



The impact of plug-in vehicles on greenhouse gas and criteria pollutants emissions in an urban air shed using a spatially and temporally resolved dispatch model

Ghazal Razeghi, Tim Brown*, G. Scott Samuelson

Advanced Power and Energy Program (APEP), University of California, Irvine, Irvine, CA 92697-3550, United States

ARTICLE INFO

Article history:

Received 27 May 2011

Received in revised form 4 August 2011

Accepted 6 August 2011

Available online 16 August 2011

Keywords:

Plug-in

Dispatch

Charging scenarios

Emissions

ABSTRACT

With the introduction of plug-in vehicles (PEVs) into the light-duty vehicle fleet, the tail-pipe emissions of GHGs and criteria pollutants will be partly transferred to electricity generating units. To study the impact of PEVs on well-to-wheels emissions, the U.S. Western electrical grid serving the South Coast Air Basin (SoCAB) of California is modeled with both spatial and temporal resolution at the level of individual power plants. Electricity load is calculated and projected for future years, and the temporal electricity generation of each power plant within the SoCAB is modeled based on historical data and knowledge of electricity generation and dispatch.

Due to the efficiency and pollutant controls governing the performance of the Western grid, the deployment of PEVs results in a daily reduction of greenhouse gases (GHGs) and tail-pipe emissions, especially in the critical morning and afternoon commute hours. The extent of improvement depends on charging scenarios, future grid mix, and the number and type of plug-in vehicles. In addition, charging PEVs using wind energy that would otherwise be curtailed can result in a substantial emissions reduction. Smart control will be required to manage PEV charging in order to mitigate renewable intermittencies and decrease emissions associated with peaking power production.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

It is projected that the world's energy consumption and electricity generation will increase 44 and 77 percent respectively from 2006 to 2030 [1] and that conventional vehicles will still be the dominant on-road fleet over the next two decades [2]. In 2006, the transportation sector accounted for 22 percent of worldwide energy consumption [1] and 20 percent of greenhouse gas emissions [3]. In California, transportation is responsible for roughly 50 percent of energy use and 40 percent of greenhouse gas emissions [4,5]. Another major contributor to greenhouse gases and criteria pollutants emissions is electricity generation that accounts for 28 percent of the total greenhouse gases in California, second only to transportation. The concerns regarding global climate change, air pollution, and high energy prices give rise to increasing demand for strategies to shift to alternative, low, or non-carbon based energy systems, from electricity generation to vehicles.

Plug-in Electric Vehicles (PEVs) represent one of the numerous strategies under consideration. These include both plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs). The

use of PEVs can reduce tailpipe emissions but will impose an additional load on the electricity grid, resulting in increased emissions from electricity generation. Existing studies suggest that PHEVs have a net emissions benefit over both conventional [6] and (non-plug-in) hybrid electric vehicles (HEVs) [7], and that the extent of improvement depends on the electricity grid mix [8], and timing and pattern of charging [9]. To analyze emissions impacts, these studies have used one of the following three grid scenarios:

1. an average grid mix [10,11],
2. the marginal generation technology (i.e., assuming that the electricity required to charge the vehicles is provided by one technology that comes online last) [12,13], or
3. the temporal dispatch of generation resources based on historical data [14].

This research develops and applies a dispatch model which is both spatially and temporally resolved. The necessary inputs of the dispatch model are introduced and calculated first, followed by a detailed description of the methodology. The model developed is then used to (1) provide a base case for year 2050 and (2) establish the effects of deploying PHEVs and BEVs on the well-to-wheels pollutant emissions, especially NO_x , and CO_2 , for a future year

* Corresponding author. Tel.: +1 949 824 0088; fax: +1 949 824 7423.
E-mail address: tmb@apep.uci.edu (T. Brown).

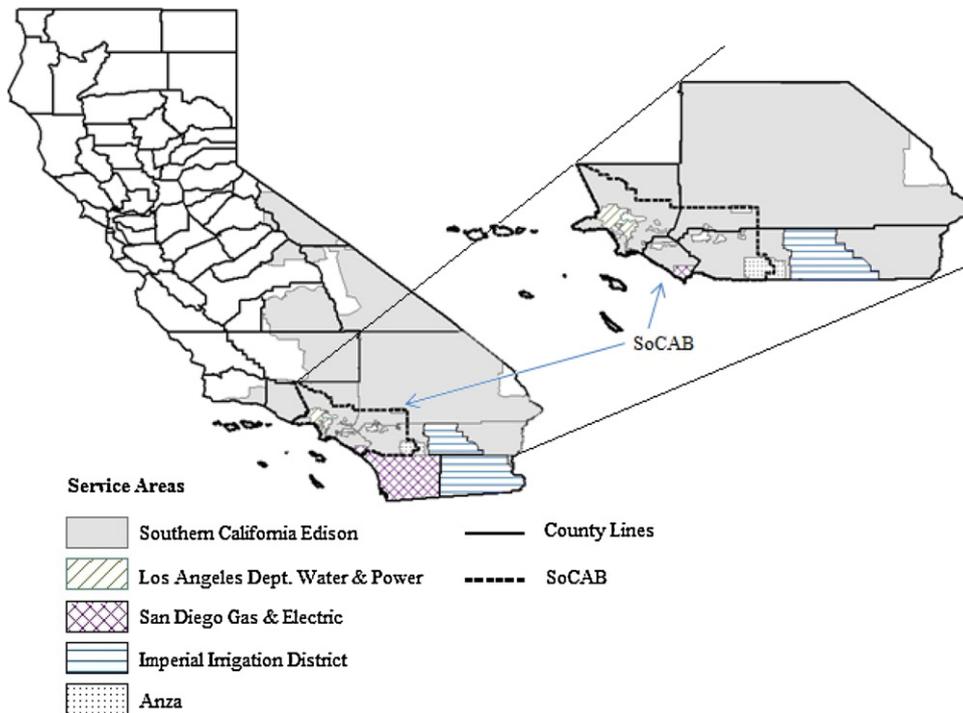


Fig. 1. Map of State of California, SoCAB and major utilities serving the area.

(2050). The major urban air shed selected for the study is the South Coast Air Basin in southern California (Fig. 1).

2. Modeling methodology

2.1. Electricity demand forecast

To study the air quality impacts (e.g., ozone, particular matter) of deploying PEVs today or in the future, spatially and temporally resolved criteria pollutant emissions are required from both mobile and stationary sources, including power plants. The first step in modeling the grid for emissions is to determine how the electricity output of each power plant changes with respect to the electricity load. Time resolved load data are not available for all generating entities within the SoCAB. As a result, it is assumed that the electricity demand is directly proportional to the population residing in the study area. This assumption is based on various California Energy Commission (CEC) reports projecting almost constant electricity consumption and peak demand per capita for the state of California [15].

Based on this population assumption, the hourly electricity demand for the entire SoCAB region can be calculated from the Southern California Edison (SCE) and San Diego Gas & Electric

(SDG&E) hourly load, which is publicly available [16]. The results are illustrated in Fig. 2 for the year 2005.

High summer electrical loads generally correspond to heavy use of air conditioning in response to extreme heat. A high load results in an increase in power generation and can lead to a “peak” hour of generation for a given year. The electricity generation profiles for the peak and average days of 2005 are presented in Fig. 3.

In order to study the impact of PEVs in the future, the electricity demand for a future year (2050) is projected based on historical trends and the following assumptions:

- (1) The electricity consumption per capita in the SoCAB remains unchanged over the next four decades and is equal to that of the entire State of California [15].
- (2) The population growth rate in the SoCAB is equal to that of the State of California [17].
- (3) The increase in hourly load is the same as the average electricity demand growth rate for that year.

Based on the first two assumptions, the annual growth in SoCAB’s demand from 2005 can be deduced using projected population. For example, in the year 2050, SoCAB’s annual electricity load is projected to be almost 61 percent more than it was in 2005. Further, it is assumed that the load growth rate for each hour is

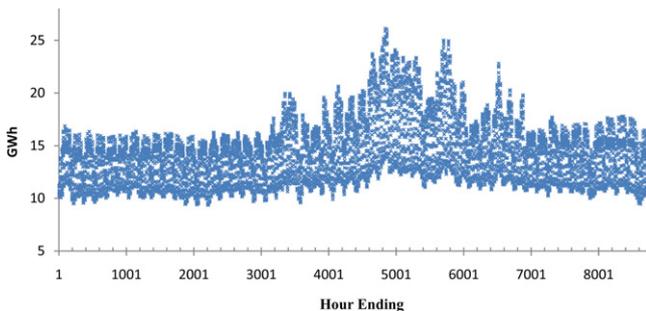


Fig. 2. SoCAB's 2005 hourly electricity load.

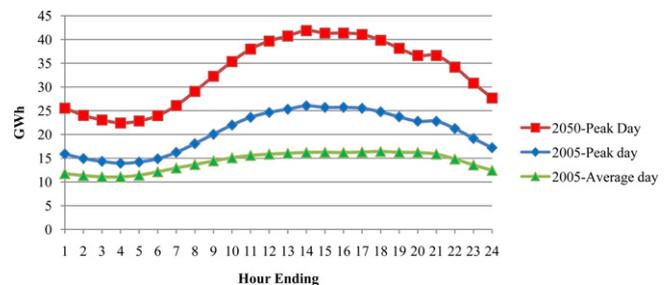


Fig. 3. SoCAB electricity demand.

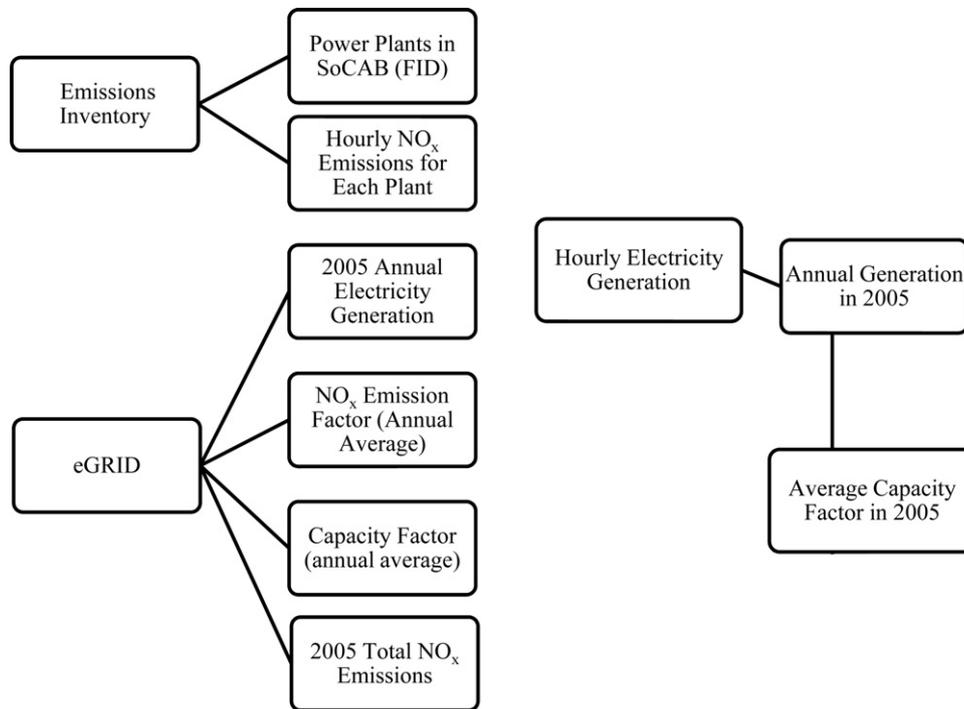


Fig. 4. Calculating the electricity generation from the emissions inventory.

constant and the same as the annual average (i.e., the SoCAB load for each hour for a specific day in 2050 is 61 percent more than the load at that same hour of the same day in 2005 as shown in Fig. 3).

2.2. In-basin generation

In order to model future electricity generation, it is necessary to (1) establish the manner by which power plants are operated today, (2) establish a trend based on historical data, (3) model the electricity outputs of each power plant in the future, and (4) determine the important factors affecting the different modes of operation.

An emissions inventory, generated for the 2007 Air Quality Management Plan by the South Coast Air Quality Management [18], includes emissions from both stationary and mobile sources for the year 2005, and CO, NO_x, SO_x, TOG and TSP emissions from each source for the entire year with a time resolution of 1 h. Using the Facility Identification (ID) codes, the name of each emission source can be determined [19] and, based on the SIC code corresponding to each source [20], those with primary function of electricity generation can be selected. () On-site self-generation facilities are excluded because they are not included in the electricity demands reported by SCE or CEC.

With the emissions from the emissions inventory and emission factors from the U.S. Environmental Protection Agency (EPA) which can be obtained from eGRID [21], the hourly generation of each power plant can be determined. The calculations are based on NO_x emissions because it is amongst the most important pollutants and is monitored at the majority of the power plants. Fig. 4 is a flow chart summarizing the process of calculating the hourly electricity generation from the emissions inventory.

For each power plant in the inventory, the electricity generation for the peak day of 2005 is calculated on an hourly basis, and by adding together the electricity outputs of power plants in a specific hour, in-basin generation for that hour is determined. It should be noted that hydro power plants are included in the dispatch model in order to accurately account for all power sources, even though they do not contribute any emissions.

It is improbable that the in-basin power plants generate the same amount of electricity every day with the same daily profile as revealed by the emissions inventory. It is noteworthy that the purpose of this inventory, in support of the Air Quality Management Plan, is to model an “episode day,” namely where the emissions and meteorological circumstances result in the worst air quality impacts. As a result, the inventory does not indicate how the in-basin plants actually operate throughout the year. In this study, a dispatch model is developed to provide the needed insight.

As a first step in the development of the dispatch model, a graph of capacity factor versus “total generation”¹ is constructed for each in-basin power plant, including hydro plants, based on the data derived from Energy Central [22] which is an online database including power plants’ generation data from 1998 to the present. Each power plant is identified as either a baseload, peaking or intermediate (load-following) unit. The dispatch model is developed so the emissions on the peak day of 2005 are consistent with the AQMD’s emissions inventory.

2.3. Electricity imports to SoCAB

Having calculated the in-basin electricity demand and the in-basin generation, the electricity imports to the SoCAB can be derived from the difference between the two; the results are depicted in Fig. 5. The figure also shows the linear relationship (coefficient of determination 0.96) between the power imported to the SoCAB and the demand within the basin, which implies that the imports serve primarily to provide load-following power. The corresponding conclusion is that the generation within the SoCAB acts almost entirely as baseload, constant generation.

¹ Total Generation accounts for the losses between the generation site and consumer which is between 7–12 percent for the state of California [23].

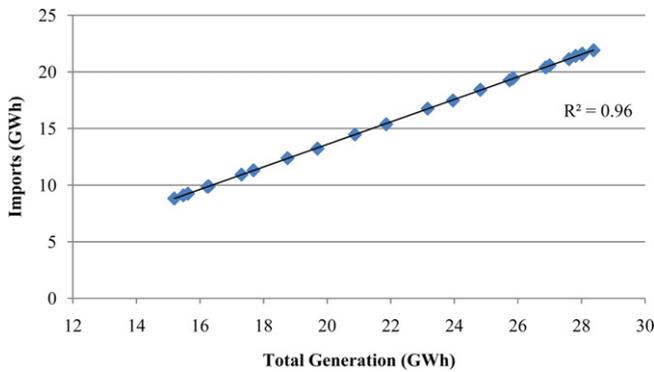


Fig. 5. Relationship between electricity imports to SoCAB and total SoCAB generation for 2005.

2.4. Dispatch model

The electricity load increases significantly (61 percent) from 2005 to 2050 and Fig. 5 suggests a corresponding significant increase in imports. However, the State of California is currently facing transmission congestion, reliability challenges, and higher costs related to insufficient transmission infrastructure [24], all of which threaten the integrity of the electrical system and the health of the economy. As a result, new transmission infrastructure is required to transport the higher imports to the SoCAB in the future. This notwithstanding, several obstacles prevent building transmission infrastructure fast enough to keep pace with the demand. These obstacles include: securing environmental permits and rights-of-way, securing regulatory approval for publicly-owned utilities and federal agencies, and local opposition due to visual and environmental impacts, as well as concerns about property values.

Due to slow development of transmission infrastructure with respect to demand, as well as the goal to model a worst case scenario for the SoCAB air quality, it is assumed that no new transmission lines are added to the current system and, as a result, the extra electricity generation needed to support the future demand is generated within the basin.

On the peak day, the capacity factors of the majority of the power plants within the basin are higher than their annual averages indicating that the in-basin generation is also at its maximum on the peak day. During heavy summer peak load periods, critical transmission paths in the state are often constrained [22], indicating that the transmission system is near saturation on the peak day. As a result, the capacity of the transmission system in this modeling is set equal to the maximum amount of imports on the peak day, which can be derived from Fig. 5. This capacity is kept constant for future peak day scenarios.

The electricity generation of each individual in-basin power plant is calculated for each hour of the 2050 peak day using the projected demand for that day. Assuming that the transmission system capacity remains unchanged, the maximum dispatchable electricity based on 2005 data will be the sum of electricity outputs from all in-basin power plants for a specific hour and the maximum allowed imports (transmission constrained). The difference between this available electricity generation and the generation required to support the demand indicates the amount of electricity that will need to be provided by in-basin units installed after 2005.

Assuming a maximum capacity factor of 0.95 for the generating units, 14.5 GW of capacity is added to the in-basin power plants. This 14.5 GW consists of 12 GW of non-peaking and 2.5 GW peaking units. This combination is chosen to ensure that the intermediate units have an annual average capacity factor of at least 30 percent, and the peaking units 10 percent or less, which matches historical trends. All the 12 GW non-peaking units are assumed to

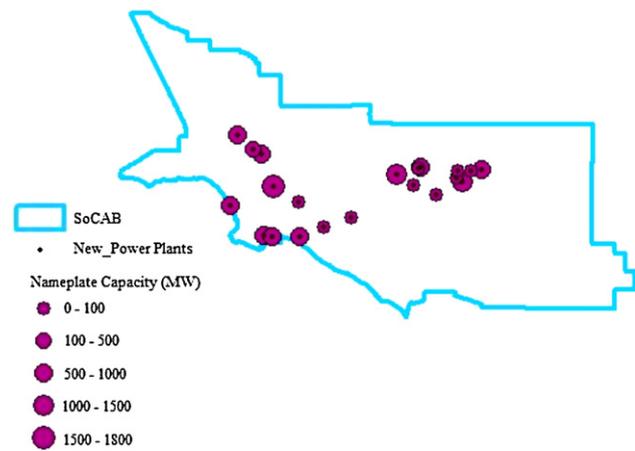


Fig. 6. Predicted location of power plants and their nameplate capacities (MW) required to meet 2050 demand.

be natural gas combined cycle power plants due to the high efficiency compared to other types of power plants and the peaker units are assumed to be natural gas combustion turbines. To determine the appropriate locations for installing the new generating units, the locations of recently retired power plants along with those that reduced their capacities due to retirement of one or more generators are taken into consideration along with land-use and permitting considerations. The locations of newly installed power plants are shown in Fig. 6.

In order to add the newly installed power plants to the dispatch model, it is necessary to establish a strategy for operating these units. Peaking units in the future are assumed to be operated in the same manner as the peaking units are operated today. In particular, peaking units come online at times of peak demand or when the increase in demand occurs suddenly and other units are not capable of ramping up in time. As for the non-peaking units, these units are operated as intermediate power plants.

It is necessary to mention that in this model, generators are retired after they have been online for fifty years and are replaced by generators with the same power capacity but with adjusted emission factors for the time of replacement.

Fig. 7 shows the generator dispatch strategy and order. Base-loading units are dispatched first, followed by intermediate units. The older, existing intermediate units are dispatched before new ones are added to ensure that first the existing capacity is utilized. Next, the model dispatches imports and in-basin peaking units if necessary to provide the electricity demand of the area. If the demand still outpaces generation, the model adds additional combined cycle facilities and restarts from the beginning.

3. Results

3.1. 2050 base case results

Emission factors corresponding to different pollutants for existing units are available. To calculate the criteria pollutants and GHGs emitted from the newly installed plants, emission factors associated with these generators need to be determined first. Knowing the fuel, the emission factors associated with that fuel (kg kJ^{-1}) and the heat rate of the system (kJ kWh^{-1}), the emission factors of the whole system (kg MWh^{-1}) can be derived. Natural gas is chosen as the primary fuel for all the new power plants. The emission factors associated with natural gas can be extracted from the EPA emission factors reports [25]. In order to include the advancements in technology that might occur in the future, and thus increase the efficiency of combined cycle systems and combustion turbines, a

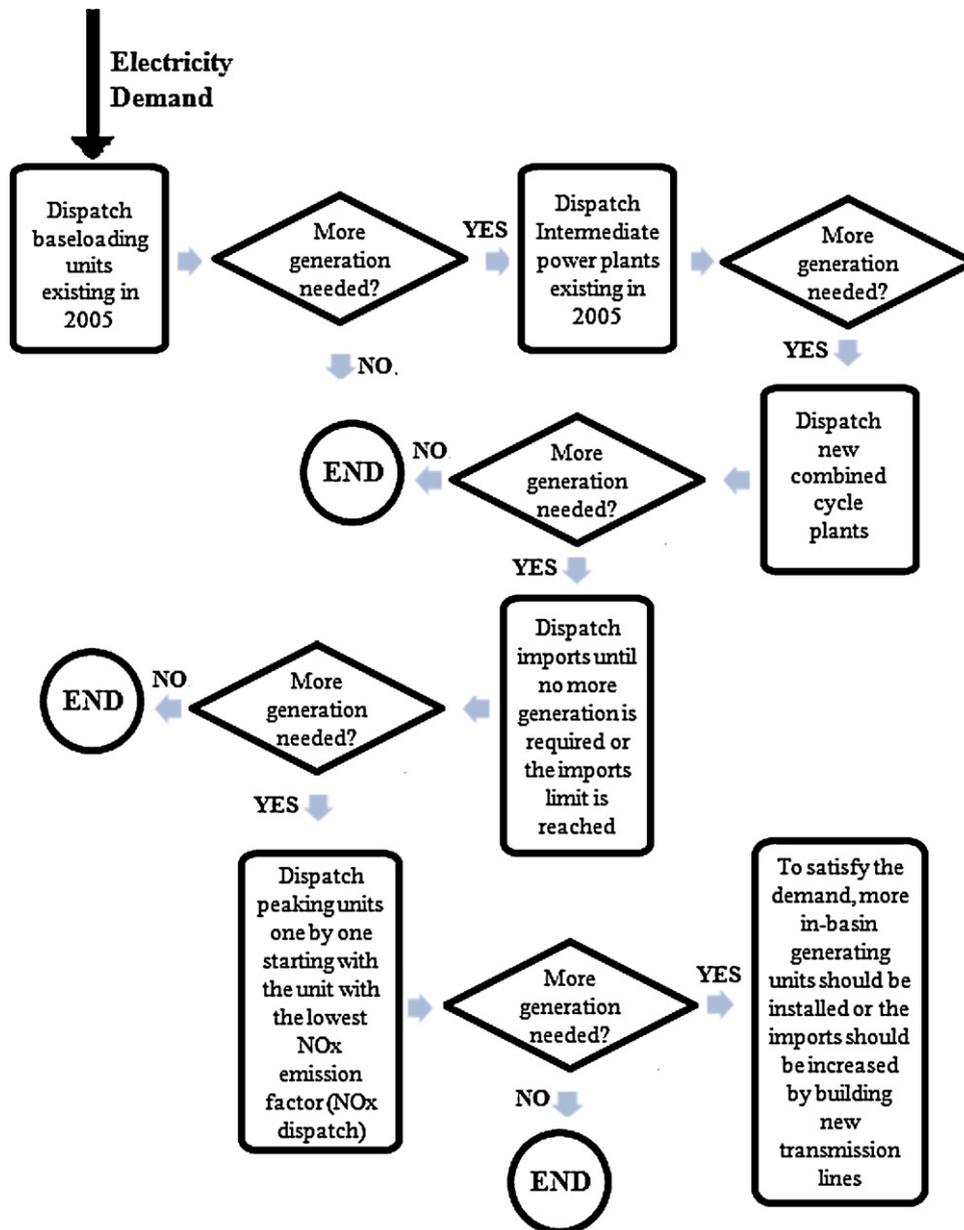


Fig. 7. Dispatch model flow chart.

projected efficiency of 65 percent is used for combined cycle systems without carbon capture and sequestration and 57.5 percent for combustion turbines [26]. The efficiencies of today's state-of-the-art plants are 59 and 33 percent, respectively [26].

Fig. 8a and b illustrates the amount of NO_x in kilograms emitted from each individual power plant at 5 am and 5 pm on the peak day of 2050 (basecase) respectively, demonstrating the spatial resolution of the methodology.

3.2. Impacts of PEVs in 2050

Replacing light-duty conventional vehicles with PEVs reduces the tailpipe emissions related to the transportation sector; however, it imposes a new load on the electricity grid and gives rise to increased emissions from power plants. In order to assess the impacts of PEVs on criteria pollutant and GHG emissions, the changes in emissions both from the transportation and electricity generation sectors must be evaluated in combination.

To determine the electricity load associated with PEVs and concomitant emissions, for each case based on the charging scenario, vehicle type (BEV or PHEV) and the penetration in the light-duty fleet, the temporal electricity demand of the PEVs are calculated and added to the base-case electricity demand. This overall electricity demand is used as the input to the dispatch model for the year 2050.

To calculate the impact on emissions resulting from replacing conventional vehicles with PEVs, characteristics of the future vehicle fleet including fleet size, emission factors for both conventional and PEVs, daily vehicle miles traveled, and the travel distribution throughout the day must first be determined. The California Air Resources Board's EMFAC [1] model projects the necessary data for future years up to 2040. Beyond roughly 2030, the vehicles emission factors approach asymptotes signaling physical and technological thresholds. To derive 2050 vehicle fleet characteristics, EMFAC's model outputs for 2040 are extrapolated. Due to the asymptotic nature of the emissions, the 2050 factors are nearly identical to those in 2040. PHEVs with a 60 km all-electric range are assumed

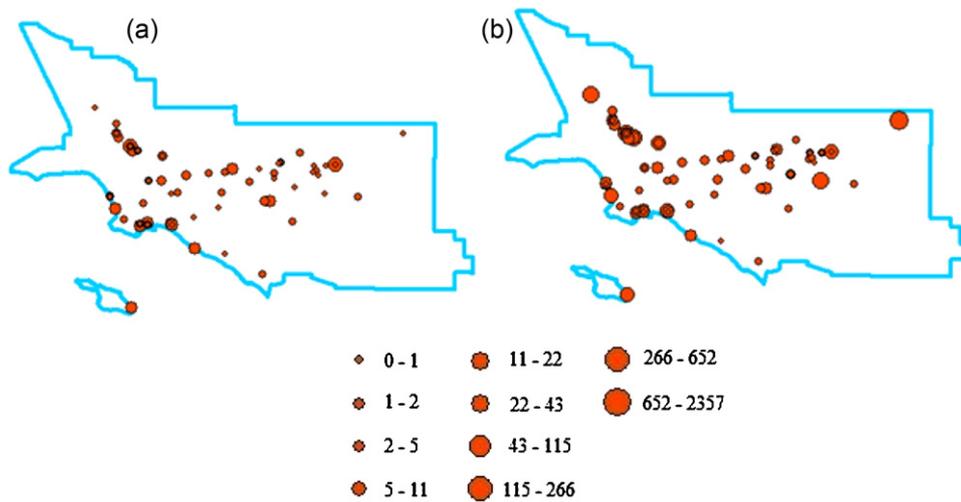


Fig. 8. NO_x (kg) emitted from each power plant during the peak day of 2050: (a) 5 am and (b) 5 pm.

and the associated emissions are calculated using a curve describing statistical driving behavior [27], the latter of which suggests that 70 percent of vehicles in Southern California are driven today less than 60 km per day.

Two particular charging profiles are considered – “business as usual” and “off-peak” charging – which have been used in previous studies [14,28]. The “business as usual” scenario assumes that both workplace and home charging are available and no incentives are in place to shift the charging towards off-peak hours.

The amount of electricity consumed by PEVs depends on the type of vehicle and the penetration in the light duty vehicle fleet. Various studies [29–31] suggest that 40 percent penetration of PHEVs in the light duty vehicle fleet for the year 2050 would be reasonable for Southern California. Fig. 9 shows the electricity required for four separate 2050 scenarios, 40 percent PHEVs charging with the “business as usual” behavior, 40 percent PHEVs charging with an “off-peak” strategy, 40 percent BEVs charging with the “business as usual” behavior, and 40 percent BEVs charging with an “off-peak” strategy.

Figs. 10 and 11 illustrate the effects of different charging profiles for PHEVs and BEVs on the grid’s NO_x emissions, and well-to-wheels NO_x emissions on the peak day of year 2050, respectively. These results show that deploying 40 percent PHEVs and 40 percent BEVs will result in a 6 and 22 percent reduction in NO_x emissions on the peak day, respectively.

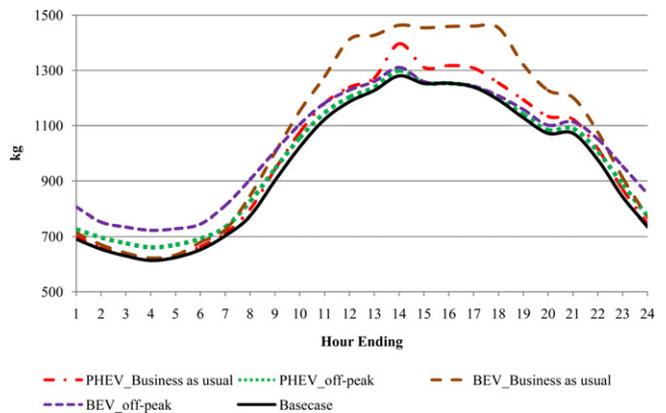


Fig. 10. NO_x emissions associated with in-basin electricity generation.

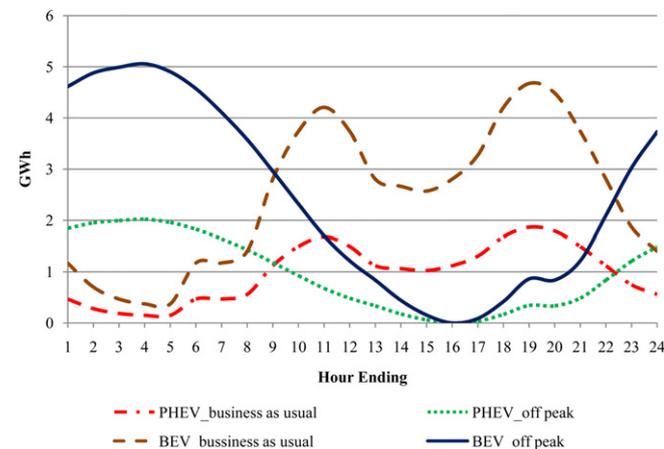


Fig. 9. Year 2050 electricity demand of PEVs with 40 percent penetration.

Fig. 12 shows the 2050 annual GHG emissions associated with different penetrations of PHEVs and BEVs and various charging profiles. The analysis shows that annual greenhouse gas emissions are reduced 7 and 25 percent corresponding to 40 percent penetration of PHEVs and 40 percent penetration of BEVs, respectively.

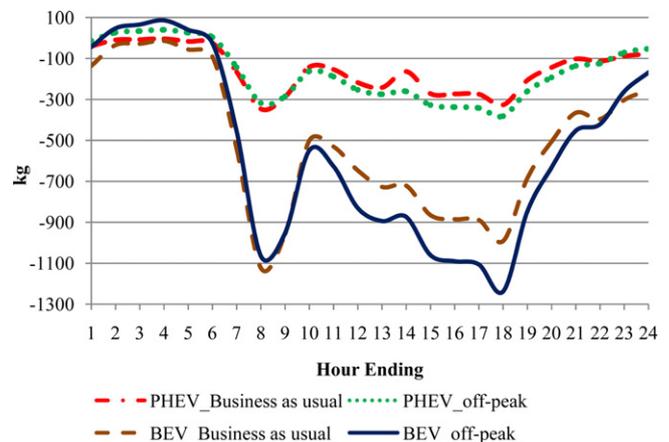


Fig. 11. Change in well-to-wheels NO_x emissions for 40 percent penetration of PEVs compared to a fleet composed entirely of advanced gasoline vehicles.

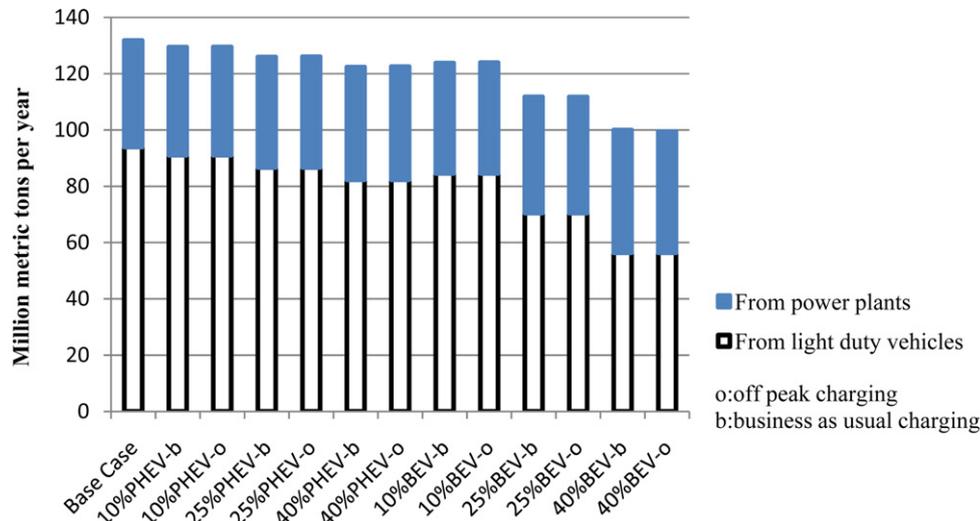


Fig. 12. Annual GHG emissions for different scenarios in 2050.

4. Discussion

This study has developed and applied a detailed dispatch model in order to characterize the hourly operation and emissions of power plants in the Western Grid. The goal was to establish the impact of PEVs, as a function of hour, on the overall emissions (tailpipe plus electricity grid) in a future year (2050) when a substantial population of PEVs would likely be deployed.

From the analysis above, the deployment of PEVs results in emission benefits at all hours of the day using the “business as usual” charging profile. For the “off-peak” charging scenario, the addition of PEVs results in an emission increase in the first 6 h of the day due to the large number of vehicles that are connected to the grid, and a small reduction from the transportation sector because of the low vehicle miles traveled at these hours. During the rest of the day, the net emissions decrease and the overall reduction is greater than the “business as usual” charging profile. Clearly, a further increase in the PEV penetration reduces the net emissions, especially in the critical morning and afternoon commute hours.

Following are the conclusions of this research:

- The deployment of PEVs reduces tail-pipe emissions and, for the Western Grid, reduces overall emissions per vehicle mile.

The deployment of PEVs transfers emissions from the tail-pipe to the electric grid. Due to the relatively low carbon footprint of the U.S. Western Grid, the addition of PEVs results in a reduction in both GHGs and criteria pollutants, and in a reduction of emissions per vehicle mile.

- The reduction in GHG emissions depends on the charging scenario.

For PHEV penetrations lower than 34.5 percent, the “business as usual” charging scenario is more effective in reducing the emissions of CO₂. For PHEV penetrations higher than 34.5 percent, the “off-peak” charging profile is more effective in CO₂ reduction. This is observed because the average grid emission factor changes with the electricity load and time of day.

- The improvement in air quality depends on the time of day in-basin criteria pollutant emissions are reduced.

The reduction in criteria pollutants is correspondingly lower in both charging scenarios. Due to the relationship between the emission of criteria pollutants and the resultant air quality, the reduction in criteria pollutant emissions between the commute hours of 6 and 9 am is expected to be especially effectual in improving air quality.

- Smart communication and control will likely be required.

For grid stability and emission reduction, charging should be (1) limited during the late afternoon and early evening periods of peak electricity power demand and (2) encouraged between 11:00 pm and 6:00 am. The early deployment of PEVs will not significantly impact either emissions or the grid ability to charge the vehicles at any time of the day. As the popularity of PEVs increase, a critical population will be reached where smart control with economic incentives will be required to (1) ensure that the majority of charging occurs overnight and off-peak, and (2) charging is incentivized during periods when grid stability and efficiency would be enhanced (e.g., when wind resources would otherwise be curtailed).

Overall, the results show that with careful planning for both transportation and power generation sectors, along with providing incentives to consumers to charge their plug-in vehicles at certain times, deployment of PEVs in the light-duty vehicle fleet will result in a reduction in criteria pollutant emissions, a reduction in greenhouse gas emissions, and help the State of California to achieve AB32 goals

References

- [1] Energy Information Administration, Department of Energy, International Energy Outlook, 2009, May, DOE/EIA-0484.
- [2] G. Wang, Journal of Power Sources 196 (2011) 530–540.
- [3] World Resources Institute, Climate Analysis Indicators Tool (CAIT) Version 7.0, 2010.
- [4] California Energy Commission, 2007 Integrated Energy Policy Report, 2007, CEC-100-2007-008-CMF-ES.
- [5] California Energy Commission, 2011–2012 Investment Plan for the Alternative Fuel & Vehicle Technology Program, 2011, CEC-600-2011-006-SD.
- [6] EPRI, Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options, 2001, 1000349.
- [7] J. Axsen, K.S. Kurani, R. McCarthy, C. Yang, Energy Policy 39 (3) (2011) 1617–1629.
- [8] A. Sioshansi, P. Denholm, Environmental Science & Technology 43 (2009).
- [9] O. Van Vliet, A.S. Brouwer, T. Kuramochi, M. van den Broek, A. Faaij, Journal of Power Sources 196 (2011) 2298–2310.
- [10] C. Silva, M. Ross, T. Farias, Energy Conversion and Management 50 (2009) 1635–1643.
- [11] M. Kintner-Meyer, K. Schneider, R. Pratt, Impact Assessment of Plug-In Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids, Part 1: Technical Analysis, Pacific Northwest National Lab, Richmond, WA, 2007.
- [12] EPRI, Environmental Assessment of Plug-In Hybrid Vehicles, vol. 1: Nationwide Greenhouse Gas Emissions, EPRI, Palo Alto, CA, 2007, 1015325.
- [13] R. McCarthy, C. Yang, Journal of Power Sources 195 (2010) 2099–2109.
- [14] K.H. Jansen, T.M. Brown, G.S. Samuelsen, Journal of Power Sources 195 (2010) 5409–5416.

- [15] T. Gorin, C. Kavalec, California Energy Demand 2010–2020 Adopted Forecast, California Energy Commission, 2009, December, CEC-200-2009-012-CMF.
- [16] California Independent System Operator, <http://oasishis.aiso.com>.
- [17] California Department of Finance, Demographic Research Unit, <http://www.dof.ca.gov/research/demographic/reports/projections/p-3>.
- [18] South Coast Air Quality Management District, Final 2007 Air Quality Management Plan, 2007, June.
- [19] Air Resources Board [Online], 2007, <http://www.arb.ca.gov/app/emsinv/facinfo/facinfo.php>.
- [20] United States Department of Labor, Occupational Safety & Health Administration, <http://www.osha.gov/pls/imis/sicsearch.html>.
- [21] EPA, eGRIDweb Version 1.0, <http://www.epa.gov/cleanenergy/energy-resources/egrid>.
- [22] Energy Central [Online], <http://pro.energycentral.com/professional/industry-data/plants/default.cfm>.
- [23] J. Casazza, F. Delea, Understanding Electric Power Systems, Wiley, New Jersey, 2003.
- [24] California Energy Commission, Five-Year Transmission Research and Development Plan, 2003, November, 500-03-104F.
- [25] Environmental Protection Agency, Emission Factor Documentation of AP-42 Section 3.1, Stationary Combustion Turbines Section 3.1, Stationary Combustion Turbines, 2000, April, EPA Contract No. 68-D7-0070.
- [26] National Energy Technology Laboratory, Cost and Performance Baseline for Fossil Energy Plants, 2007, August, DOE/NETL-2007/1281.
- [27] National Household Travel Survey, US DOT Federal Highway Administration, 2001.
- [28] K. Parks, P. Denholm, T. Markel, Costs and Emissions Associated with Plug-In Hybrid Electric Vehicle Charging in the Xcel Energy Colorado Service Territory, National Renewable Energy Laboratory, 2007, May, NREL/TP-640-41410.
- [29] J. Ogden, M. Ramage, DOE Light-Duty Vehicle Workshop, 26, July, 2010.
- [30] T.A. Becker, I. Sidhu, B. Tenderich, Electric Vehicles in the United States: A New Model with Forecasts to 2030, Center for Entrepreneurship & Technology, University of California, Berkeley, CA, 2009, <http://cet.berkeley.edu/dl/CET.Technical%20Brief.EconomicModel2030.f.pdf>.
- [31] D.J. Santini, How Will Light Duty Plug-in Hybrid Vehicle Electric Drive Emerge and Evolve? An Examination of Recent and Current Developments, Argonne National Laboratory, 2007, <http://www.transportation.anl.gov/pdfs/HV/483.pdf>.