

# Electric Vehicles: A future Projection

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Interactive Qualifying Project

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## ABSTRACT

This study examined necessary steps needed be achieved if all automobiles in California 2040 are replaced by electric vehicles (EVs); pure electric vehicles (PEVs) and plug-in hybrid electric vehicles (PHEVs). The analysis was based on a *ceteris paribus* model where current data and trends were examined and forecasted for the year of 2040. Results showed that the electricity consumption of all electric vehicles in 2040 amounts to 80% of the forecasted consumption statewide. California may reduce CO<sub>2</sub> emissions by 40 million metric tons should this change in its automobile fleet is achieved. Approximately 1.1 million public charging stations must be installed to accommodate this change and several power stations must be built to provide adequate electricity for the State's needs, but specific numbers depend upon several factors elaborated in this analysis.

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Additionally, I would like to thank Miss Deborah Scott for taking the time to share her useful personal experience with a plug-in hybrid electric vehicle, Miss Liz Tomaszewski who provided knowledge on charging stations and Professor John Orr for providing essential technical knowledge on electricity generation, transmission and distribution. Last but not least, I would like to thank Mr. John Swanton, spokesman of the California Air Resources Board, who analytically answered to clarifying questions regarding the Zero Emission Vehicle Action Plan.

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## I. INTRODUCTION

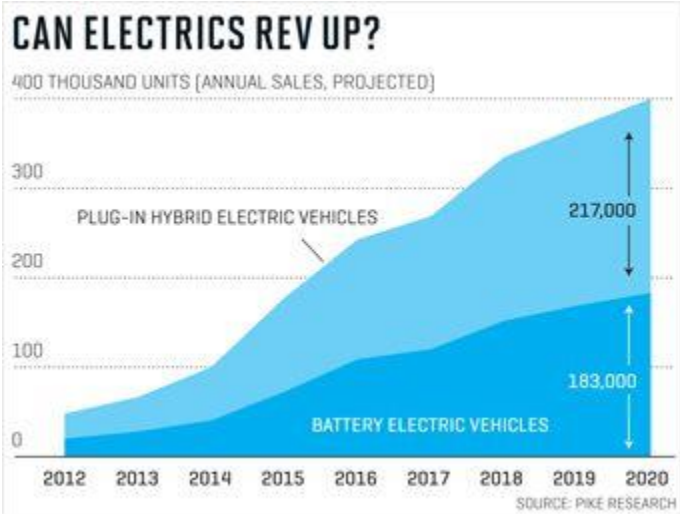
Since the appearance of the internal combustion engine towards the end of the 19<sup>th</sup> century and specifically its installation and use in wheeled automobiles, motorcars have been creating pollution as a result of their emissions to the environment. The degree of this pollution has been increasing over time with more and more automobiles appearing on the roads through the years. It was only in the early 1950's when air pollution and automobiles were first linked by a California researcher who determined that vehicle traffic was the cause for the smoggy skies over the city of Los Angeles [1]. In relatively recent years, there have been several attempts to regulate these emissions, such as the first auto emissions law which was passed in California in 1964 and the establishment of the United States Environmental Protection Agency in 1970 under the presidency of Richard Nixon. Despite the several emissions regulations, the internal combustion engine, powered by fossil fuels, will inevitably continue to emit and cause environmental pollution. This fact, coupled with the rapid technological developments through the late 20<sup>th</sup> century until today, has stimulated corporations worldwide to pursue and develop alternative means to vehicle power, in an overall effort of both reducing environmental harm and abiding to stringent emission laws passed by national governments around the globe.

Hybrid and electric vehicles have gained significant popularity over the past few years as they are generally believed to be a 'greener' solution compared to their gasoline peers. It is well known that vehicle emissions are responsible for large amounts of greenhouse gas production and are leading contributors toward smog and general air pollution. Consumers as a whole are starting to be more environmentally aware of these problems. With gas prices skyrocketing over the past few decades consumers have yet another reason to start paying more attention to the

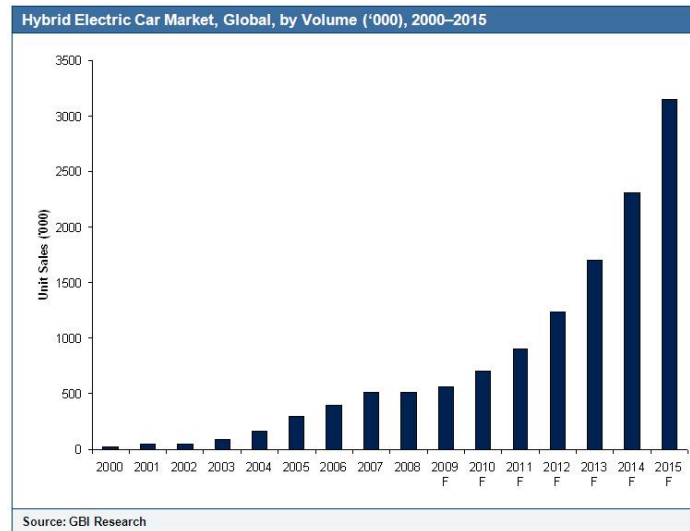


benefits of using alternative, low-emission vehicles. At the same time, car manufacturers around the world have been developing new technologies to promote the usage of hybrid and electric vehicles. “The market for electric cars is sputtering, but the price of the technology is falling” [2], says Michael Law, an analyst at Needham & Co. Electric vehicles’ annual sales statistics who also supports this prediction.

**Figure 1: ‘Can Electrics Rev up?’ [2]**



**Figure 2: Hybrid Electric Car Market Annual Sales [2]**



In the United States the federal government has been supportive towards these emerging technologies by offering tax credits to owners of such vehicles while incentivizing consumers to purchase such vehicles by offering mandates and other subsidies.

Specifically in California, a government plan, known as the Zero-Emission Vehicle Plan, has been developed to promote ownership and usage of hybrid and pure electric vehicles [3]. Meanwhile, a big question is still left unanswered, "when and how can low-emission vehicles replace traditional petroleum ones?" Current electric and hybrid vehicle technology does not offer the vehicle functionalities and conveniences that their gasoline peers provide. Indicatively, a Nissan Leaf has a city mile range between 84 and 107 miles but needs 24 hours on average (at 110 Volts) and an average of 7 hours (at 220 Volts) for a full charge. A Chevrolet Volt requires a shorter time for a full charge with 13 hours to be the usual at 110V and up to 4.5 hours at 220 Volts. However, according to owner's testimonials the car's battery range is short, compared to the range of a gasoline-powered vehicle, being approximately 50 miles during spring season and down to 26 miles during winter [4]. Moreover, internal combustion vehicles have dominated the

market since their appearance until today that at least one gas station is located in every town across the U.S. The same cannot be claimed for electric and hybrid cars as the number of electric stations and charging outlets across the country has been increasing only in the past few years. Nationwide, about 10,000 publicly available EV chargers compete with about 114,000 gas stations, according to Department of Energy data.

To provide adequate electricity to EV's, a considerable amount of charging stations might need to be built, let alone power plants to support them. The current conditions, though, do not prevent California Governor Edmund G. Brown Jr. from believing in the fate of these vehicles. He has ordered that 1.5 million zero-emission vehicles "be on California roads" by 2025 as a regulatory weigh station in order to meet the state's goal of cutting its greenhouse emission to 80% below 1990 levels [3]. Governor's interagency working group has prepared the zero-emission vehicle action plan in a coherent attempt to achieve these goals.

This statement provides the drive of this study which more specifically investigates some of the necessary steps needed be achieved if all automobiles in California of 2040 were to be replaced by pure electric vehicles (PEV's) and plug-in hybrid electric vehicles (PHEV's), altogether referred to as electric vehicles (EV's), and the associated benefits and challenges of this.

Initially, relevant background information regarding the State of California is provided and projected for the year of 2040. Further, the current status of EV's, including a brief history of the electric vehicle and currently available charging methods are looked at. An emission analysis follows and an estimate of EVs' annual operating cost. Results on the number of electric charging stations and power plants needed to be built in order to accommodate this change are

provided. Finally, the report closes with a discussion of the benefits and limitations of electric vehicles and their future.

## II. BACKGROUND

### 2.1 CALIFORNIA RELEVANT STATISTICS

#### 2.1.1 TRANSPORTATION STATISTICS

As mentioned in the previous section, the main objective of this project is to analyze and evaluate certain aspects of future California 2040 when all non-commercial vehicles (also referred to as passenger vehicles) will be replaced by electric or hybrid electric cars. Since we cannot simply predict relevant for our calculations data we need to look at the current statistics and project those in 25 model years from now. It is forecasted that the population of California will increase from 37.8 million people in 2015 to 48.2 million while the number of registered automobiles will rise from 33 million to 43 million for the same period [5]. We are interested in the number of non-commercial vehicles, reported as automobiles in this study, therefore we need to estimate how many of those vehicles will be non-commercial in 2040. According to California DMV statistics there are 32,980,355 registered vehicles as of January 1, 2015 in the state of California out of which 23,805,920 are automobiles, a 72% out of the total registered vehicle fleet [6]. Using the same ratio we estimate that there will be approximately 30.7 million non-commercial vehicles in California roads in 2040. The following table summarizes the above.

**Table 1: Forecasted population and number of automobiles in California, 2040**

	2015	2040	Percentage Increase
Population (millions)	37.8	48.2	27.5%
Automobiles (millions)	23.8	31.0	29.9%

## 2.1.2 ELECTRICITY GENERATION AND CONSUMPTION STATISTICS

An estimate of the current electricity consumption in the State of California is necessary in order to forecast the electricity consumption demand for our hypothetic scenario in future California of 2040 where all automobiles will have been replaced by electric and hybrid vehicles. Available data on the electricity consumption for the state of California dates up to the year of 2014. The following table provides population and electricity consumption statistics for a ten-year period from 2005 to 2014 along with a forecasted estimate of these numbers for the year of 2040.

**Table 2: Electricity Consumption in California 2005-2014 [7] and 2040 projected consumption**

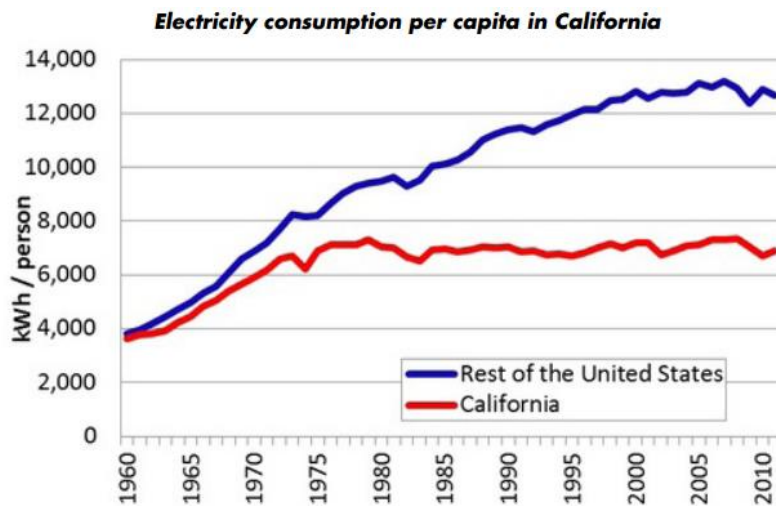
Year	Population	Electricity consumption (GWh)	Per capita consumption (GWh/person)
2005	35,834,207	274,576.4	0.00766
2006	35,947,461	282,736.4	0.00787
2007	36,185,908	287,168.6	0.00794
2008	36,538,008	287,195.7	0.00786
2009	36,887,615	278,935.0	0.00756
2010	37,253,959	274,336.9	0.00736
2011	37,6680,00	275,723.9	0.00732
2012	37,966,000	282,497.5	0.00744
2013	38,435,208	280,574.8	0.00730
2014	38,847,736	282,154.7	0.00726
2040*	48,160,000*	364,089.6*	0.00756*

\*: Projected values based on the average per capita electricity consumption of 0.00756 (GWh/person) during 2005-2014

The average per capita electricity consumption in the state of California during the years 2005 to 2014 is estimated to be equal to 0.00756 GWh/person. Using this number as an indicative average it is forecasted that the electricity consumption in California in 2040 will amount to 364,089.6 gigawatt-hours (GWh). It should be noted that this is only a forecasted approximation supported by historic data and trends assuming a *ceteris paribus* ('all other things being equal') analysis. More on this approach will be found in the *Methodology* section of this report. Furthermore, this predicted value for the net electricity consumption in California in 2040 does not take into account the overall impact of the relative energy and electricity aspects due to the shift of the California automobile fleet to electric and hybrid vehicles.

The following graph shows electricity consumption per capita in California (shown by the red line) over a fifty year period from 1960 to 2010.

**Figure 3: California's per capita electricity consumption [8], 1960-2010**



We can observe in the above graph that the electricity consumption per capita in California falls in the range of approximately 7000 kWh/person (0.007 GWh/person) on average after the 1970's and onwards which is consistent with our forecasted results despite their assumptions.

The following table shows California’s electrical energy generation plus net imports for the years 2005 to 2014. In other words, this is the amount of the total electricity that is generated within the California state plus the total amount of electricity that the state imports from external sources for each of the listed years. The state’s electricity consumption over the state’s electricity generation plus its net imports for each of those years is also provided as a percentage.

**Table 3: California Electricity Generation plus Net Imports [9]**

Year	Electricity generation plus net imports (GWh)	Electricity Consumption over Net electricity generation + net imports (%)
2005	289,141	95.0
2006	298,310	94.8
2007	304,900	94.2
2008	307,448	93.4
2009	298,502	93.4
2010	291,141	94.2
2011	293,761	93.9
2012	302,239	93.5
2013	296,203	94.7
2014	296,843	95.1
2040*	386,507*	94.2*

\*: Projected values based on the 94.2% average yearly ratio of California’s electricity consumption over its net electricity generation plus net imports calculated for the years 2005-2014



The ratio of California's yearly electricity consumption over its yearly net electricity generation plus its net imports is calculated as a percentage for each of the years from 2005 to 2014. The average of these percentage ratios was estimated to be equal to 94.2%. That is, on average for the time period from 2005 to 2014 the state of California consumes 94.2% of its total net electricity generation which results from in-state but also out-of-state sources. The amount of electricity that California will be generating in 2040, in-state plus from its net electricity imports, was forecasted assuming that the state will be consuming 94.2% of this amount and using the predicted electricity consumption for the same year (364,089.6 GWh), provided in Table 2. Again, this is a forecasted approximation using past historic data and assuming that all other things are kept equal (*ceteris paribus*). These data, actual and forecasted, will be essential for the analysis which will follow in the 'Results and Discussion' Section of this report.

### 2.1.3. ENERGY STATISTICS

#### 2.1.3a) ELECTRICITY POWER PRODUCTION MIX

To address the initial questions that comprise the main drive of this study as they were elucidated in the *Introduction* section of this report, certain energy – relevant aspects regarding the state of California should be looked at. It is therefore of great relevance to this study to look at California's total electricity system power, which refers to the State's annual total energy requirement for all the utilities with end-use within the State. The following table summarizes California's total system power for the year of 2014 – the most recent available data – and the components (the various fuel types and other sources) it consists of.

**Table 4: California's Total Electricity System Power, 2014 [10]**

<b>Fuel Type</b>	<b>In-State Generation (GWh)</b>	<b>Percent of CA In-State Generation</b>	<b>Net Imports (GWh)</b>	<b>California Power Mix (GWh)</b>	<b>Percent California Power Mix</b>
<b>Coal</b>	1,011	0.5%	17,877	18,888	6.4%
<b>Large Hydro</b>	14,052	7.1%	2,298	16,350	5.5%
<b>Natural Gas</b>	121,934	61.3%	10,152	132,087	44.5%
<b>Nuclear</b>	17,027	8.6%	8,193	25,220	8.5%
<b>Renewables</b>	44,887	22.5%	14,916	59,803	20.1%
Biomass	6,721	3.4%	786	7,507	2.5%
Geothermal	12,186	6.1%	844	13,030	4.4%
Small Hydro	2,426	1.2%	361	2,787	0.9%
Solar	10,557	5.3%	2,009	12,566	4.2%
Wind	12,997	6.5%	10,917	23,913	8.1%
<b>Unspecified Sources*</b>	N/A	N/A	44,433	44,433	15.0%
<b>Total</b>	198,973	100.0%	97,870	<b>296,843</b>	100.0%

\*: Unspecified Sources of Power generally includes spot market purchases, wholesale power marketing, purchases from pools of electricity where the original source of fuel is not determined, and "null power". Null power is the generic electricity commodity that remains when the renewable attributes, renewable energy credits, are sold separately. [10]

Furthermore, the following table is a summary of California's percent total electricity system power mix for the year of 2014, listed in descending order.

**Table 5: California’s Total Electricity System Power Mix, 2014** [produced from values in Table 6]

<b>Fuel Type</b>	<b>Percent California Power Mix</b>
Natural Gas	44.5%
Renewables	20.1%
Unspecified Sources	15.0%
Nuclear	8.5%
Coal	6.4%
Large Hydro	5.5%
Total	100.0%

As it shown in Table 7, California produced most of its electricity to meet its energy demands for the year of 2014 from natural gas, amounting to nearly half of its total power mix, followed by renewable sources with wind power to be the predominant one among them (as it can be seen in Table 6). A 15% of the State’s power mix originated from spot market purchases and pools of electricity in which the original source of fuel could not be determined by the government’s energy commission.

The following section includes relevant information on California’s power stations, also known as power plants, along with an explanation of some useful relevant terms which will be used later on to produce results and facilitate further discussion.

### 2.1.3b) POWER STATIONS

The following table provides a list of power stations in the state of California based on the type of fuel they use or their source of electricity generation. The list is based upon the most recent

available data which dates up to 2014 and includes power stations with an electric generation capacity of 1 mega-watt (MW) and above. It should also be noted that this is only an approximate list as both the operation and the electric generation capacity of the power stations depends on several factors, including seasonality, electricity demand and prices and various other specifications. However, it provides a good representation of the most recent number of power stations in the state of California according to their type.

**Table 6: California Power Plants by type [11], 2014**

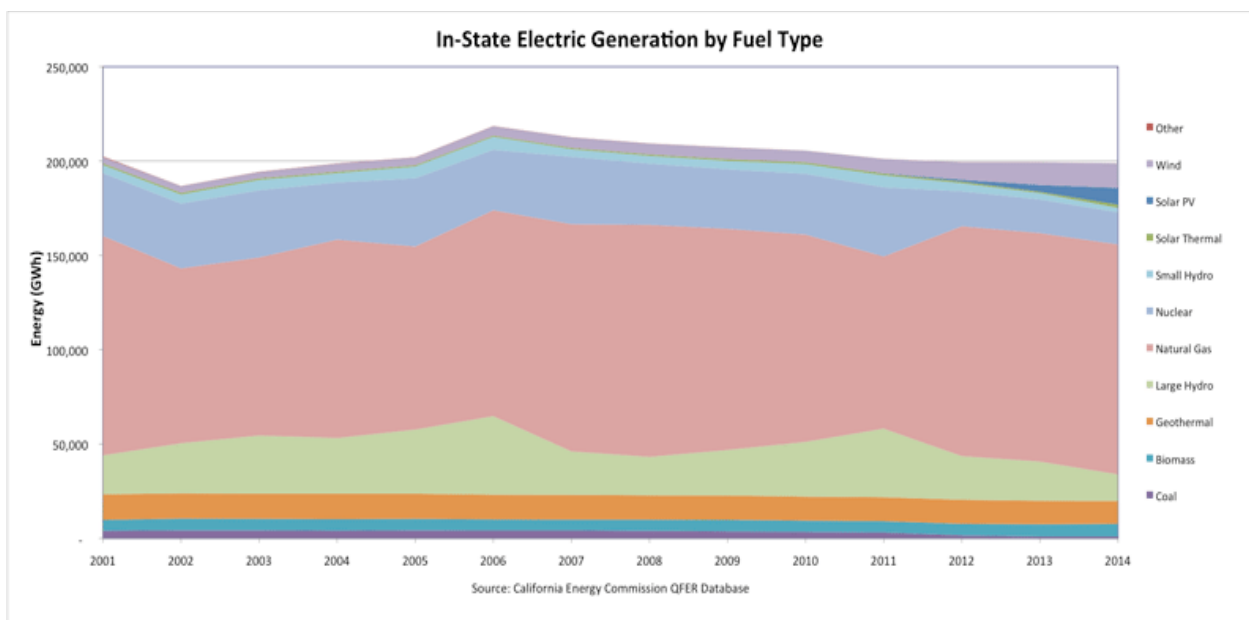
<b>Type</b>	<b>Number of Plants</b>
Hydroelectric	43
Natural Gas	36
Biomass	28
Solar	15
Geothermal	8
Wind	7
Coal	7
Thermal	4
Nuclear	1

There are some key terms need to be explained which will provide a better understanding of the discussed information regarding power stations and electricity production. The ability of a power station to produce electricity is determined by its capacity and capacity factor. In general, electricity generation capacity refers to the maximum electric output a generator is able to

produce under specific conditions. It is determined by the generator’s manufacturer and indicates the maximum output that it can produce without exceeding design thermal limits [12] (also known as nameplate or installed capacity). This is different to electricity generation which refers to the amount of electricity a generator produces over a specific period of time at its capacity and is usually measured in Mega-Watts (MW). Furthermore, net electricity generation is the amount of gross electricity a generator produces minus the electricity used to operate the power station [12]. Last but not least, another key-term when it comes to any type of power production is the capacity factor. For a power plant that produces electricity, the capacity factor is the ratio of the net electricity generated over a period of time (actual output), to the electricity that could have been generated if the plant was operating at continuous full-power operation – at its nameplate capacity – during the same period of time (potential output) [13].

The following figure shows California’s in-state electric generation by fuel type (in GWh) for the years 2001 to 2014.

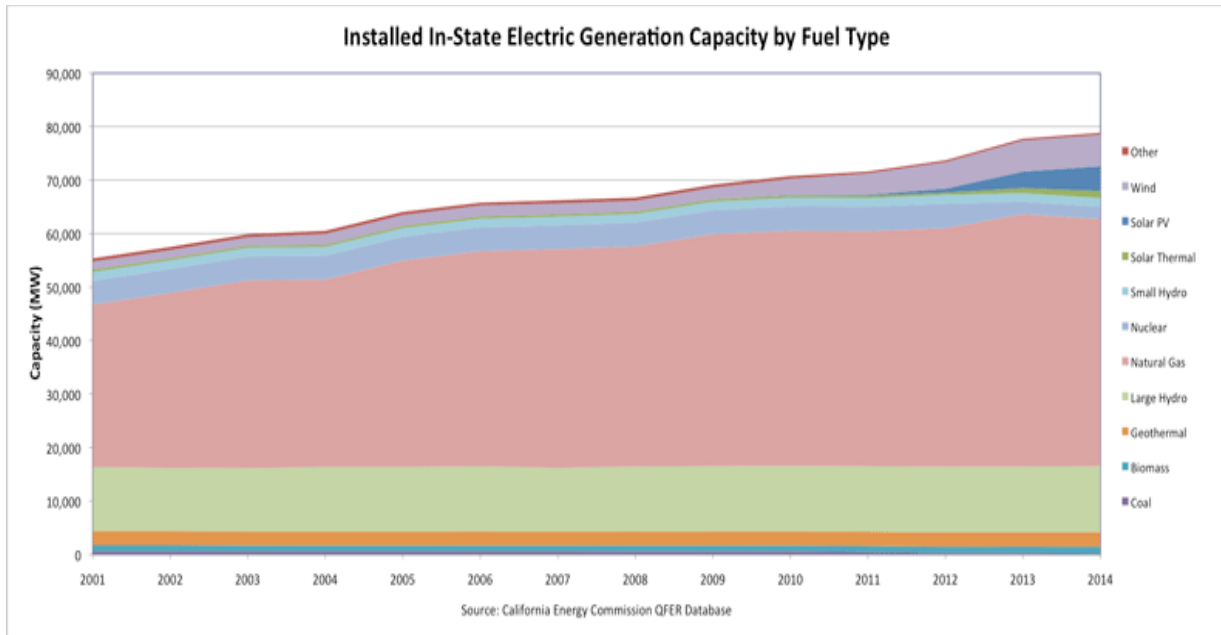
**Figure 4: In-State electric generation by fuel type (GWh), 2001-2014 [14]**



The figure above highlights California's power production mix during the time period 2001-2014, as was indicated in the previous section of this report 2.1.3a). Moreover, it provides a visual representation of the contribution of each of the listed energy sources to the net amount of electricity generated during these years. To this contributed the breakthrough, in the relatively recent years, in the photovoltaic technology which led to the adoption and installation of several photovoltaic units and panels across the state of California. Most of the electricity generated comes from natural gas sources, followed by the renewable sources of energy - which is the net sum of biomass, geothermal, small hydroelectric, solar and finally wind sources – followed by nuclear power which alone surmounts the electricity generated by the individual components that comprise the renewable sources. Furthermore, the 'unstable', seasonal character of some of the renewable sources such as wind, small hydroelectric and solar - which are greatly dependent upon the weather and other climate conditions - relatively to the more consistent nature of other sources such as geothermal and biomass is also depicted. Finally, there is a gradual decrease in the net electricity generation coming from coal as the State is moving away towards more environmental – friendly sources, such as solar energy which conversely started gaining ground during the most recent years. Nuclear power despite its high contribution – due to its known high capacity factor (possessing the highest capacity factor against all other sources of energy) – to the net electricity generation, has lost some ground in 2014 relatively to previous years (as in 2006) as a result of State shutting down nuclear power plants leaving only one operating (as it was also shown in Table 8).

Similar trends can be seen in the following figure which shows California's installed in-state electric generation nameplate by fuel type (in MWh) for the years 2001 to 2014.

**Figure 5: Installed in-State electric generation nameplate capacity by fuel type (GWh), 2001-2014 [14]**



It is evident from both representations that the State of California is opting towards more environmental-friendly energy resources through the years abandoning the use of more traditional fossil fuels such as coal and oil. However, natural gas remains the dominant source of the State's net electricity generation.

Capacity factors were calculated for each type of fuel and for each year separately during the period 2001-2014, using the in-state electricity generation by fuel type (provided in GWh) and the installed in-state electric generation capacity by fuel type (provided in MW) data, available from the California Energy Commission Energy Almanac [14]. Since the electricity generation data is given per annum and measured in GWh the following equation was used to calculate the

capacity factor for each type of fuel for every year, consistent with the definition of the capacity factor provided earlier in the report.

**Equation 1: Capacity Factor Calculation**

$$\text{Capacity Factor} = \left[ \frac{\text{Electricity Generation (GWh)} * 1000}{\text{Electricity Generation Capacity (MW)} * 24 * 365} \right] * 100\%$$

Based on the equation above, the following table was produced.

**Table 7: Percent Capacity Factors of California’s power stations by type of source of energy used, 2001-2014**

<b>Energy Source</b>	‘01	‘02	‘03	‘04	‘05	‘06	‘07	‘08	‘09	‘10	‘11	‘12	‘13	‘14
<b>Coal</b>	77.5	82.0	81.9	78.4	82.2	80.4	80.9	79.5	74.0	66.9	80.2	65.6	42.3	67.5
<b>Biomass</b>	57.5	62.0	64.1	65.3	64.9	61.8	60.9	62.7	63.8	61.7	60.0	60.1	61.7	59.8
<b>Geothermal</b>	58.8	58.3	58.0	58.7	57.8	56.6	57.8	56.7	55.6	54.9	54.7	53.8	52.7	51.4
<b>Nuclear</b>	85.3	88.0	91.2	77.5	92.6	82.1	91.4	83.2	80.7	80.3	91.4	46.1	87.8	83.7
<b>Natural Gas</b>	43.7	32.3	30.7	34.2	28.7	31.0	33.6	34.1	30.8	28.5	23.7	31.2	29.3	30.1
<b>Large Hydro</b>	19.7	25.6	29.7	27.9	32.2	39.1	22.1	19.1	22.6	27.1	33.8	21.5	19.3	13.0
<b>Small Hydro</b>	30.4	33.8	39.0	35.1	44.1	48.9	28.6	29.1	31.8	36.8	45.3	30.4	23.5	17.1
<b>Solar Thermal</b>	23.2	25.6	22.9	22.3	19.9	17.5	19.0	20.8	23.5	24.6	24.9	24.3	8.24	14.3
<b>Wind</b>	24.1	26.2	24.1	23.6	22.6	27.1	30.8	31.7	32.7	23.3	21.7	21.2	23.5	25.2

\*: All listed numbers are expressed as percent numbers

A notable drop in the capacity factor corresponding to nuclear energy is observed in the year of 2012 which can be justified by the closure of the San Onofre Nuclear Generating Station, located in the San Diego County, during the year of 2012.

Average capacity factors were then calculated for each type of energy source for the years 2001-2014 based on the values listed on Table 9. Values are listed in descending order.



**Table 8: Percent Average Capacity Factors of California’s power stations by type, 2001-2014**

<b>Energy Source</b>	<b>Capacity Factor (%)</b>
Nuclear	83.0
Coal	74.2
Biomass	61.9
Geothermal	56.1
Small Hydro	33.9
Natural Gas	31.6
Wind	25.6
Large Hydro	25.2
Solar Thermal	20.8

As expected, nuclear power plants come first on the list with the highest average capacity factor over the period 2001-2014 followed by coal-powered stations. The average capacity factor for the sum of the renewable sources (this includes biomass, geothermal power, small hydroelectric, solar thermal and wind power) turns out be equal to 39.7%, for the years 2001-2014 in the State of California.

#### 2.1.4 ZERO-EMISSION GOALS AND PLANS

Motor vehicles are one of the most significant sources of greenhouse gases in California and therefore providing alternative transportation options, such as zero-emission vehicles (ZEV’s), will help improve air quality and reduce transportation-related air pollution. The current general and long-term goal for the state of California is to have 1.5 million ZEV’s on its roads by 2025

and to reduce transportation-related greenhouse gas emissions by 80% below 1990 levels by 2050 [3]. Successful commercialization of ZEV's will be guaranteed through consistent statewide efforts to install adequate charging infrastructure, through developing streamlined metering options for homes equipped with electric vehicle chargers, by evaluating opportunities to reduce vehicle operating costs and increasing electric system efficiency through time-of-use electricity rates and net metering for electric vehicles, and strengthening the connection between ZEVs and renewable energy.

More specifically, the State's plan of action is divided into three time periods, 2015, 2020 and 2025, each with distinct goals [3]. By 2015, the goal is that the state's major metropolitan areas will have adequate infrastructure to be able to accommodate zero-emission vehicles and specifically plug-in electric vehicles. While private investment and manufacturing in the ZEV sector is expected to be growing, by 2015 the State's academic institutions are expected to contribute to ZEV market expansion by building understanding of how ZEV's are used. In the next five years, the state's infrastructure is expected to be able to support up to one million zero emission vehicles. Moreover, the cost of the zero-emission vehicles will not only be competitive with the conventional combustion vehicles but also zero-emission vehicles will be accessible to mainstream consumers. Finally, by 2025 with the goal of 1.5 million ZEV's on California roadways it is projected that the clean and efficient zero-emission vehicles will annually displace at least 1.5 billion gallons of petroleum fuels coming from the ordinary combustion vehicles. To put some numbers, so far more than \$25.3 million has been awarded in a variety of infrastructure projects [3]. In 2010, there were 1,300 charging stations at 401 different sites in the state of California with most of them located in the Los Angeles and San Francisco Bay Areas [3]. To date, the Energy Commission has begun establishing the foundation for a zero emission

transportation feature through the funding of approximately 6,200 electric vehicle charging stations. Also, by 2025 it is projected that new automobiles will emit 34 percent fewer global warming gases and 75 percent fewer smog-forming emissions [3]. It is also estimated that consumer savings on fuel costs will average \$6,000 over the life of the car. The savings more than offsets the average \$1,900 increase in vehicle price for the ultra-clean, high-efficiency technology.

## 2.2 ELECTRIC AND PLUG-IN HYBRID VEHICLES

### 2.2.1 A HISTORICAL NOTE

Although electric vehicles started getting attention during the last decade, the concepts that led to their genesis dates back in the early 20<sup>th</sup> century when Danish physicist Hans Christian Orsted discovered in 1920 that electric currents create magnetic fields, a significant aspect of electromagnetism.

One of the very first electric vehicles can be tracked back to a Scottish man named Robert Anderson in 1832. However, this electric carriage was powered by non-rechargeable batteries and therefore did not succeed [15]. The first successful commercial electric vehicles, known as the “Electrobat” and the “Riker Electric Vehicle”, were manufactured by the “Electric Vehicle Company” in the late 1890’s [16]. The “Electrobat” was a lead-acid battery based vehicle created by an engineer and chemist, Henry G. Morris and Pedro G. Salom respectively.

**Figure 6: Robert Anderson's Electric Vehicle, 1832**



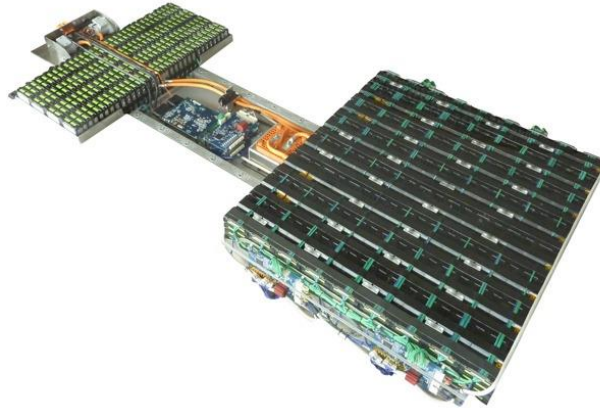
During the 1900s the electric vehicle starts to receive great competition from the internal combustion engine which consumes cheap gasoline and for which the gas tank can be filled in just a small fraction of the time required to charge a car battery. It was only until 1996 when General Motors releases the EV1 with a promising 80 mile driving range on a single charge of its lead-acid battery pack. However, the program was abandoned as the company found it to be non-profitable [15].

The breakthrough is made in the 2000s when Toyota releases the 'Toyota Prius', a hybrid-electric vehicle that utilizes both an electric motor and an internal combustion engine. With gas prices increasing in the recent years along with raising environmental concerns, both consumers and manufacturers are becoming progressively interested in electric and hybrid cars. Currently, many of the major car manufacturers possess at least one model of all-electric or hybrid-electric vehicle.

## 2.2.2 PURE ELECTRIC VEHICLE

A pure electric vehicle (PEV), also known as all-electric vehicle, operates solely on electricity as its name suggests. An on-board battery pack module (shown in the figure below) stores the electricity used to power the vehicle. The battery charge can be additionally extended while the vehicle is being operated through the regenerative braking system. The otherwise lost kinetic energy from braking is saved in a storage battery which can be used later to power the motor when in need. When the vehicle is not in use, the battery pack is recharged by plugging the vehicle into an external electric power source such as a charging station or a home outlet.

**Figure 7: Typical PEV battery pack**



Since pure electric vehicles do not have a gasoline engine, they do not have any tailpipe emissions (they do not possess a tailpipe at all). However, these vehicles do cause emissions which take place elsewhere, such as at the electric power plant and the manufacturing facility (most of them originating from the battery's construction) with amounts varying greatly based on the source of electricity and energy used. All-electric vehicles are more energy efficient

compared to conventional gasoline vehicles, as they are able to convert about 59%-62% of the electrical energy provided by the grid to power the wheels, whereas a typical gasoline vehicle is only able to convert about 17%-21% of the energy stored in gasoline to useful power [17].

Their driving range on a full charge typically ranges between 60-100 miles, according to the most recent (2015) available models, with a few exceptions which can reach up to 200-300 miles, as in the Tesla Model S 85D (\$85,000) with a boasting rating of 270 miles on a full battery charge [18]. Fully recharging the vehicle's battery pack typically takes between 4-8 hours, according to the charging technology used. There is the option of what is known as a 'superfast charge', which can recharge the vehicle's battery to 80% capacity in about 30 minutes [17]. More on current available charging technologies is provided in section *2.3 Charging Station Technology*.

### 2.2.3 PLUG-IN HYBRID ELECTRIC VEHICLE

On a technical scale, plug-in hybrid electric vehicles are conceptually more similar to the all-electric car than they are to the traditional internal combustion vehicles. The traditional car requires an internal combustion engine (ICE) to rotate a drive shaft which propels the car. Instead of an engine, PHEVs use four motors, one in each wheel, which relies on electricity to run the vehicle. Contrary to the pure electric vehicles which do not have an engine, plug-in hybrid electric vehicles (PHEV's) possess both an internal combustion engine and an electric motor which uses a battery pack module stored-on board, as in an all- electric vehicle. Therefore, they are powered by a combination of conventional or alternative fuels and the electricity stored in the battery. During urban driving, a PHEV would power its motion from the stored electricity

in the battery, assuming the battery is charged. On average, for short distances – about 10 to 40 miles in current models - and relatively low speeds the electric motor on its own suffices. This is commonly referred to as “the all-electric range” of the vehicle [19]. The internal combustion engine would kick in in case the vehicle requires more power. The battery is charged through the internal combustion engine, an external electric power source or through regenerative braking. This allows for a smaller engine capacity and therefore results in improved fuel economy, compared to a pure gasoline vehicle, without sacrificing performance at the same time. A PHEV’s fuel economy varies depending on the distance traveled between battery charges. For instance, if the vehicle travels a shorter distance than its “all-electric range” and is plugged in for charging between consecutive trips, it might be able to operate solely on electric power. A PHEV’s battery capacity is typically lower than in an all-electric vehicle, and therefore requires a shorter charging time, with typical values ranging from 1 to 4 hours depending on the charging method used [20].

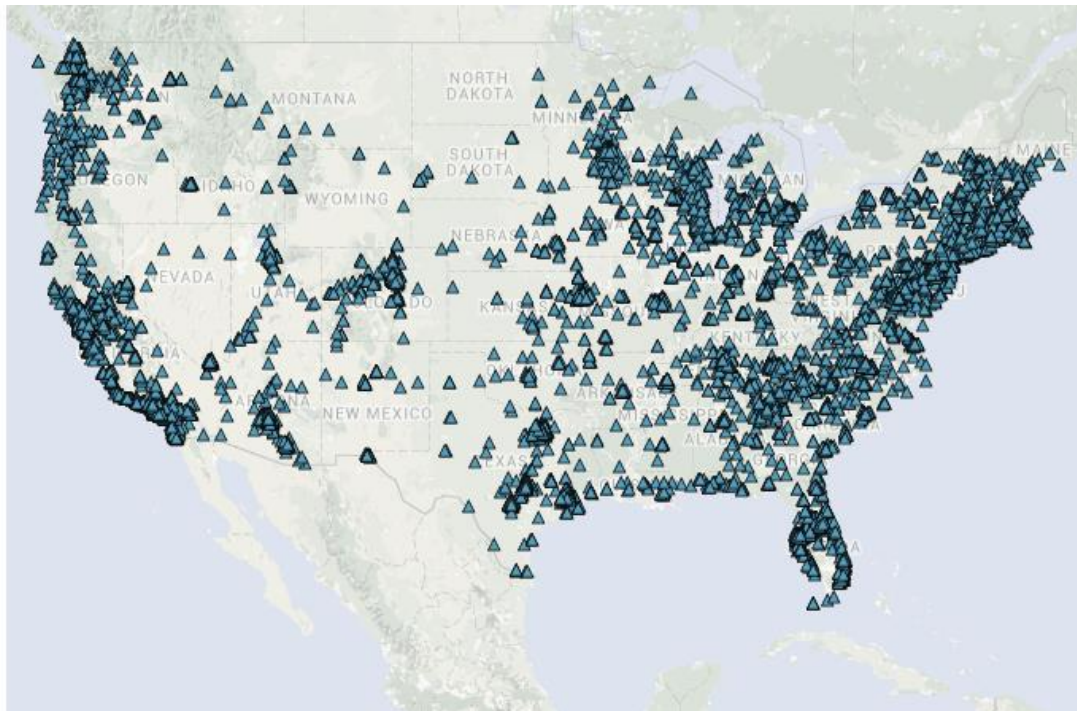
## 2.3 CHARGING STATIONS AND METHODS

### 2.3.1 CHARGING STATIONS IN THE U.S.

According to most recent available data from the U.S. Department of Energy, there are currently 11,822 electric charging stations across the nation, which provide a total of 29,901 available charging outlets (these numbers exclude privately owned charging stations). During the last year there were built 3,731 charging stations nationwide which provide 10,267 additional charging outlets today. In the state of California alone, there exist 2,821 electric charging stations – 24% of the entire nation - providing a total of 8,687 available charging outlets [21].

The figure below shows the distribution of available electric charging stations across the United States (privately-owned charging stations are excluded from this depiction).

**Figure 8: Electric Charging Stations in the United States, 2015 [21]**



It can be seen in the figure above that the available electric charging stations are distributed mainly between the States located on the East Coast part of the country and the state of California, whereas in the middle part of the country extending from northern states, such as Montana and North Dakota, to southern ones such as the state of New Mexico, the availability of electric charging stations is scarce.

### 2.3.2. CHARGING BASICS

The charging equipment for plug-in vehicles (including PEV's and PHEV's) is referred to as EVSE (electric vehicle supply equipment) and it is classified by the rate at which the vehicle's



battery is charged [22]. Charging times vary depending on several factors such as the battery's electric capacity, its type (Lithium-ion, lead-acid, etc.), how depleted the battery is, the type of EVSE used and the electricity supply. There are currently three different types of EVSE; AC Level 1 Charging, AC Level 2 Charging and DC Level 2 Charging, also known as 'DC Fast Charging'. The first two use alternating current as their name suggests whereas the third one utilizes a direct current flow. The following table provides a summary of their most important features.

**Table 9: Charging Equipment [22]**

Type	Voltage Input (Volts)	Charging Rate (miles of range per 1 hour of charging)
AC Level 1	120V AC	2-5 miles/charging hr
AC Level 2	240V AC	10-20 miles/charging hr
DC Level 2	480V AC three-phase	50-70 miles in 20 minutes

The AC Level 1 EVSE provides charging to the battery through a 120V AC plug via a power cord. Most of the plug-in vehicles currently in the market come with an AC Level 1 charging cordset and therefore no additional charging equipment is needed to be purchased by the owner [22]. This type of charging provides the slowest charging rate, as it can be seen in Table 11, and so it is typically used when there are only 120V outlets available. With this type of charging equipment one can easily charge their plug-in vehicle from home. The AC Level 2 charging equipment utilizes a 240V electrical supply, offering a higher charging rate than the AC Level 1 does and thus reduces the vehicle's charging time considerably. It is widely used for public

charging equipment and also for home charging, where the EV owner can fully charge their vehicle overnight. However, some homes might have insufficient electrical capacity for AC Level 2 charging equipment [23]. AC Level 2 equipment uses the same type of connector as in AC Level 1 charging and therefore all commercially available plug-in electric vehicles have the ability to charge using either of these two charging methods, with the exception of Tesla vehicles which require a special adapter in order to do so [22]. Finally, the DC Level 2 charging equipment, or DC fast charging equipment, provides the fastest charging method currently available. Utilizing a three-phase 480V input, it enables fast charging along heavy traffic corridors at installed stations [22]. This type of charging method offers a restricted charge, stopping at 80% of the battery's state of charge level, or changes charging rate after this limit is reached to avoid potential damage to the vehicle's battery.

### III. METHODOLOGY

#### 3.1 THE ANALYSIS APPROACH

As mentioned in the Introduction section of this report, the drive and purpose of this investigation originated from California's Governor E.G. 'Jerry' Brown Jr. who ordered '1.5 million zero-emission vehicles be on the roads of California by 2025', as a regulatory weight station in order to meet the State's goal to cut down its greenhouse emission levels to 80% below 1990 levels [3]. Based on this proposal, the study of a hypothetical scenario emerges in which the California State will have replaced all of its automobiles with pure electric (PEV's) and plug-in hybrid vehicles (PHEV's) by 2040. In order to be able to predict relative aspects and conditions 25 model years ahead, a certain assumption is needed to be made. Current relevant data and important aspects were looked at based upon, as it is known in the engineering world, a 'steady-state' assumption in order to avoid the unpredictability of the transient and dynamic nature of the aspects involved in this study. Specifically, present-day data for California were collected and based upon historic trends by averaging data of earlier years the same data for California 2040 were forecasted. These data namely include the number of registered vehicles, California's population, the State's electricity generation and consumption, the number and type of power stations. This ceteris paribus analysis (assuming 'all else kept equal') does not take into account several underlying factors which at times could prove to be rather determining. Most important of these factors would be the rapid, exponential development of technology which in 25 model years from now could end up producing a far more different 'picture' of the one forecasted by this analysis. Aspects, relevant to this study, to which the rapid evolution of technology contributes, are further elaborated in the *Discussion* section of this report but indicatively include battery technology, improvements in the electricity grid distribution, energy

production, charging technology and infrastructure. Other unforeseen factors which could influence the consistency of this report's results and predictions may include changes in the nation's political scene, which specifically to the state of California may impact and determine the future of the zero-emission vehicles in several ways from alternative governmental regulations to the State's net imported quantities, potential financial crises, and other natural (like earthquakes) or socio-economical disasters. Despite all this, this scientific approach of forecasting future data by inferring it from present and past trends provides a good, consistent method of analysis and furthermore exactly pinpoints to the certain limitations and assumptions involved, giving rise to a more meaningful and qualitative analysis.

### 3.2 THE BACKGROUND RESEARCH

A rather extensive background research was needed to be done in order to get an insightful comprehension of the topic under investigation and to further determine the scope of this study by narrowing it down to the most relative and essential aspects while neglecting and leaving out non-essential information. In order to gain a basic understanding on charging stations and electricity transmission and distribution an interview with Professor John Orr of WPI's Electrical and Computer Engineering Department was conducted. Insightful knowledge on charging stations and charging costs was obtained through an interview with Miss Liz Tomaszewski, WPI's Sustainability Coordinator. Additionally, through an interview with WPI's Chief Information Officer, Deborah Scott, valuable knowledge on plug-in hybrid electric vehicles was gained from a personal user's point of view which was used to facilitate relevant results and further discussion.

Overall, this gathered information enabled to narrow down the scope of this study and understand what areas and information need to be further looked at. Consequently, data on transportation, current EV's technology, power stations and sources of electricity generation along with greenhouse emissions were further collected. Useful articles and reviews from various standpoints were investigated in order to provide a more coherent and objective view on the topic. Finally, a list of questions regarding concepts and information needed further clarifying, mainly drawn from the study of the '2013 Zero-emission Vehicle Action Plan' was developed. Useful answers and information were provided from Mr. John Swanton of the California Air Resources Board.

## IV. ANALYSIS

### 4.1 TRANSFORMATION OF CALIFORNIA'S CAR FLEET IN 2040

Purpose of this study was to investigate related aspects of future California 2040 when all the State's automobiles will be replaced by pure electric vehicles (PEV's) and plug-in hybrid vehicles (PHEV's). In the California Energy Demand 2012-2014 Final Forecast, updated in January 2014 and being the most recent available data, the projected number of PEV's and PHEV's on the road statewide is given for a high and a low demand scenario for selected years. These numbers are listed in the following table.

**Table 10: Projected number of electric vehicles in California for selected years [24]**

<b>Year</b>	<b>High Scenario</b>			<b>Low Scenario</b>		
	<b>PEVs</b>	<b>PHEVs</b>	<b>Total EVs</b>	<b>PEVs</b>	<b>PHEVs</b>	<b>Total EVs</b>
<b>2015</b>	30,995	312,504	343,499	29,960	78,427	108,386
<b>2018</b>	63,100	1,397,607	1,460,707	58,737	151,214	209,950
<b>2020</b>	127,295	2,135,277	2,262,572	112,577	262,541	375,118
<b>2024</b>	344,489	3,330,826	3,675,315	335,536	688,593	1,024,129

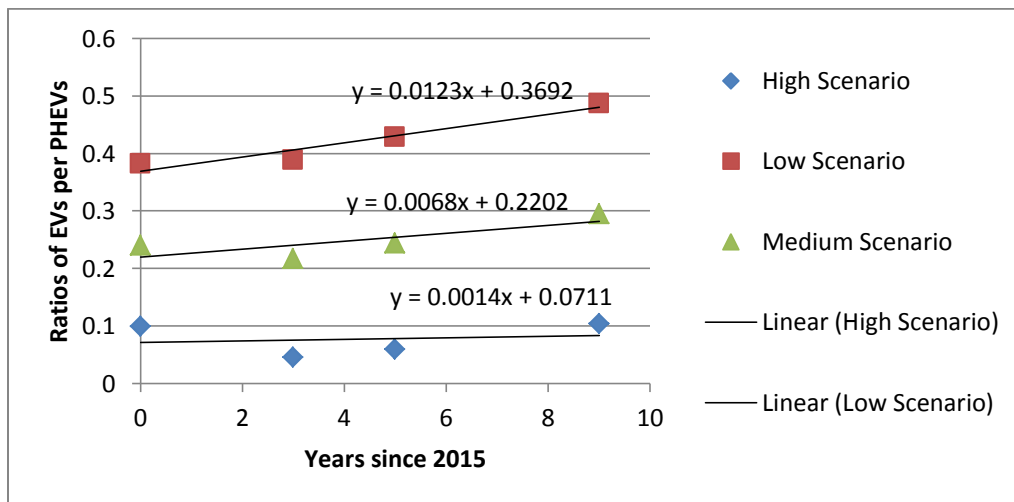
Based on the values listed above a medium scenario was calculated as the average of the high and low scenarios. The ratios of PEVs to PHEVs for each of the listed years and for all three scenarios were calculated and the results are listed in the following table.

**Table 11: Ratio of PEVs to PHEVs for selected years**

Year	High Scenario	Low Scenario	Medium Scenario
2015	0.099182	0.38201	0.24060
2018	0.045149	0.38844	0.21680
2020	0.059615	0.42880	0.24421
2024	0.10342	0.48728	0.29535

We are interested in forecasting the ratio of PEV's to PHEV's for the year 2040. A valid approximate method to do this would be to find the relationship between the rate of increase of the number of PEV's to the rate of increase of PHEV's for the listed years. Plotting the ratios of the listed years in Table 13 for each scenario and using a linear regression model, an equation is derived - through the derivation of a best fit line connecting those points - which represents the relationship between the data points (the ratios of the selected years for each scenario case). This is shown in the following figure.

**Figure 9: Ratio of PEVs to PHEVs for the three different scenarios, linear regression model**



Using these equations, corresponding to each best fit line, one is able to predict the ratio of PEV's to PHEV's for any year after 2015 by replacing the number of years past 2015 for the unknown variable ('x'). Since we are interested in the year 2040 'x' will be replaced by the number 25 (2040 is 25 years past 2015). By doing so, the projected ratio of PEV's to PHEV's in the year 2040 is calculated for each of the different scenarios. These results are listed in the following table.

**Table 12: Ratio of PEVs to PHEVs in 2040 for each different scenario**

<b>Year</b>	<b>High Scenario</b>	<b>Low Scenario</b>	<b>Medium Scenario</b>
<b>2040</b>	0.105025	0.67745	0.391275

To avoid ambiguity, it should be noted (as also mentioned earlier above) that the terms 'high' and 'low' scenario do not refer to the calculated projected ratios, rather to the initial assumptions used by the California Energy Commission in forecasting the projected number of PEV's and PHEV's for the years 2015-2024.

We are interested in finding the number of PEV's and PHEV's in the state of California in 2040 where all automobiles will have been replaced by PEV's and PHEV's. Recalling that the projected number of automobiles in California in 2040 will be 31,000,000 (Table 1) and knowing the projected ratio of PEV's to PHEV's in 2040, the medium scenario ratio is used being the average of the other two scenarios, we can calculate the projected mix of all automobiles in California of 2040. Based on the above, the following system of linear equations is formed.

$$\begin{aligned} \text{PEVs} &= 0.391275 * \text{PHEVs} \\ \text{PEVs} + \text{PHEVs} &= 31,000,000 \end{aligned}$$

Solving the above system of linear equations yields 22,281,720 PHEVs and 8,718,280 PEVs.



**Table 13: Projected number of PEVs and PHEVs in California 2040**

	<b>PEVs</b>	<b>PHEVs</b>
<b>2040</b>	<b>22,281,720</b>	<b>8,718,280</b>

#### 4.2 TAILPIPE EMISSION RATES COMPARISON

Inarguably the most important goal in replacing all internal combustion vehicles with plug-in electric vehicles (pure and hybrid, PEV's and PHEV's) is to reduce the greenhouse gas emissions to the atmosphere. One of the main objectives of California's Zero-Emission Vehicle Action Plan is to reduce greenhouse emissions to 80% below 1990 levels, as mentioned earlier in this report [3]. This section focuses on tailpipe emissions only, that is emissions produced from the vehicle's tailpipe/exhaust due to the internal combustion of the engine's fuel (in this case gasoline). PHEV's apart from their tailpipe emissions have related emissions taking place for the most part at the battery's production facility, the manufacturing of the vehicle itself as well as the emissions originating from the electricity generation needed to charge them which predominantly depends on the source of energy used in the respective electricity generation station (power station/plant). Pure electric vehicles have zero tailpipe emissions as they solely run on an electric motor (no combustion of fuel is taking place) but have associated emissions similar to the PHEV's.

The main greenhouse gas from tailpipe emissions is carbon dioxide (CO<sub>2</sub>). According to the United States Environmental Protection Agency, CO<sub>2</sub> emissions from a gallon of gasoline amount to 8,887 grams CO<sub>2</sub>/gallon. Moreover, the typical fuel economy of an average gasoline

automobile in 2015 on U.S. roads is estimated to be 22 miles per gallon (MPG) [25] and is expected to rise to 24.5 MPG in 2040 [26], as a result of the continuously evolving automobile technology. The following table summarizes the information above and provides an estimate of the total CO<sub>2</sub> emissions of all registered automobiles in the State of California for the years 2015 and 2040, assuming they are all gasoline-powered vehicles with an average annual mileage of 12,000 miles/year [26].

**Table 14: Light-duty gasoline vehicle’s CO<sub>2</sub> tailpipe emissions, 2015 and 2040**

	<b>2015</b>	<b>2040</b>
<b>MPG</b>	<b>22</b>	<b>24.5</b>
<b>CO<sub>2</sub>/mile (grams)</b>	<b>404</b>	<b>363</b>
<b>Annual CO<sub>2</sub>/car (metric tons)</b>	<b>4.847</b>	<b>4.353</b>
<b>Total annual CO<sub>2</sub> emissions (metric tons)</b>	<b>115,358,600</b>	<b>134,943,300*</b>

\*: Projected if all automobiles are gasoline-powered

A plug-in hybrid electric vehicle produces tailpipe emissions when it operates on the power supplied by its internal combustion engine only; the electric motor does not combust any fuel to supply the vehicle with power and therefore does not produce any tailpipe emissions. Using the same CO<sub>2</sub> emission rate as before, since the common fuel in both cases is gasoline, and assuming the same annual travel range, the CO<sub>2</sub> emission rate for California in 2040 where all automobiles will have been replaced by PEV’s is calculated. This calculation is based upon two important considerations. First being that according to Federal Highway Administration only 34.5% of automobiles on the road drive more than 50 miles per day [27], and therefore it is valid to assume that 34.5% of PHEV’s had to use gasoline after depleting their battery after two full

battery charges (the typical all-electric range of PHEV's being 25 miles) [28]. Second, it should be noted that as projected in Table 14 the automobile fleet of the State of California consists of PEV's and PHEV's. However, only the number of PHEV's (22,281,720) – and actually based on the first consideration 34.5% of it – will be used for the following calculations since this section compares strictly tailpipe emissions only and PEV's do not have tailpipe emissions. With an average MPGe (miles per gallon equivalent – accounting for both the electric range and the gasoline range of the hybrid vehicle and factoring in the average usage between its electric motor and gasoline engine) of 75.6 MPGe [29] and assuming that it stays the same in 2040, the following table is produced.

**Table 15: Plug-in Electric Hybrid (PHEV) CO<sub>2</sub> tailpipe emissions, 2040**

	<b>2040</b>
<b>MPG</b>	<b>75.6 MPGe</b>
<b>CO<sub>2</sub>/mile (grams)</b>	<b>117.6</b>
<b>Annual CO<sub>2</sub>/car (metric tons)</b>	<b>1.41</b>
<b>Total annual CO<sub>2</sub> emissions (metric tons)</b>	<b>10,838,943*</b>

\*:Projected data if all automobiles are electric (PHEV's and PEV's)

Comparing the findings in Tables 15 and 16, it can be inferred that California can reduce about 124 million metric tons of tailpipe emissions if all automobiles in 2040 are PEV's and PHEV's. It should be noted again that this analysis reflects only tailpipe emissions; net greenhouse emissions are calculated in the following sections.

### 4.3 AUTOMOBILE OPERATING COSTS

Annual operating costs of gasoline, pure electric and plug-in hybrid vehicles are compared in this section for 2015 and 2040. It is assumed, as in the previous section, that a vehicle travels 12,000 miles per year both for 2015 and 2040. Based on the U.S. Energy Information Administration, gasoline price rates at \$2.64/gallon on average in 2015 and it is forecasted to rise at \$3.90/gallon in 2040 [30]. Average fuel capacities for all types of vehicles were used as before and the following table was thus produced. The cost per mile as its name suggests is derived by dividing the gas price corresponding to the appropriate year by the vehicle's fuel capacity. It should be noted that the numbers are not adjusted to factor for inflation.

**Table 16: Annual Operating Costs of gasoline vehicles, PEVs and PHEVs**

	<b>Vehicle Type</b>	<b>MPG</b>	<b>Cost per mile (\$/mile)</b>	<b>Annual Cost (\$)</b>
<b>2015</b>	<b>Gasoline</b>	22	0.120	1440
	<b>PHEV</b>	75.6 (MPGe)	0.035	419
	<b>PEV</b>	99 (MPGe) <sup>[31]</sup>	0.027	321
<b>2040</b>	<b>Gasoline</b>	25	0.156	1872
	<b>PHEV</b>	75.6 (MPGe)	0.0516	619
	<b>PEV</b>	99 (MPGe)	0.0393	473

From the table above it can be seen that the annual operating cost of PEV's and PHEV's is considerably lower than the one required for a gasoline-powered vehicle. In 2040 the annual operating cost of a PEV and PHEV ranges roughly from \$500-\$600 whereas for a typical

gasoline vehicle the annual operating cost in 2040 is projected to be \$1872. With an average EV's battery life of 10-15 years [32] and an average 30KWh rating the typical battery cost, which currently rates at \$300/KWh [33] is estimated at \$9000 and is expected to further decline in the future. Thus, for the period between 2015-2040 (25 years) with an average annual cost of PEV's and PHEV's for this entire period amounting to \$458 dollars, a consumer, purchasing the PEV or PHEV in 2015, would have to replace the vehicle's battery once totaling to an overall cost of \$20450 compared to \$41400 that he/she would have to spend on gas to fuel a gasoline vehicle for the same period.

### **Important comments**

It should be noted here that the year of 2015 is an exception, an outlier one could say, deviating far from the 'norm' when it comes to gasoline prices, upon which the results of Table 17 are obtained. With an average yearly gasoline price rating at an extreme low of \$2.64/gal it stands out compared to the nation's gas prices of the last decade which average at about \$3.5/gal. This fact, coupled with a forecasted gasoline price for 2040 at \$3.90/gal justifies the observed increased annual cost for PHEV's and PEV's in 2040. To this contributes the assumption of keeping the fuel capacity for PEV's and PHEV's constant from 2015 to 2040 - which in essence factors out any expected developments in these technologies which would yield a lower, if all else kept equal, annual cost than today – making their annual cost dependable upon the gas price. However, this still remains consistent with our analysis approach as described in the *Methodology* section of this report and furthermore validates the unpredictable, transient nature of this study as discussed in the aforementioned section.

## 4.4 BENEFITS OF EVs

### 4.4.1 CONSUMER'S FINANCIAL BENEFITS

As shown in section 4.3 in Table 17 the annual operating cost for PEV's and PHEV's is 3-4 times less than that of a gasoline-powered automobile. As mentioned in previous sections, there are financial benefits offered by federal and state governments to incentivize the purchase of EV's, whose up-front cost might seem at first daunting. Specifically, there are federal tax credits which bring the price of EV's down by \$7,500 [34]. Moreover, the State of California offers \$2,500 [34] rebates to electric vehicle buyers, in an effort to increase market share and promote these technologies. These combined government incentives can reduce the price of a Nissan electric Leaf down to \$18,000 [34]. As more consumers invest in this technology, there will be less of a demand for oil, which reduces the cost of importing foreign oil giving more 'freedom' to the government to allocate its resources.

Through an interview with Miss Deborah Schott, an employee at WPI and owner of a 2012 Chevy Volt, a plug-in hybrid electric vehicle, useful information was obtained from the perspective of a personal user. One of the most important benefits that the vehicle offers is its significantly reduced operational cost compared to a typical gasoline -powered car. Miss Deborah Scott estimates that on average she pays \$20 dollars a month [4] to charge her vehicle at home (as she can infer from her monthly electric bill). She further emphasized on the benefits of being able to charge her vehicle at her workplace location as in that way she manages to commute from her house to her job using only the power coming from the car's battery without needing to use the gas engine and thus avoiding gas money but also tailpipe emissions. Compared to her previous gasoline car, she estimates that she now saves approximately \$200 a month [4] which would otherwise go towards paying for gasoline. This translates to a total of

\$2400 yearly savings. Apart from replacing the tires, she did not have any additional maintenance costs. This is common for this type of vehicles as they possess a minimal amount of moving parts.

Moreover, many electric companies offer discounted rates on electricity consumption during off-peak hours to try to encourage consumers to charge their vehicles at night rather than during the day during peak hours. While batteries may still seem to be an issue due to their high prices, the average lifespan of a battery is 12-15 years and will only improve as the technology advances. Additionally, as mentioned in earlier sections of this report, the battery's price is on a constant decline. "We have an internal target to go down by at least a factor of two by 2020" [35], says Prabhakar Patil, Chief Executive officer of LG Chem. Power Inc.

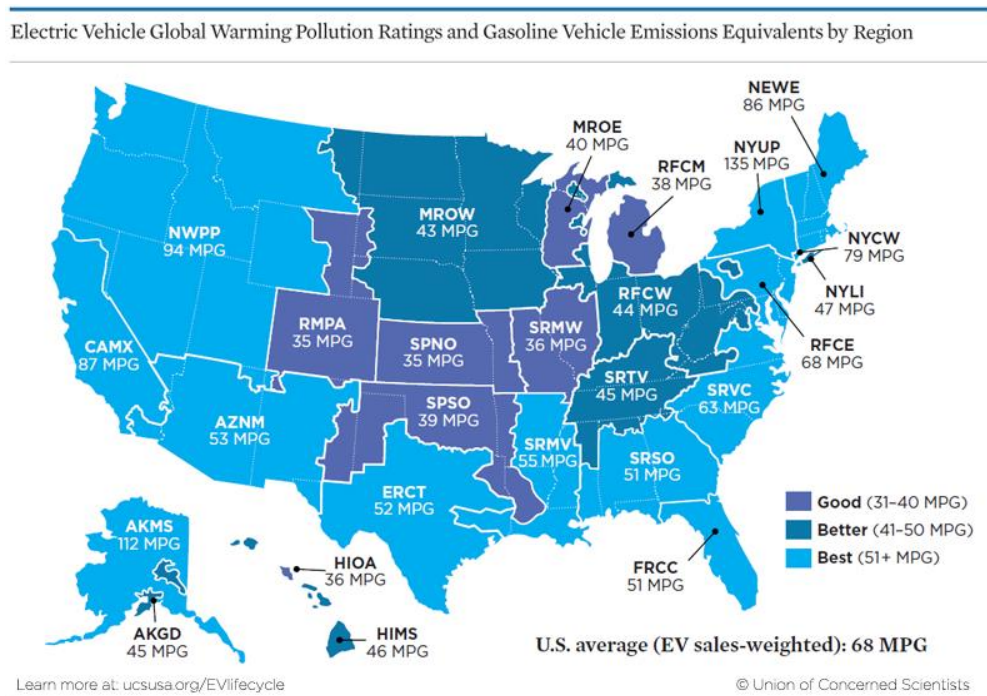
#### 4.4.2. ENVIRONMENTAL BENEFITS

Along with the economic benefit of having to rely less on foreign oil, as consumers utilize more electric vehicles, there will be less need to use gasoline-powered vehicles which in turn will cause less greenhouse gas emissions. While burning coal at electric power plants is not that much better than burning oil, the electricity generated for electric vehicles can also come from power plants fueled by other energy sources that are much cleaner than oil and coal: hydro power, nuclear, geothermal, solar power and wind power. Companies in the private sector have begun giving their employees incentives to take advantage of solar technology by subsidizing solar panels in the roofs of their employees' homes to make clean energy. As these technologies improve, the emissions associated with generating electricity for electric vehicles will be further reduced.

As it was shown in section 4.2, switching from gasoline vehicles to electric vehicles (PEV's and PHEV's) will significantly reduce tailpipe emissions. Specifically, it was calculated from the results of Table 15 and Table 16 that the State of California can reduce CO<sub>2</sub> tailpipe emissions by a total of 124 million metric tons, if it replaces its current vehicle fleet by electric vehicles in 2040.

Generally, it is estimated that the average electric vehicle driving solely on electricity produces global warming emissions equal to a gasoline vehicle with 68 miles per gallon fuel economy rating [36]. The following figure compares EV's pollution ratings to gasoline vehicle emissions equivalents by region.

**Figure 10: EV's Pollution ratings vs Gasoline Vehicles' emissions by region\*, 2015 [36]**



\*: The MPG value listed for each region is the combined city/highway fuel economy rating of a gasoline vehicle that would have emissions equivalent to driving an electric vehicle. The regional emissions are based on most recent power plant data. The comparisons include gasoline and electricity fuel production emissions.



Furthermore, electric vehicles will become even ‘cleaner’ as more electricity is generated by renewable sources of energy. National data from 2013-2015 show a declining percentage of electricity generated by coal power and an increasing in renewable sources, such as wind and solar which suggests that emissions from operating electric vehicles are most likely to keep falling [26]. According to the Union of Concerned Scientists, in a grid that is composed of 80% renewable electricity, the manufacturing of an all-electric vehicle will result in an over 25% reduction in manufacturing’s emissions and an 84% reduction in emissions from driving, resulting to an overall emissions reduction of more than 60% [36].

## 4.5 CHALLENGES

### 4.5.1 CHARGING STATIONS

If all automobiles in the State of California are replaced by electric vehicles (PEV’s and PHEV’s) in 2040, it is consequent that a great number of charging stations will be needed to build and installed in order to accommodate this change. In table 14 of section 4.1 it was found that if the 2040 projected California car fleet of 31 million automobiles is entirely replaced by electric vehicles, there will be 22,281,720 plug-in hybrid electric vehicles and 8,718,720 pure electric vehicles on California roads in 2040. Infographic data shows that 69% of U.S. drivers drive less than 60 miles on weekdays [37] and this information will be assumed to be true for 2040 California drivers as well. Sixty miles is well within the driving range of a pure electric vehicle on a single full charge – even the tiny Smart EV delivers up to 68 miles on a full charge [38]. Now, the total projected number of automobiles in California 2040 was found to be 31 million, Table 1 of section 2.1.1, so based on the aforementioned infographic data and related

assumptions 31% of these automobiles will drive more than 60 miles on a weekday which translates to a total of 9,610,000 automobiles. But of the 31 million automobiles 22,281,720 will be plug-in hybrid electric vehicles and 8,718,280 will be pure electric. Therefore, a total of 2,702,667 pure electric vehicles will drive more than 60 miles needing a second battery charge additional to the assumed one they receive overnight at home. The average all-electric range of a typical (within a reasonable vehicle price) plug-in hybrid electric vehicle is estimated to be 26 miles. The PHEV can switch to using its gasoline engine when the battery is depleted, however it is assumed that for the 31% of the drivers what will run more than 60 miles on a given weekday, it is likely that they would aim for a recharge during the day and while at work to avoid using the car's gasoline engine and thus avoiding extra operating cost and unnecessary emissions. Therefore, a total of 6,907,333 plug-in hybrid electric vehicles may need to use a publicly available charging station giving a net total of 9,610,000 electric vehicles requiring a recharge at a public electric charging station in the state of California in 2040.

Charging times may vary depending on different aspects, such as the type of vehicle (PEV or PHEV), the vehicle's battery technology and condition, the battery's charging status (how depleted the battery is – the fuller the battery the slower the charging time gets), the charging method used, the grid's electricity capacity and current usage. Typically, as mentioned in previous sections a PEV achieves a full battery charge in 6 hours and a PHEV in about 3 hours using AC Level 2 charging. Moreover, as mentioned in 2.3.1, there are currently 2,821 public charging stations in the state of California giving a total of 8,678 charging outlets with an average ratio of 3 outlets per station. Therefore, for any given weekday assuming a 12 hour working period an electric charge station may provide charging for 6 PEV's or 12 PHEV's. Since the ratio of PHEVs to PEVs in California 2040 is nearly 3:1, and taking into account the

aforementioned assumptions, a charging station is able to charge a total of 9 electric vehicles on a given weekday. Based on these results, a total of **1,067,778 charging stations** need to be publicly available to adequately power the State's car fleet in 2040. From 2.3.1 there are 2,821 public electric charging stations currently in California and therefore based on this analysis 1,064,957 charging stations needs to be additionally built by 2040 resulting in 42,599 charging stations needed to be built per year during this 25 year model period. From 2014-2015 the State of California built 1,110 charging stations which indicates that in order to meet this goal the State has to increase its yearly installment of charging stations by a little more than 38 times. As the building and installment of each station comes with associated financial costs, the feasibility of this goal is dependent upon several factors, mainly including the effort to attract and convince the public to switch to these technologies. With an increased demand in electric vehicles, market share will increase reducing all associated costs – including the price of the vehicles themselves, the costs of the battery alone, the price of the charging stations and their installment – as manufactures will lower prices to meet the increased market demand. Moreover, as electric charging stations technology advances, faster and more efficient charging methods are being developed, such as the DC 'superfast' charger, mentioned in 2.3.2, which may come with increased prices – which are likely to fall with increasing demand as explained – but provides a very fast charging time (about 30 minutes) which could thus translate in a decreased number of charging stations needed to be built.

#### 4.5.2. ELECTRICITY CONSUMPTION

It is of paramount interest to estimate the energy required to power California's automobile fleet in 2040 which, based on this study, will be comprised solely by PEV's and PHEV's and compare that to the energy required to fuel California's automobiles in 2040 if they were all gasoline-powered.

Based on the information and assumptions listed in the previous section, 4.5.1, on a given day 31% of the total number of PEV's, that is 8,718,280 PEV's, will require two battery charges, with the rest requiring just one and the same ratio holds for the total number of PHEV's, translating to 22,718,280 PHEV's requiring a second charge on a given day. Now, based on most current data the average battery capacity of a typical PEV is estimated to be 24KWh and for a PHEV 8.5 KWh [39]. In other words, 24 KWh are required to fully charge an average PEV whereas 8.5 KWh are needed for a PHEV, respectively. Putting all this together, a net 797.26668 GWh of electricity are required to adequately power 2040 California's fleet on a given day, consisting entirely of PEV's and PHEV's, based on the aforementioned analysis and stated assumptions. Therefore for the entire period of 2040, the State of California will need to supply **291 TWh** of electricity - which corresponds to 80% of the State's projected electricity consumption in 2040 (Table 2) - to adequately power its automobile fleet, which consists of PEV's and PHEV's only.

Now, let us compare what would the energy demand to fuel California's automobile fleet if that consists entirely of gasoline-powered vehicles. Based on 2014 data, the State consumed 12.3 billion gallons of gasoline [40] which roughly translates to 517 gallons per automobile for that year. With 31 million automobiles in 2040, all of them assumed to be gasoline-powered in this

case and assuming all else kept equal, the State is expected to consume a total of 16 billion gallons of gasoline. Moving on, the energy content for a gallon of gasoline is  $1.3 \times 10^8$  Joules [41] which translates, through the necessary conversions, to 36.11 KWh/gallon. Therefore, the State will need to supply an equivalent total of **578 TWh** to fuel its entire automobile fleet, if this is comprised only of gasoline cars, in 2040.

**Table 17: Energy consumption of California’s automobile fleet in 2040, in TWh**

	<b>2040</b>
<b>Electric Vehicles</b>	291 TWh
<b>Gasoline Vehicles</b>	578 TWh

We therefore see that if all gasoline automobiles are replaced by electric vehicles, PEV’s and PHEV’s, in California 2040, the State may save 287 GWh, nearly 50%, in energy supplied to fuel its automobile by doing so.

#### 4.5.3. POWER STATIONS AND EMISSIONS

From section 2.2.1 it was projected that the electricity generation including net imports for California in 2040 will amount 386,507 GWh while the State’s electricity consumption was projected to be 364,089.6 GWh leaving an available net balance of 22,417.4 GWh or 22.4174 GWh. In order for the State to be able to reach the goal of 291 TWh (Table 18) and assuming that it cannot increase its imports, the in-state net electricity generation must be 268.6 TWh. Now, assuming that the State’s production power mix stays the same (Table 7) in 2040, the amount of electricity in TWh that each different energy source contributes to the net in-state

generation (which must equal the required 268.6 TWh) is calculated. Moreover, based on the available data on the in-state electricity generation by fuel type for 2014 [14] and the number of power stations for each energy source (Table 8), an average electricity production is estimated for a given power plant corresponding to each energy source. Based on all the above, the number of power plants needed to be built in 2040 to meet the 291 TWh goal while keeping the power production mix equal to the one for the year of 2014 is estimated. Results are given in the following table.

**Table 18: Number of Power Stations needed to be built in 2040**

<b>Energy Source</b>	<b>Power Plants to be built</b>
Hydro	58
Natural Gas	49
Biomass	28
Solar	82
Geothermal	8
Wind	7
Nuclear	2

It should be noted that coal power plants are excluded from this list as in 2014 they only contributed to 0.5% of the net power production and since they are linked to the production of the highest amount of emissions, the State is putting efforts to move away completely from this source of energy (also discussed in 2.1.3b). Moreover, since calculated numbers were rounded up in order to ascertain that the 291 TWh is met, this more than makes up for the ‘missing’ coal factor. For nuclear power, having the highest capacity factor among all the energy sources (83%,

Table 10), the lowest number of plants is required to be built while solar energy, on the other hand, having the lowest capacity factor due to mainly its seasonal nature, requires the highest number of additional power stations to be built in order to match its projected contribution to the net electricity generation needed to fuel California's automobile in 2040.

While, emissions from renewable sources – namely biomass, solar, wind and geothermal – and from nuclear plants are negligible, data shows that the average CO<sub>2</sub> emissions rate of a natural gas power plant is 1135lbs/MWh [42]. For the required 268.6 TWh energy demand which should be met by building additional power plants in 2040 and using the same production power mix as in 2014 – process explained in the same section further above – the total amount of electricity that should be generated by natural gas plants is estimated to be 164,652 GWh which thus translates to a total of 84,776,414 metric tons of CO<sub>2</sub> emissions. In section 4.2 it was calculated that if all vehicles on 2040 California roads are gasoline-powered the overall tailpipe emissions would be 134,943,300 CO<sub>2</sub> metric tons. Moreover, in the same section it was estimated that if all vehicles switch to electric cars in 2040 (PEV's and PHEV's) the overall tailpipe emissions would be 10,838,943 CO<sub>2</sub> metric tons. Therefore, if all cars are replaced by electric vehicles in 2040 the overall CO<sub>2</sub> emissions for the year, assuming the current production power mix which heavily depends on natural gas – which bears the associated CO<sub>2</sub> emissions - will be 95,615,357 (tailpipe emissions plus related emissions to power them) which results in about **40 million metric tons CO<sub>2</sub> reduction** if they were all gasoline. From the 95,615,357 million CO<sub>2</sub> tons, 87% comes from the power plants – the ones using natural gas as their primary source in this case – which supply electricity to fuel the State's automobile fleet.

#### 4.5.4 LIMITATIONS OF EV's

This section summarizes a few of the related limitations and concerns relating to electric vehicles and their associated technologies which are likely to hamper consumers' interest towards them.

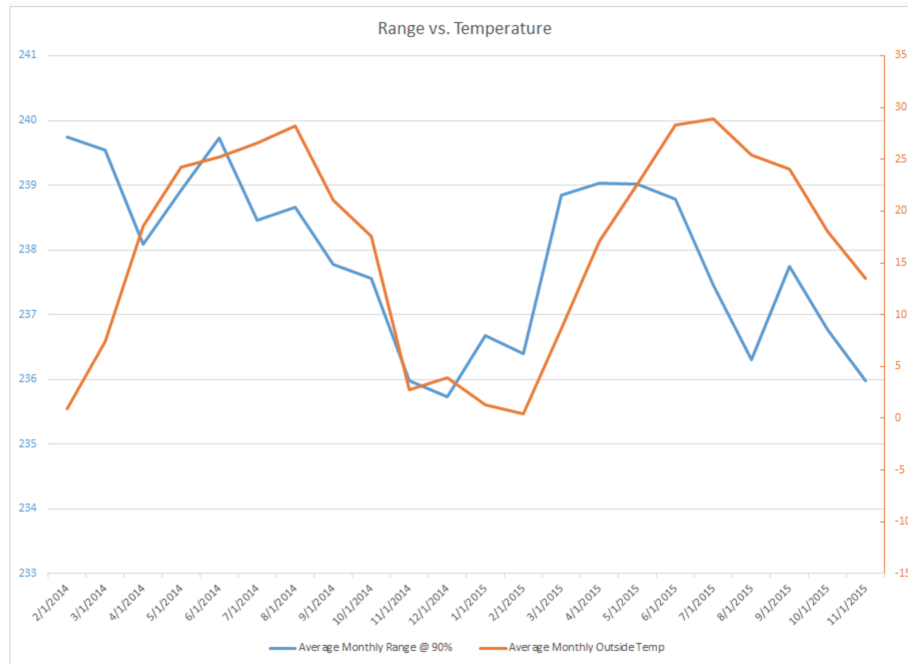
Current battery life and battery cost is one of them. With current battery life, as mentioned in previous sections, averaging around 8 years or 100,000 miles and its high average price amounting typically to 25% of the vehicle's total cost [43] and coupled with the fact that gasoline-powered vehicles are getting better and better fuel economy ratings, the average consumer is less likely to explore the option of electric vehicles as they might seem less cost effective. Adding to this, comes the worry of a significant portion of consumers who fear that the range of the EV's battery is short and might 'die' leaving them stranded in an uncomfortable scenario, what is known as 'range anxiety' [44].

Moreover, climate temperature conditions, driving faster, carrying loads and battery's age could further reduce the vehicle's driving age [45]. Mentioned earlier in this report, Miss Deborah Scott, owner of a Chevy Volt (a plug-in hybrid electric car), says that in very cold days (around 35 Fahrenheit degree or under) she would get 26 miles or maybe lower from the battery, while in spring season she can get approximately 50 miles in electric range [4]. In addition, she observes that extra energy is needed to be spent to keep her car's interior warm, and as there is no engine, the outside of the car remains very, very cold. Under very cold weather the car will use power to keep the battery warm enough [4]. She further notes that when the battery is running low the user can feel the vehicle's response to be more sluggish.



Charging data from a Tesla owner reflecting range after charge further indicates the ‘seasonality’ in the battery’s range, which as it is shown below is depended on ambient temperature.

**Figure 11: Range vs Temperature, Tesla owner personal usage data [46]**



The red line represents average monthly outside temperature whereas the blue line represents average monthly range at 90% charge level. The two lines follow the same trend suggesting a direct relationship between ambient temperature and battery’s effective range, further facilitating the aforementioned comments on battery’s performance.

Another major issue is the current infrastructure and charging station availability. Section 2.3.1 discussed on current available public charging stations and outlets across the nation and as suggested by Figure 5 there is a rather scarce supply of publicly available charging stations in States located in the middle of the country with most of the existing charging stations being shared among the east and west coast. “With a range of 60 to 100 miles on one charge, it was too much of a risk to drive the car out West like a traditional gas car. During the trip, we could go

days without seeing an electric charging station”, an owner of an electric Nissan Leaf reports. She further notes, “The trouble is, those are fewer and farther between than you’d expect; you’d think they’d be everywhere” [47]. “I think one of the biggest challenges facing the industry is how to get charging infrastructure” [47] states Cal. Lankton, director of global EV infrastructure for Tesla Motors. He adds, “We have to adopt our infrastructure policy to meet the needs of consumers” [47]. Another EV user states “we do not have a range issue, we have a charging issue” [45]. He made a 3,500 mile trek in 44 days using his electric Zero DS motorcycle which is nearly ten times longer than someone using a gasoline-powered motorbike would have done.

Overall, the infrastructure/charging station availability seems to present a ‘chicken and the egg’ scenario. Consumers will stay reluctant to purchase EVs without knowing they can conveniently recharge their vehicles, while manufacturers will not install charging stations until they know they can make profits from consumers utilizing the stations.

#### 4.6 SOCIAL/UNINTENDED CONSEQUENCES

As electric vehicle usage increases, so will the job opportunities associated with supporting EVs. Vehicle repair, maintenance of charging stations, and various other new jobs will emerge and may contribute in reducing the overall unemployment rate in the United States. There is also the view, though, that the electric car will realize only modest scale economics in that, as a car, it already is a largely mature product and that after all it does not stop being an energy device which can thus expect to benefit from marginal efficiency enhancement [48].

Skeptics on the actual benefits that electric vehicles are believed to bring, both on a personal and on a more general societal level, protest that taxpayers' money should not be used to subsidize the hobby of 'the few' [49]. Moreover, this federal 'war', as characterized by Robert L. Bradley Jr. in his article 'The cost of demonizing carbon', against consumer-chosen fossil fuel energy to promote 'green' energies survive will have a great impact to the free-market energy – oil, gas and coal – the bright spot of the American economy supporting 9.8 million American jobs and paying \$200 billion in direct wages to U.S. employees and is expected to create another one million new positions over the next 10 years [49].

## V. CONCLUSIONS AND RECCOMENDATIONS

This study looked at future California 2040, 25 model years from now, when it was assumed that all automobiles will have been replaced by electric (PEVs and PHEVs) vehicles only. Certain assumptions were needed to be held in order to forecast various types of data, essential to the process of obtaining related results.

Results showed that the annual cost of operating a PEV or a PHEV, in California 2040, is 3 to 4 times as low compared to a gasoline-powered car, not including battery's replacement cost. Furthermore, it was estimated that the cost to fuel California's automobile fleet in 2040 would be half of that required had there been only gasoline-powered vehicles on the roads of California. The study also calculated the net tailpipe emissions of all automobiles in 2040 for the two cases where in the first case they are all electric (PEVs and PHEVs) and in the second they are all gasoline-powered.

It was found that if California switches to electric vehicles it would reduce its CO<sub>2</sub> emissions by 40 million metric tons. The number of power stations needed to be built to meet the electricity demand to power the State's automobile fleet in 2040 was estimated by the type of energy source the plant uses, assuming the State's power production mix is the same between now and 2040. However, as the State is expected to increasingly keep moving towards renewable sources, in order to meet its goal of reducing its emissions by 80% of 1990 levels, California is likely to reduce even further the projected 40 million metric tons of CO<sub>2</sub> emissions. Moreover, should the State decide to resort to using nuclear sources of energy more widely in the future, not only it will be able to reduce substantially its CO<sub>2</sub> emissions but also will need to build far fewer plants due to the very high capacity factor nuclear source brings into the mix.

Another great challenge that the State will need to overcome in order to accommodate the transformation of its future, 2040, automobile fleet into an electric-based one (consisting solely of PEV's and PHEV's) is the construction and installment of a great number of charging stations. Specifically, based on the stated assumptions, it was estimated that the State will need to build on average 42,599 charging stations per year in the period 2015-2040 a rate 38 times higher to the one between 2014 and 2015. However, with developments in charging technology in combination to an increased demand for electric vehicle technologies the number of required charging stations may decrease along with the cost of their construction.

Through this study, overall, it is apparent that the benefits that EV's bring, assumed not only on a personal for the consumer level but also for the general well-being, are significant. However, major steps need to be taken towards battery technology and charging planning and infrastructure. But, since a free market is dictated by the economic laws of supply and demand, it is equally important that consumers' view on these technologies must change in order to propagate such revolutions. On a more individual level, I believe that it is duty of us all to be as adequately aware of these, and any developing, technologies in order to be able to make responsible, to ourselves, the others and the planet, decisions.

*'The more you know, the less you need'.*

-Yvon Chouinard

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## Appendices

### A. Interviews

Interviews were conducted in cooperation with Khoa Nguyen.

#### **1. Interview with Miss Deborah Scott**

Ms. Scott purchased her Chevy Volt (a 2012 model) in December of 2011 in California at cost of \$39,000. The Chevy Volt is a hybrid car, which means that it can run using power both obtained from its battery and its gas engine. However, the gas tank is not connected to the drivetrain, but is there to provide extra power when the battery is running low or to completely take over when the battery is empty. When the battery is running low the user can feel the vehicle's response to be more sluggish. After a full charge, the Chevy Volt has a range of 40 miles on average by just using its battery. After attending the Seminar by the director of R&D at A123 systems, we recognized how temperature affects the battery's performance (very low and very high temperatures). That is the reason we specifically asked Ms. Scott if she notices any difference in her vehicle's performance and available mile range in very cold days. She said that in very cold days (around 35 Fahrenheit degree or under) she would get 26 miles or maybe lower from the battery. During spring season, she can get approximately 50 miles. In addition, extra energy is needed to be spent to keep her car's interior warm, and as there is no engine, the outside of the car remains very, very cold. Even when the car is charging or after is fully charged but not operating, under very cold weather the car will use power to keep the battery warm enough.

We also asked her if she has noticed any difference in her battery's performance (range, life cycles, charging time) since she first bought it compared to now, but since her battery is so new she said that it has been the same. At WPI, and in various public places, she charges her vehicle

at 240 Volts output which translates up to 4 hours for the vehicle to be fully charged. At home, she uses 110 Volts and therefore needs about 8 hours for full charge. So far she has not had any maintenance costs besides the typical ones (change of tires).

On average she pays \$20 dollars a month to charge her vehicle at home (as she can deduce from her monthly electric bill). Ms. Scott believes that it is very important and beneficial for charging stations to be located where she works, as in that way she manages to commute from her house to work using only the battery, and thus saving gas money and reducing emissions. She charges her vehicle once at WPI and once at home overnight unless she has to travel where she would use one of the public stations (which she can locate through a phone application) many of which she does not have to pay for besides the normal parking fee for occupying the spot. When I asked her if she has realized a difference in cost in operating a hybrid vehicle compared to a gasoline vehicle she said that she estimates that now she saves approximately \$200 dollars a month (which would go towards paying for gasoline) which translates to the considerable amount of \$2400 a year.

Her overall experience with the Chevy Volt hybrid has been very satisfactory. She particularly likes how the driving and performance feels (a very strong and responsive car), how the technology is so well integrated allowing her to communicate with her car and do certain functions remotely using just her smartphone (like turning the heating on prior to entering the car so that it is already warm for when she gets there) and, of course, that she is being environmentally considerate. However, she does not like that the car is a 4-seater since the battery occupies a lot of space in the back of the car and the car remains very cold on the outside since there is no engine to keep it warm.

## **2. Interview with Professor John Orr**

From our meeting with Professor Orr, we obtained some more technical information on the specifics of how electricity transmits from the generator in the factory to the charging station that is directly connected to the electric or hybrid vehicle. A mechanical (usually rotating) device, called the generator, is used in the factory to generate the electricity and from there it passes through a transformer and a transmitter where its voltage ranges between 69 and 500 kV. Then it passes through another transformer which lowers the voltage somewhere between 6 and 50 kV, the typical value is 13.8 kV, to end up to a distributor. From there it passes through another transformer which brings it down to 120V, 240V or 480V depending on the type of the charging station and then it is used to charge the vehicle. Therefore, one very important consideration is how to minimize transmission losses while delivering high power. They are estimated to be on average about 10% from end-to-end (so from the output voltage value of the generator to the output transformer value of the charging station). The 480V, being at a higher voltage, gives out more power than the rest of the voltage output values. Some other topics that came up from our discussion with Professor Orr was the ‘Smart Grid’ which refers to the effort to reduce generating stations and replacing them with distributors. Also the efficiency of the charger in its connectivity with the battery. How to store the energy efficiently using a pump hydro and a reservoir located on a hill in which case the potential energy of the falling water is used to generate electricity. Also environmental concerns arise with issues like producing the battery, disposing of it, and, of course, generating the electricity for it. One thing is for sure, as Professor Orr says, that if the electricity for the battery comes from a coal-powered plant then it is ‘dirtier’ than simply using gasoline vehicles.

### **3. Interview with Miss Liz Tomaszewski**

From our meeting with Ms. Liz Tomaszewski we obtained the following information based on our questions. There are currently two fully functional EV charging stations located on the WPI campus. They are both duals, meaning that each has two parking positions so that two vehicles can use the station to recharge at the same time. However, not all four spots are active (or live) so there are three spots, in total, available for recharge use. The first charging station, located next to Goddard Hall, was built in April of 2012 from Coulomb Manufacture and the second one which is located at parking garage on Park Avenue was introduced to the campus in January of 2013 and was made by the same manufacturer. WPI received a grant which covered the infrastructure, implementation, maintenance, and any charging costs for those two charging stations and therefore the user is not required to pay anything for using the station . Both stations have similar technical specifications (AC Type 2) with a charging output of 240 volts which translates to an average time of four hours to fully charge an electric vehicle. The two charging stations are not connected with each other; however they do use the same electricity grid.

The daily power consumption to use the charging station, according to Ms. Tomaszewski's estimations, is \$0.65 per user , and is considered a negligible amount which further justifies the fact that no charge fee is required from the user. Also, note that the charging stations are available to the whole public and not just the WPI community.

Now, when it comes to organizational issues and whether or not they EV owners are able to always use the stations, the statistics (obtained from a special application by chargepoint which shows relative daily usage, trends in the usage of the charging stations and other useful data) show that WPI is on average at half capacity and has never been on full capacity. What this practically means is that on a daily basis, for example, an average of two people will use the

charging stations. Therefore, as Ms. Tomaszewski says there is no current need to open up the fourth available charging spot. Through the *Chargepoint* network EV users are able to be informed when their vehicle is done charging. Finally Ms. Tomaszewski says that in case demand rises then the fourth charging spot will be available, and if it is further needed a new charging station will be implemented (a superfast one is also a possibility). However, there have been occurrences where non-EV's have been found to be occupying charging spots. Those instances fall under the campus police authorities to give tickets and maintain order. Last but not least, after our request on the specific daily (permanent) number of EV's that use the WPI charging stations, Ms. Tomaszewski contacted WPI police which informed her that there is only one registered (a Chevy Volt).