

The Implementation of the Electric Auto-Vehicle in North America: An Issue of Power Generating Capability and Power Quality

Florian Misoc*

Department of Electrical and Computer Engineering Technology, Kennesaw State University, GA, USA

Abstract

From the first electric automobile built in 1888 (Flocken Elecktrswagen) to the present electric cars build by Nissan, Chevrolet, or Tesla Motors, the need to periodically recharge the vehicles' batteries is still a challenge. Besides the battery charging process, recharging stations and the power electronics needed to optimize the energy transfer to the electric vehicles' batteries, the question of electric power availability is inevitable.

The authors of this study do not intend to emphasize the approaching end of petroleum and coal resources, facts already known; instead it is focused on the electric energy generation and consumption. The energy cycle of supply and demand has currently reached a dangerous level. Aside from the well-known fact that the world's oil resources are nearly exhausted, the feasibility of a complete electrification in transportation is questionable. This study is based solely on the official data, publicly available, and considers the best-case scenario, as well as the worst-case scenario, with regard to implementation of electric vehicles as sole mode of transportation.

The predicted electric power demand is factored in, based on national statistics and demographic trends, as the comparative study explores the possible changes in the transportation industry, based on current state of the art technology.

The authors of this study refrain from making any predictions or prognosis vis-à-vis economic impact based solely on the conclusions expressed in this herein

Keywords: Electric vehicles; Power generation; Battery recharge rate; Battery charging condition

Introduction

Considering the increase consumption of petroleum-based fuels world-wide over the last decade, due in part to world population increase and in part to improvements in the standard of living in many countries, the supply and demand balance of petroleum has reach a critical point. As the petroleum resources have been substantially reduced, the need for alternative methods of transportation has become clear. One a possible solution is the electric vehicle. Thus, it is crucial to determine the feasibility of large-scale implementation of a wide range of electric vehicle types (motorcycles, passenger cars, busses, and trucks), as substitute for the internal combustion-powered vehicles, in the near future [1].

The main objective of this study was to determine the equivalent electric energy necessary to replace the petroleum-based energy for road vehicles; automobiles, trucks, and busses in the United States. To achieve this goal, the maximum installed electric power generation in the United States was explored over a ten-year period then extrapolated until the year 2030, as well as an estimation of the total number of auto-vehicles for the time frame 2010-2030 was done, using the same approach [1,2].

This research was limited by the accuracy of the available data, made public by the United States government offices, specifically the vehicle registration data, and by the United Nations office for the installed power data. This research explores the feasibility of replacing the entire fleet of internal combustion-driven vehicles with a fleet of electric-driven vehicles in the United States of America. No evaluation or speculation of available fossil fuel resources is made, explicitly or implied.

The best-case scenario assumes a grid-power utilization of 5/100, meaning: 5% of all electric vehicles are charging at any given time,

utilizing power from the electric grid, while the worst-case scenario, assumes a grid-power utilization of 20/100, meaning: 20% of all electric vehicles are charging at any given time, utilizing power from the electric grid.

Installed Power Statistics

During the period of time 2000-2009, the installed power growth is characterized by an increase of 26.36% in the power generation capability in the United States, to accommodate the electricity needs for industrial and residential customers [3], which is considered in this study as a realistic "best case scenario", or very optimistic growth. However, this power generation increase was not sufficient to offset the power demand in the US, hence substantial power (25 billion kilowatt-hour/year) is imported, generally from Canada [4].

The total installed power in the US, shown in Table 1, presents an increase in the installed power over the ten-year period 2000-2010, where the slowest growth is recorded for 2005-2006 time frame, with only 8,415 Mega Watt additional installed power, or a 0.86% increase [3], which is considered in this study as a realistic conservative growth-rate, or the "worst case scenario".

Conventional power generation technology was characterized by a nearly stagnant trend in the nuclear and hydro-electric power

***Corresponding author:** Florian Misoc, Associate Professor, Department of Electrical and Computer Engineering Technology, Kennesaw State University, GA, USA, Tel: (678) 915-7423; E-mail: fmisoc@kennesaw.edu

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generation, while the thermo-electric power generation technology exhibited an increase in the installed power for the period 2000-2005, and it stagnated thereafter.

However, in the renewable energy industry, a dramatic increase in the installed power was exhibited by the wind-energy technology, with the solar and geothermal-energy technology stagnant, as shown in Table 1 [3]. Meanwhile, the population in United States has continuously increased, and incidentally, the demand for more electric energy has grown accordingly.

Auto-Vehicles in North America

Registered auto-vehicles in the United States

Vehicle registration, by state, is reported annually to the US Department of Transportation, which keeps a rigorous evidence of all registered vehicles in the US [5-14]. The number of vehicles, per categories was compiled in Table 2, spanning over a period of ten years, from 2000 to 2010 inclusive.

As indicated in Table 2, the number of cars registered in the US over the period 2000-2010 was relatively constant, with an increase of 1,258,180 cars in an eleven-year time frame, or an average annual rate increase of 0.9% (less than 1% per year). The number of trucks has steadily increased, over the same period, at an average annual rate of 2.7% [5-14].

Data recorded in Table 2, indicates a low increase rate of busses registered in the time frame 2000-2010, with an increase of 95,868, equivalent to an average annual rate increase of 1.28% [5-14]. The number of motorcycles registered in the same time frame increased at an average annual rate of 8.24% [5-14].

Types of electric auto-vehicles registered in the United States

For this study, the performance characteristics of four

representative electric vehicles were considered: the ZERO-S-ZF-11.4 motorcycle, the NISSAN LEAF-S compact car, shown in Figure 1, the BYD-eBus, and the SMITH-NEWTON truck, shown in Figure 2. The electric vehicle selection was based on current manufacturing volume, and on vehicles' marketability (name recognition). Vehicles specifications are compiled in Table 3, for all four selected electric vehicles [15-18].

Based on the available data, dependent on the population growth in the United States, a predicted fleet size was computed for each class of vehicles, as shown in Figure 3.

Characteristics of electric auto-vehicle

The sharp increase in the number of trucks that is predicted to be registered in the US is, to great extent, due to the vehicle classification method in the US, which includes pick-up trucks, vans, sport-utility vehicles (SUVs), and motor-homes. Thus, the total number of "trucks" will include also the following industrial-purpose vehicles: tractor-semitrailers, straight-trucks, and delivery-trucks. As shown in Table 3, the battery charging time varies between 6 hours to 8 hours, or an average of 7 hours. This translates in almost one third of a 24-hour cycle (one day).

Miles traveled; statistics and future trends

United States Department of Transportation; Federal Highway Administration (FHWA) collects annually information on the average distance traveled by vehicles registered in the US, per categories, i.e., motorcycles passenger vehicles, etc. From this information, relevant data was selected to compile graphical representations, shown in Figure 4, where the available data (until 2010) was publicly disclosed, in which the average mile traveled is represented as related to the number of vehicles registered in the United States. Given the large difference in the number of cars and commercial trucks registered in

| Year | Thermal | Nuclear | Hydro | Wind | Solar | Geothermal | Total |
|------|---------|---------|---------|--------|-------|------------|-----------|
| 2000 | 610,124 | 97,860 | 98,881 | 2,377 | 595 | 2,793 | 812,630 |
| 2001 | 645,044 | 98,159 | 98,580 | 3,864 | 459 | 2,216 | 848,322 |
| 2002 | 699,851 | 98,657 | 99,729 | 4,417 | 457 | 2,252 | 905,363 |
| 2003 | 741,496 | 99,209 | 99,216 | 5,995 | 681 | 2,133 | 948,730 |
| 2004 | 755,916 | 99,628 | 98,405 | 6,456 | 751 | 2,152 | 963,308 |
| 2005 | 767,792 | 99,988 | 98,887 | 8,706 | 881 | 2,285 | 978,539 |
| 2006 | 772,636 | 100,334 | 99,282 | 11,329 | 1,099 | 2,274 | 986,954 |
| 2007 | 775,674 | 100,266 | 99,771 | 16,515 | 1,439 | 2,214 | 995,879 |
| 2008 | 782,214 | 100,755 | 99,788 | 24,651 | 1,618 | 2,229 | 1,011,255 |
| 2009 | 786,425 | 101,004 | 100,678 | 34,296 | 2,086 | 2,382 | 1,026,871 |
| 2010 | 793,898 | 101,167 | 101,023 | 39,134 | 3,373 | 2,405 | 1,041,000 |

Table 1: Net installed power (Mega Watt) in the United States of America (2000-2010).

| Year | Nr. of Cars | Nr. of Trucks | Nr. of Buses | Nr. of Motorcycles | Total Vehicles |
|------|-------------|---------------|--------------|--------------------|----------------|
| 2000 | 133,621,420 | 87,107,628 | 746,125 | 4,346,068 | 225,821,241 |
| 2001 | 137,633,467 | 92,045,311 | 749,548 | 4,903,056 | 235,331,382 |
| 2002 | 135,920,677 | 92,938,585 | 760,717 | 5,004,156 | 234,624,135 |
| 2003 | 135,669,897 | 94,943,551 | 776,550 | 5,370,035 | 236,760,033 |
| 2004 | 136,430,651 | 100,016,691 | 795,274 | 5,780,870 | 243,023,486 |
| 2005 | 136,568,083 | 103,818,838 | 807,053 | 6,227,146 | 247,421,120 |
| 2006 | 135,399,945 | 107,943,782 | 821,959 | 6,678,958 | 250,844,644 |
| 2007 | 135,932,930 | 110,497,239 | 834,436 | 7,138,476 | 254,403,081 |
| 2008 | 137,079,843 | 110,241,587 | 843,308 | 7,752,926 | 255,917,664 |
| 2009 | 134,879,600 | 110,561,293 | 841,993 | 7,929,724 | 254,212,610 |
| 2010 | 141,743,935 | 99,470,559 | 846,051 | 8,009,503 | 250,070,048 |

Table 2: Registered motor-vehicles in the United States of America (2000-2009).



Figure 1: ZERO-S- ZF-11.4 motorcycle & NISSAN LEAF-S car.



Figure 2: BYD-eBus & SMITH-NEWTON truck.

| Vehicle type | Range City/highway | Motor Max. Power | Battery type capacity | Charging time (100%) | Equivalent efficiency |
|------------------------------|----------------------------|----------------------------------|-----------------------|----------------------|--------------------------------------|
| Motorcycle ZERO-S-ZF-11.4 | 137/85 miles 220/137 km | DC-brushless 40 kW 54 HP | Li-ion 11.4 kWh | 7.9 hours | 463/246 MPGe 0.5/1.0 Le/100 km |
| Car NISSAN LEAF-S | 70/105 miles 110/169 km | PM-synch 79.78 kW 107 HP | Li-ion 24 kWh | 7.58 hours | 130/102 MPGe 55.05/43.2 Le/100 km |
| Bus BYD-eBus | 155 miles 249.4 km | PM-synch 160 kW 214.6 HP | Fe 300 kWh | 6 hours | 27.74 MPGe 13.69 Le/100 km |
| Truck SMITH-NEWTON | 150 miles 190 km | DC-brushless 134 kW 180 HP | Li-ion 120 kWh | 7.7 hours | 23.6 MPGe 10 Le/100 km |

Table 3: Electric vehicle types and their characteristics [15-18].

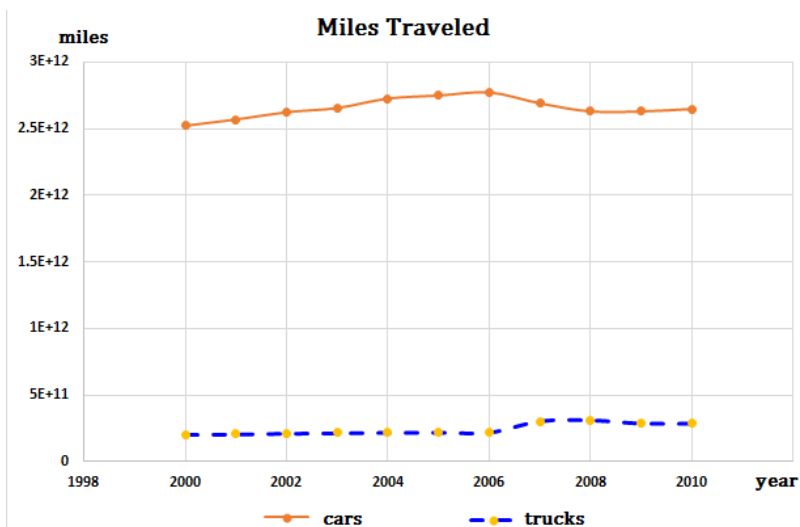


Figure 3: Average miles travelled, cars and commercial trucks (2000-2010).

the United States, as compared to the motorcycles and busses, of two orders of magnitude, two separate graphs were compiled, to illustrate the number progression over the period considered. Numerical values for miles traveled per year, for the time frame 2000-2010, are compiled in Table 4.

The average miles traveled by cars and by commercial trucks, each year, have remained virtually constant over the ten-year period, as shown in Figure 3, while the miles traveled by motorcycle and by buss have shown an increase during the 2006-2008 time frame, as shown in Figure 4.

Thus, the average traveled miles by all vehicles combined, over the time-frame 2000-2010 has remained virtually constant, although the number of vehicles, in all four classes, registered in the United States has increased over the same period, as shown in Table 4.

Therefore, the average miles travelled per vehicle exhibited a slight decrease over the ten-year period 2000-2010, for all types of vehicles combined.

Average daily consumption of equivalent electric power

Considering the average miles traveled daily by each type of vehicle, as well as the average operating range specific to each type of vehicle, a coefficient of battery recharge can be easily computed:

$$\text{recharge rate} = \frac{\text{miles traveled daily}}{\text{vehicle range}} = \frac{\text{total miles traveled per year}}{(\text{number of days per year}) \times (\text{total number of vehicles}) \times \text{vehicle range}} \quad (1)$$

For cars, this study uses one of the most popular electric vehicles in the United States: Nissan Leaf, with a maximum range of 70 miles (city) and 105 miles (highway), as shown in Table 3.

Thus, the two rate of recharge for electric cars in the year 2010 were:

$$\text{recharge rate(city)} = \frac{2.64846 \times 10^{12}}{(365.25 \times 141,743,935) \times 70} = \frac{51.156}{70} = 0.73 \quad (2)$$

Thus, the battery needs to be recharged approximately three (3) times in four (4) days period.

$$\text{recharge rate(highway)} = \frac{2.64846 \times 10^{12}}{(365.25 \times 141,743,935) \times 105} = \frac{51.156}{105} = 0.487 \quad (3)$$

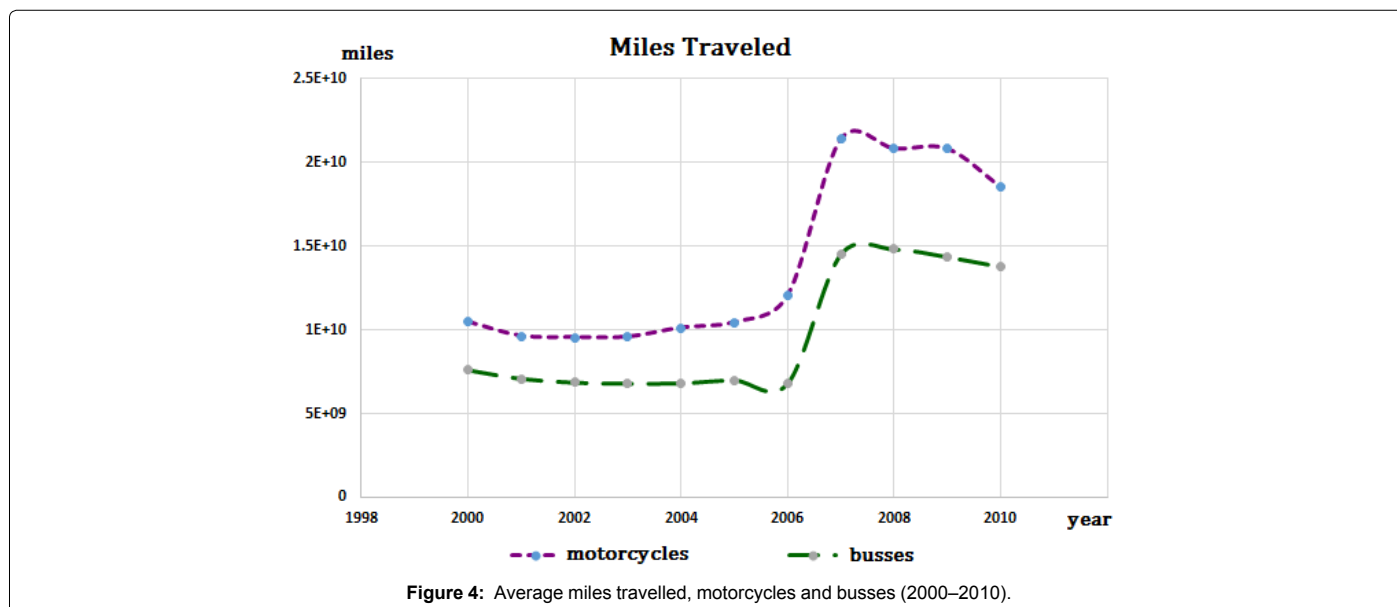
As such, the battery needs to be recharged once every two (2) days.

Through similar computations, all recharge rates are computed and shown in Table 5.

Thus, the proportion of vehicles under “battery charging condition” γ can be determined as:

$$\gamma = \frac{\text{recharge rate}}{24 \text{ hours}} \times (\text{battery charging time}) \times 100\% \quad (4)$$

Table 6 compiles all charging conditions for all types of vehicles during the time-frame considered in this study.



| Year | Motorcycles | Cars | Buses | Trucks |
|------|----------------|-------------|-------------|-------------|
| 2000 | 10469000000 | 2.52335E+12 | 7590000000 | 2.0552E+11 |
| 2001 | 9633000000 | 2.56998E+12 | 7070000000 | 2.08928E+11 |
| 2002 | 9552000000 | 2.62451E+12 | 6845000000 | 2.14603E+11 |
| 2003 | 9576000000 | 2.65599E+12 | 6782000000 | 2.17876E+11 |
| 2004 | 10122000000 | 2.72705E+12 | 6801000000 | 2.20811E+11 |
| 2005 | 10454000000 | 2.74947E+12 | 6980000000 | 2.22523E+11 |
| 2006 | 12049000000 | 2.77303E+12 | 6783000000 | 2.22513E+11 |
| 2007 | 21396000000 | 2.69103E+12 | 14516000000 | 3.04178E+11 |
| 2008 | 20811000000 | 2.63021E+12 | 14823000000 | 3.1068E+11 |
| 2009 | 20800000000 | 2.63034E+12 | 14358000000 | 2.88005E+11 |
| 2010 | 1,8513,000,000 | 2.64846E+12 | 13770000000 | 2.86527E+11 |

Table 4: Miles traveled per year, 2000-2010 time-frames.

Therefore, the maximum charging condition factor γ is a weighted figure, representing the average number of vehicles connected to battery charging stations at any given time Table 7, and is:

The average charging condition factor γ_{average} for the maximum and minimum values was computed with formula (5)

$$\gamma_{\text{average}} = \frac{\sum_{k=1}^6 (\text{Recharge rate})}{\sum_{k=1}^6 (\text{charging condition})} \quad (5)$$

Thus, to account for eventual erroneous data, the two extreme charging condition factors were considered as 5% for the low charging condition factor, and 20% for the high charging condition factor. This way, a more realistic image of driving behavior is used to model future trends, especially in the case of electric vehicles' characteristic low-cost per mile, implying a possible increase in the number of miles traveled.

Feasibility Analysis

Predicted installed power

Based on available data, and considering the average increase in installed power over a period of ten years, a predicted installed power was computed over the following twenty years, including the year 2030, as shown in Figure 5.

Predictions on the electric auto-vehicles

The available data, compiled in Table 2, was used to estimate the number of auto-vehicles that will be registered in the United States over the following twenty years, including the year 2030, as shown in Figure 6. Eventual demographic variations or population fluctuations, due to immigration policies were not considered. Thus, this is only an estimate, not intended to be a measuring gauge of population growth in the United States.

Comparison of future power generated vs. future power demand

(You have not attempted to predict the adoption rate of electric vehicles and the associated abandonment of internal combustion

| Year | City-rate motorcycles | Highway-rate motorcycles | City-rate cars | Highway-rate cars | Rate buses | Rate trucks |
|------|-----------------------|--------------------------|----------------|-------------------|------------|-------------|
| 2000 | 0.077 | 0.048 | 0.738 | 0.492 | 0.179 | 0.043 |
| 2001 | 0.063 | 0.039 | 0.730 | 0.486 | 0.166 | 0.041 |
| 2002 | 0.061 | 0.038 | 0.755 | 0.503 | 0.158 | 0.042 |
| 2003 | 0.057 | 0.035 | 0.765 | 0.510 | 0.154 | 0.041 |
| 2004 | 0.056 | 0.034 | 0.781 | 0.521 | 0.151 | 0.040 |
| 2005 | 0.054 | 0.033 | 0.787 | 0.524 | 0.152 | 0.039 |
| 2006 | 0.058 | 0.036 | 0.801 | 0.534 | 0.145 | 0.037 |
| 2007 | 0.096 | 0.059 | 0.774 | 0.516 | 0.307 | 0.050 |
| 2008 | 0.086 | 0.053 | 0.750 | 0.500 | 0.310 | 0.051 |
| 2009 | 0.084 | 0.052 | 0.762 | 0.508 | 0.301 | 0.047 |
| 2010 | 0.074 | 0.046 | 0.730 | 0.487 | 0.287 | 0.052 |

Table 5: Batteries recharging rates.

| Year | City motorcycles | Highway motorcycles | City cars | Highway cars | Buses | Trucks |
|------|------------------|---------------------|-----------|--------------|-------|--------|
| 2000 | 2.53% | 1.58% | 23.30% | 15.53% | 4.47% | 1.37% |
| 2001 | 2.07% | 1.28% | 23.05% | 15.34% | 4.15% | 1.31% |
| 2002 | 2.01% | 1.25% | 23.84% | 15.88% | 3.95% | 1.34% |
| 2003 | 1.87% | 1.15% | 24.16% | 16.10% | 3.85% | 1.31% |
| 2004 | 1.84% | 1.12% | 24.66% | 16.45% | 3.77% | 1.28% |
| 2005 | 1.77% | 1.08% | 24.85% | 16.54% | 3.8% | 1.25% |
| 2006 | 1.91% | 1.18% | 25.29% | 16.86% | 3.62% | 1.18% |
| 2007 | 3.16% | 1.94% | 24.44% | 16.29% | 7.67% | 1.60% |
| 2008 | 2.83% | 1.74% | 23.68% | 15.79% | 7.75% | 1.63% |
| 2009 | 2.76% | 1.71% | 24.06% | 16.04% | 7.52% | 1.50% |
| 2010 | 2.43% | 1.51% | 23.05% | 15.38% | 7.17% | 1.66% |

Table 6: Battery charging condition factor for each type of electric vehicle.

| Year | Average max | Average min |
|------|-------------|-------------|
| 2000 | 14.38% | 9.77% |
| 2001 | 14.05% | 9.53% |
| 2002 | 14.40% | 9.77% |
| 2003 | 14.42% | 9.79% |
| 2004 | 14.43% | 9.80% |
| 2005 | 14.30% | 9.70% |
| 2006 | 14.22% | 9.65% |
| 2007 | 13.87% | 9.48% |
| 2008 | 13.50% | 9.24% |
| 2009 | 13.53% | 9.24% |
| 2010 | 13.83% | 9.45% |

Table 7: Maximum and minimum average charging condition factor for all electric vehicles.

vehicles. We could look at the half-life of a typical vehicle, and then assume each will be replaced by an electric type. Otherwise, you should explain that, for analysis purposes, for computation purposes, the data in Figure 7 assumes all vehicles since 2010 forward are electric. In other words, had all vehicles in 2010 been electric, the power needed to power 20% of the vehicles charging at any one time, a little over 5 million Megawatts would be needed from the grid. This would have exceeded the total electrical output in 2010 by 5 times. This need grows to 8.2 Million Megawatts by 2030, which exceeds the predicted best case power base by 4.5 times. This shows that installed power growth may catch up with the growing needs of transportation given enough time. This assumes residential and industrial power demand stays flat.)

We make no prediction on the adoption rate of electric vehicles. To illustrate the power needed and relative growth rates, we assume all vehicles since 2010 have electric powered. This shows total transportation energy needed should that power all be drawn from the

electric grid. As shown in Figure 7, the best-case scenario, with only 5% of the electric vehicles parked and charging, the power demand exceeds the predicted installed power for the best-case scenario trend (an annual increase in capacity at a rate of 2.6%). This analysis does not account for the residential and industrial demand of electric power. Thus, the installed electric power, during the next twenty years, will be offset by the demand of electric power due solely to a shift in the transportation technology, focused exclusively on the electric vehicle.

In the worst-case scenario, the predicted electric power demand to charge the batteries of future electric vehicles fleet, with 20% of electric vehicles parked and charging, far exceeds the best-case scenario of predicted installed power. Based on this analysis, the demand of electric power in the year 2030 will be between 2.038 and 8.152 Terra Watt, while the predicted installed power will be between 1.229 and 1.773 Terra Watt. The best-case scenario of 5% of entire electric vehicle

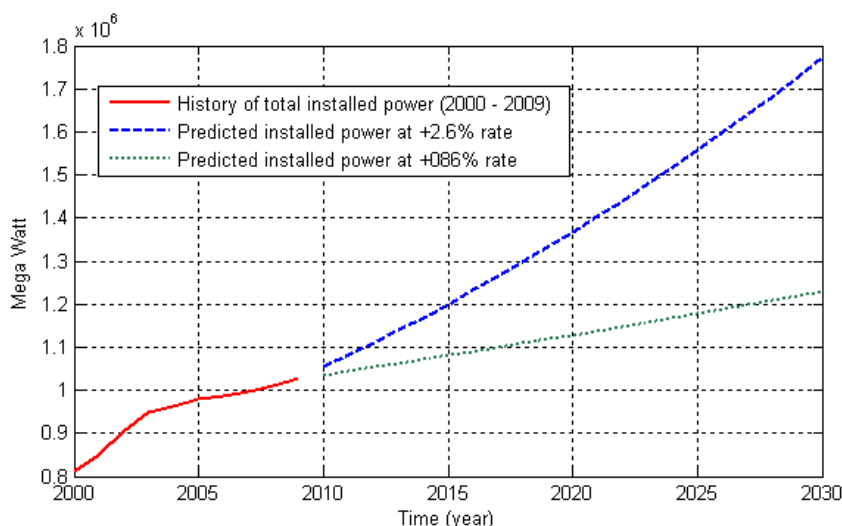


Figure 5: Predicted installed power in the US (2010 – 2030).

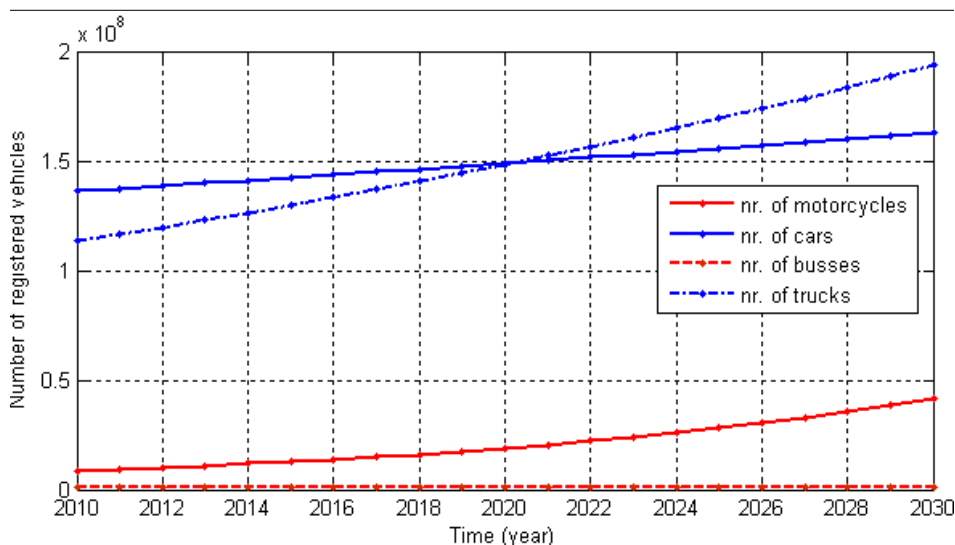


Figure 6: Predicted number of registered vehicles in the US.

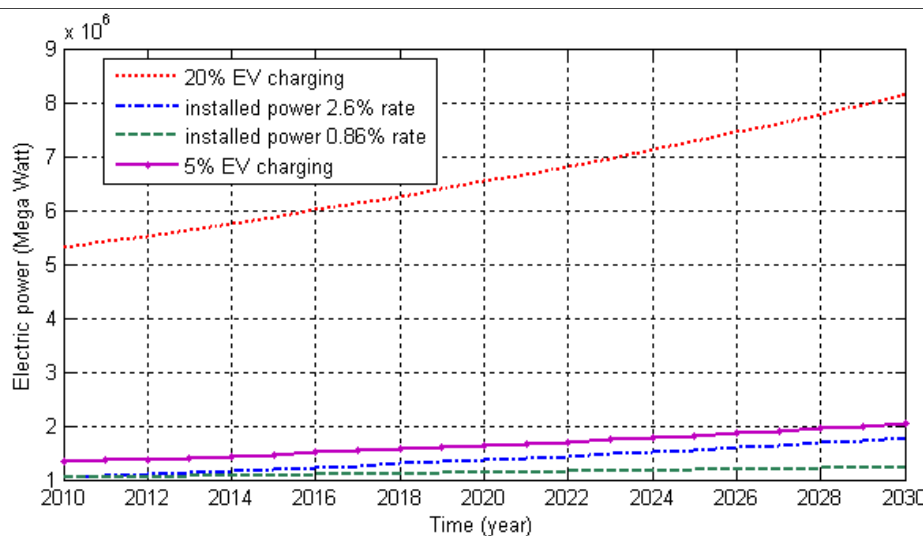


Figure 7: Predicted Installed power vs. predicted power demand through EV in the US.

fleet exceeds the predicted best-scenario installed power in the United States, over the entire time-frame considered in the study.

Conclusions and Future Work

Based on the numerical analysis of the extrapolated data, it is highly improbable that the electric vehicle alone will be able to replace the internal combustion-powered vehicles in the United States. Compounded to the shortage of petroleum, the coal resources are not inexhaustible; limiting the available power provided by thermo-electric power generation units in the future. It is thus concluded, that only an aggressive and speedy implementation of renewable energy infrastructure could balance the supply-and-demand energy crisis. However, with the undeniable exhaustion of petroleum reserves throughout the world, a solution for the future transportation method is not yet clearly defined, and remains an open subject with unpredictable outcomes.

It is known that the internal combustion engine is limited by the fuels it can operate with, requiring a minimum octane number (87-92), for those operating as Otto cycle, or a minimum cetane number for Diesel engines (46-60). The efficiency of each type of engine is well understood, and is limited by the practical compression ratios of each engine's thermodynamic cycle: 25-30% thermal efficiency for gasoline engines (Otto cycle), and 40-50% thermal efficiency for Diesel engines. In general, the actual drive-train efficiency is lower than the engine's thermal efficiency, due to the multiple stage gear ratios in the transmission and differential gear boxes. Currently, the most efficient traction-electric motor is the brushless DC motor (85-90%, and as high as 96.5%), which presents the benefit of regenerative braking, thus improving a vehicle's overall energy efficiency. Based on these facts, future exploration on how to optimize highway transportation, focused on hybrid-electric or electric vehicle, is paramount.

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