery swapping, vehicle's battery will be exchanged with a new charged one in the next morning before leaving for work. During day time, the vehicle will use the solar energy stored in the vehicle's battery. Meanwhile the battery taken out from the vehicle will be installed to home based solar (possibly wind also) charging system and this battery will be recharged till next morning. In the next morning, the depleted battery will be exchanged with charged one and the cycle will continue in the same manner.

It should be kept in mind that in such cases where stored energy is low or not present at all when no sunshine is available, the vehicle will use its regular internal combustion engine. Addition of wind power to charge the batteries would also allow the possibility of battery recharging under conditions of no availability of sunshine.

III. Results and Conclusion

The amount of energy stored in the batteries was constantly measured and recorded via a charge controller. In order to minimize daily and seasonal variations, the measurements were taken for a duration of 5 months, from August 2010 to mid-December 2010. Solar energy stored is obviously dependent on the weather conditions. Data taken during cloudy days were discarded from the data base and were not considered in evaluating the energy storage potential of the system. If daily total solar energy storage was below 100 Wh, that data were not taken into account. Fig. 5 shows average daily solar energy stored in the batteries for complete period of data collection. This data reveals that around 400 Wh of solar energy per day could be transferred to and stored in the batteries out of a solar panel with a surface area of 1 m^2 in Kocaeli region where the data are taken. In some very sunny days, solar energy stored could be as high as 600 Wh as seen in Fig. 6.

The information given in Fig. 5 and 6 reveals that a home based solar energy storage system is feasible in reaching goal of reducing fuel consumption by 50 percent. In order to realize the aim of this study, to lower the daily fuel consumption by 50%, 32 km of battery only vehicle travel should be accomplished. 32 km of vehicle travel requires 5.152 kWh daily solar energy storage in batteries. Based on the results of this study, 13 times the area of the solar panel shown in Fig.3 is needed to store the required amount of

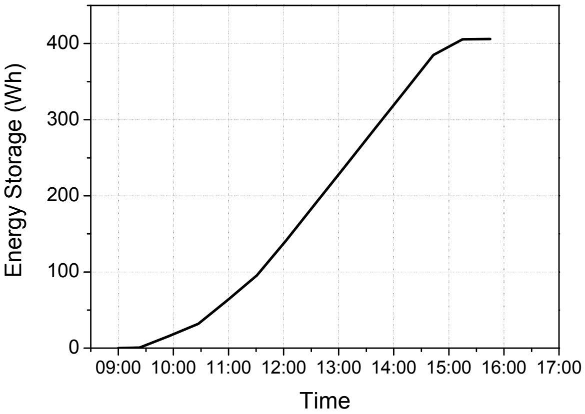

Figure 5. Daily average solar energy storage.

energy. This system is shown installed on the roof a house in Fig. 7. Here shown in this picture is a personal gas station! The energy stored in the battery serves the same function as the gasoline in the fuel tank of a conventional vehicle.

It is clear that only one side of the roof surface area would provide the necessary energy storage in the batteries. The design of the battery charging infrastructure is acceptable and does not pose any disturbance and discomfort to residents and neighbors. Therefore, the data taken during the test reveal that 50% of the total energy requirement for a person's daily commute could be harnessed via a residential photovoltaic array. If a sun tracker is used in a more sophisticated solar charging system, energy storage would be increased even further.

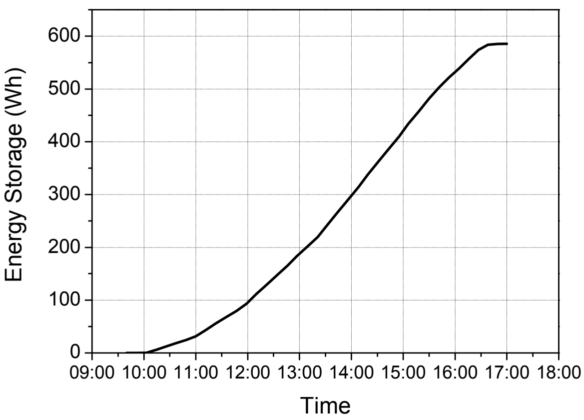

Figure 6. Solar energy storage on September 25, 2010.

A solar powered PHEV will not cause "range anxiety" because a back-up internal combustion engine will always be present as range extender. For daily commute, a PHEV could satisfy driving needs while emitting less CO_2 and consuming less fuel. The daily measurements of the stored energy via a solar panel show the potential of traveling on renewable sources of energy without burning fossil fuels and indicate that PHEVs can play a major role in transportation technologies of the near future.

Acknowledgment

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