LBNL-XXXXXX

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

All Electric Passenger Vehicle Sales in India by 2030: Value proposition to Electric Utilities, Government, and Vehicle Owners

Nikit Abhyankar
Anand Gopal
Colin Sheppard
Won Young Park
Amol Phadke

Energy Analysis and Environmental Impacts Division

January 2017

This work was funded by the U.S. Department of Energy's Office of International Affairs under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

Disclaimer

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or The Regents of the University of California.

Ernest Orlando Lawrence Berkeley National Laboratory is an equal opportunity employer.

Acknowledgements

LBNL would like to thank the US Department of Energy for providing financial support to this work. Preliminary results of this analysis were presented at various fora and meetings. We are thankful to Dr. Rashid Waraich of Lawrence Berkeley National Laboratory for a very helpful review of this report. Any errors or omissions are authors' responsibility.

This work was funded by the U.S. Department of Energy's Office of International Affairs under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

Contents

All Electric Passenger Vehicle Sales in India by 2030:
Value proposition to Electric Utilities, Government, & Vehicle Owners

Nikit Abhyankar, Anand Gopal, Colin Sheppard, Won Young Park, Amol Phadke

1. Introduction

In India, there is growing interest among policymakers, planners, and regulators for aggressive electrification of passenger vehicles. For example, Piyush Goyal, the Minister of State for India's Ministry of Coal, Power, New and Renewable Energy, announced an aspirational goal of converting all vehicle sales in India to battery electric vehicles (BEVs) by 2030 (Economic Times, 2016). In 2012, India has already announced the National Mission on Electric Mobility (NMEM) sets a countrywide goal of deploying 6 to 7 million hybrid and electric vehicles (EVs) by 2020 (DHI, 2012). A major policy motivation for transport electrification is to reduce India's oil import dependency. While electrifying transportation will reduce India's oil imports, it is not clear if switching to electric vehicles will lower greenhouse gas emissions. In fact, many hold the view that electric vehicles will increase India's greenhouse gas emissions due to the high level of dependence on coal for the country's electricity production (Doucette & McCulloch, 2011). Also, given the chronic power shortages in the country, there are significant concerns amongst policymakers regarding the capability of the grid to reliably handle such additional load from BEVs.

There have been numerous studies that assess the economic and environmental impacts of battery electric vehicles (BEVs) in the US and European context. See for example, (Campanari, Manzolini, & Garcia de la Iglesia, 2009; Hawkins, Gausen, & Strømman, 2012; Kennedy, Ibrahim, & Hoornweg, 2014; MacPherson, Keoleian, & Kelly, 2012; McCleese & LaPuma, 2002). However, there is very limited literature on this topic in India. We have only found one peer-reviewed study that models the greenhouse gas emissions associated with BEVs in India (Doucette & McCulloch, 2011). Doucette and McCulloch (2011) find that BEVs will increase CO_2 emissions in India relative to conventional vehicles. However, their analysis uses the grid emission factors from 2010 and it is not temporally explicit with respect to electric vehicle trips or the power system. Under its Nationally Determined Contribution (NDC) for the Paris Climate Agreement, India has already committed to significantly reducing the carbon intensity of its power system. Also, temporally explicit assessments are more appropriate to inform policy in India, where massive power system expansion will be needed over the next decade regardless of BEV power demand (Abhyankar et al., 2013a). Of the few other studies that do model temporal power generation and charging demand variation, none cover India (Axsen, Kurani, McCarthy, & Yang, 2011; EPRI and NRDC, 2007; Hadley & Tsvetkova, 2009; Jansen, Brown, & Samuelsen, 2010; McCarthy & Yang, 2010; Parks, Denholm, & Markel, 2007). Similarly, several studies have assessed the impact of electric vehicles on utility load, energy costs, and how "smart" or "optimal" charging of electric vehicles can help renewable energy grid integration as well as overall ancillary services costs in the US and European context (Kempton & Letendre, 1997; Lopes, Soares, & Almeida, 2011; Lund & Kempton, 2008; Rahman & Shrestha, 1993; Rotering & Ilic, 2011). Unfortunately, no such studies could be found in India.

The objective of this paper is to assess the effect of full electrification of vehicle sales in India by 2030 on the key stakeholders such as BEV owners, electric utilities, and the government. Specifically, we attempt to answer the following questions:

(a) How does the total vehicle ownership cost of BEVs compare with the conventional vehicles?
(b) What is the additional load due BEV charging?
(c) What is the impact on the power sector investments, costs, and utility revenue?
(d) How can smart BEV charging help renewable energy grid integration?
(e) What is the impact on the crude oil imports?
(f) What is the impact on the greenhouse gas (GHG) emissions?

We conduct the analysis using three simulation-optimization models that are soft-linked: (a) Plug-in Electric Vehicles Infrastructure (PEVI) model, which is an agent based BEV travel and charging demand model that simulates BEV driving and charging behavior, (b) PLEXOS, which is an industry standard simulation software for least-cost investment planning and economic dispatch of the power system, and (c) Economic and Environmental Impacts model, which is a spreadsheet based tool that assesses the impact on emissions, oil imports, and utility finances. Note that an implicit assumption in the study is that the appropriate policies and incentives are in place for such aggressive electrification of the passenger vehicle fleet; assessing the feasibility or risks of our pathway is out of the scope of this report. The remainder of the paper is organized as follows. Section 2 describes our modeling method, key assumptions, data we have used and its sources. Section 3 shows the key results of our analysis followed by the conclusion and policy recommendations in section 4.

2. Methods, Data, and Assumptions

We conduct the analysis using three simulation-optimization models that are soft-linked: (a) Plug-in Electric Vehicles Infrastructure (PEVI) model, which is an agent based BEV travel and charging demand model that simulates BEV driving and charging behavior, (b) PLEXOS, which is an industry standard simulation software for least-cost investment planning and economic dispatch of the power system, and (c) Economic and Environmental Impacts model, which is a spreadsheet based tool that assesses the impact on emissions, oil imports, and utility finances. In this section, we describe our modeling approach, key features of the models, assumptions, and data.

Figure 1 summarizes our overall modeling approach.

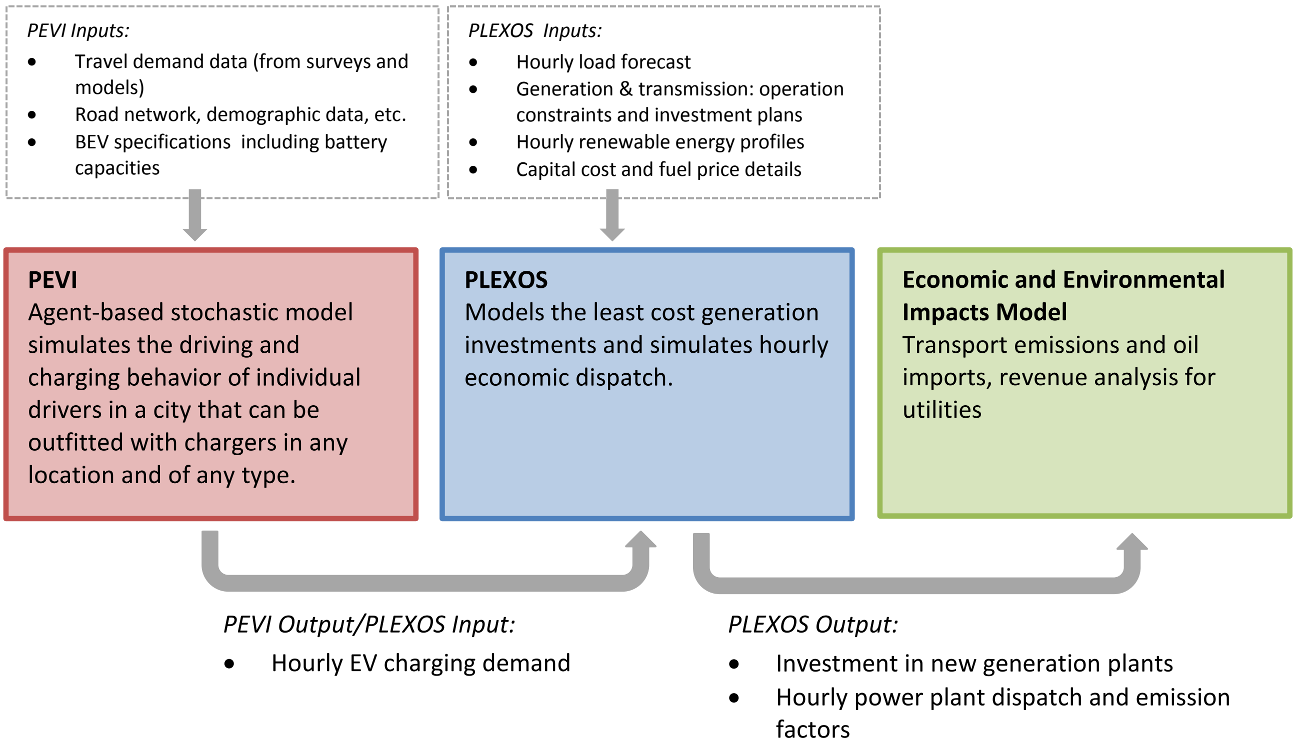


Figure 1: Summary of the modeling approach

Using the assumptions on travel demand in 2030, total BEV penetration and efficiency, and agent based modeling of the charging behavior, PEVI estimates the BEV charging load for each hour of the year. Using official government data and historical trends, we project hourly electricity demand in the country from sources other than BEVs. We then simulate the 2030 power system in India using certain assumptions on operational constraints and by creating the following two scenarios for the generation capacity mix:

(a) Business as Usual (BAU), which includes the new electricity generation investments that have been identified in India's 12th five-year plan (up to 2022), extrapolated to 2030, and

(b) NDC Compliant Scenario, which includes the aggressive RE targets committed to by India in its NDC (100 GW solar and 60 GW wind by 2022), extrapolated to 2030.

In each scenario, we simulate least cost generation capacity expansion and hourly economic grid dispatch so that the electricity demand (non-BEV as well as BEV) is fully met. We then use the capacity expansion and hourly power plant operation results to (a) estimate the temporally explicit grid emission factors, which are in turn used to assess the BEV emissions, (b) assess how smart BEV charging could reduce the overall system cost, (c) assess the total BEV charging load and the impact on utility finances. We also conduct sensitivity analysis to assess the robustness of our findings given the uncertainties in multiple key parameters.

Note that our modeling approach is significantly data intensive. While we could build a national power system model for India, we only had access to detailed travel demand data for the National Capital Territory region (NCT) of Delhi. We assume that the travel demand in rest of the country by 2030 is identical to that in the NCT region. For the following four reasons, we believe that this assumption is valid for the levels of vehicle electrification that we study. First, due to the massive concentrations of wealth and transport demand in India's medium and large cities, it is likely that almost all EV uptake over the next two decades will be concentrated in these cities (Das & Parikh, 2004). Second, due to its relatively higher income levels, New Delhi's current trip shares by mode and time of day are expected to reflect travel patterns in other medium and large Indian cities in the future as their incomes increase to New Delhi's levels (Bose, 1998). Third, growth in electricity demand from non-BEV sources (like air conditioners) is expected to be similarly explosive in all urban areas (Phadke, Abhyankar, & Shah, 2013). Fourth, the long-run electricity generation mix is likely to be similar in most parts of the country due to rapid build out of transmission capacity and regional uniformity in power plant costs by fuel (Abhyankar et al., 2013b).

2.1. Plug-in Electric Vehicle Infrastructure (PEVI) Model

PEVI is an agent-based stochastic model that simulates the driving and charging behavior of individual drivers for each hour of the day in a virtual road network that can be outfitted with public and private charging infrastructure of any type (i.e. Level 1, Level 2, or DC Fast). In PEVI model, we include a representation of the National Capital Territory (NCT) of Delhi, split into 53 travel analysis zones (TAZs), and its road network. Chargers of the following types can be placed in any TAZ:

- Level 1: low power chargers up to 1.5kW (in Delhi, service voltage is 230V, so any charger on a circuit with a capacity up to 6.5 amps is considered Level 1)
- Level 2: medium power chargers up to 20kW
- DC Fast: direct current fast chargers ranging from 30-100kW

Individual EV drivers are simulated as they conduct their travels and charge their vehicles. Drivers begin a day with a vehicle, an itinerary of trips, and a set of behavioral rules, which include the following:

- Drivers attempt all of their daily trips.
- They include a factor of safety in their range estimations (10%).
- They may or may not have home in the region but all drivers have accesses to a charger at home.
- They seek a charger when they need it
- Sometimes, they would seek a charger even if they have enough charge to complete their trip due to "range anxiety" (according to a random process based on observed usage of public chargers in the United States by plug-in hybrid electric vehicle drivers).
- They consider neighboring and en-route zones in their list of candidate charging sites, but only if desperate for charge (within one hour of departure without sufficient range).
- They choose the charging option that minimizes their cost, a calculation that places a monetary value on their time (Rs 28/hour based on the average income levels of Delhi).

The itineraries that drivers follow are based on two critical sources of data: 1) results from the most recent travel demand model commissioned by the NCT of Delhi and implemented by RITES Ltd. with projections up to 2021 of travel intensities throughout the Delhi metropolitan area (RITES, 2005), and 2) results from the most recent household travel survey with 45,000 respondents (RITES & MVA Asia, 2008). Based on the survey, the average vehicle kilometers traveled (VKT) in a year by two-wheelers in Delhi are 2,942 km/yr and that by cars are 2,893 km/yr. A stochastic, non-parametric resampling technique was used to blend these two data sources into dozens of unique sets of itineraries, which were used in the context of Monte Carlo simulation to include a suitable amount of variability in the analysis. In addition, data from The EV Project, a large-scale demonstration project in the United States, were used in the development of probability distributions that characterize aspects of driver behavior as well as for model calibration (Ecotality, 2013). Please refer to Gopal et al (2014) for more details on the PEVI modeling approach. As explained previously, we assume that by 2030, the travel demand and driver behavior in the rest of the country is identical to that in New Delhi.

2.1.1. Total Vehicle Stock in 2030

We project the future stock of vehicles using a simplified stock turnover model. We take the current number of registered vehicles in India as reported by the Ministry of Road Transport and Highways. This is shown in Table 1.

Table 1: Total number of registered vehicles in India (in millions)

	2000	2005	2010	2013
Two-wheelers	34	59	92	133
Cars, Jeeps, and Taxis	6	10	17	25
Buses	0.6	0.9	1.5	1.9
Goods Vehicles	3	4	6	9

Others	5	7	11	15
Total	**49**	**81**	**128**	**182**

Data source: (MORTH, 2015)

Unfortunately, the registered vehicle data for later years was not available in the public domain. Note that these are cumulative numbers of all registered vehicles and does not take into account vehicle retirement. According to (Guttikunda & Mohan, 2014), only 70% of these vehicles are actually operating on the road. Therefore, the total active vehicle stock in 2013 is assumed to be about 128 million; this includes about 93 million 2-Wheelers and 17 million cars. We then project the vehicle sales up to 2030 based on the historical trends. We take the historical vehicle sales data from The Society of Indian Automobile Manufacturers (SIAM) as shown in Table 2.

Table 2: Total vehicle sales in India (in millions)

Category	2000	2005	2010	2015
Passenger Vehicles (Cars)	0.6	1.1	2.0	2.6
Two Wheelers	3.8	6.6	9.4	16.0

Source: (SIAM, 2011)

It is clear from Table 1 and Table 2 that the vehicle sales have been growing rapidly. Between 2000 and 2015, cars and two-wheeler sales have more than quadrupled indicating a Compounded Annual Growth Rate (CAGR) of 10% per annum; during the same period, the number of registered vehicles have quadrupled as well.

For projecting the vehicle stock in future, we use a simplified vehicle stock turnover model. We assume that the car sales will continue to grow at the same rate as observed historically i.e. the sales nearly quadruple in about 15 years. In case of 2-wheelers, we assume that the sales growth rate would slow down due to increased incomes especially in the urban areas; we assume that the 2-wheeler sales will only double between 2015 and 2030. This assumption roughly matches the industry forecasts and other studies (Guttikunda & Mohan, 2014). All vehicles (cars and two-wheelers) are assumed to have a life of 15 years. Table 3 shows our projections of the vehicle sales and total active vehicle stock up to 2030.

Table 3: Projected Total Vehicle Sales and Active Vehicle Stock (millions)

		2015	2020	2025	2030
Sales	Two-wheelers	16	20	26	32
	Cars	2.6	4.1	6.5	10
Active stock	Two-wheelers	122	204	289	367
	Cars	22	38	59	89

Note: This number only represents the active vehicles operating on the street. Number of registered vehicles would be more than this.

2.1.2. BEV Stock in 2030

We assume that by 2030, all vehicle sales in India are BEVs. The BEV sales numbers in 2015 are very small (about 20,000 total). We assume a log-linear growth of BEV sales with the growth rate changing every five years between 2015 and 2030. As shown in the Table 3, we assume that the total vehicle sales (and stock) will remain the same whether the consumers choose BEVs or conventional IC Engine (ICE) vehicles. Therefore, as the BEV sales grow, ICE vehicle sales drop and by 2030 BEVs account for 100% vehicle sales in India as shown in Table 4.

Table 4: Projected BEV sales (millions) by 2030

Vehicle Sales (millions)								
	Two-wheelers				Cars			
	2015	2020	2025	2030	2015	2020	2025	2030
ICE	16.0	19.7	20.2	0.0	2.6	3.8	4.1	0.0
BEV	0.0	0.5	5.4	32.3	0.0	0.3	2.4	10.3
Total	16.0	20.2	25.6	32.3	2.6	4.1	6.5	10.3

To achieve the 100% vehicle sales electrification goals, the 2-wheeler BEV sales will need to increase from about 2,000 in 2015 to about 32 million by 2030; for cars, the BEV sales need to increase from about 20,000 in 2015 to about 10 million in 2030.

Table 5 shows the active BEVs and ICE vehicles stock by 2030.

Table 5: Active Vehicle Stock (millions) of BEVs and ICE Vehicles up to 2030

Active Vehicle Stock (millions)								
	Two-wheelers				Cars			
	2015	2020	2025	2030	2015	2020	2025	2030
ICE	121.9	203.5	275.9	262.0	22.2	37.0	51.7	49.9
BEV	0.0	0.7	13.6	105.1	0.0	0.6	7.0	39.0
Total	121.9	204.2	289.5	367.1	22.2	37.7	58.6	88.9

The active vehicle stock at the national level is distributed among all states based on their historical shares. By 2030, BEVs represent about 29% of the total active 2-wheeler stock and about 44% of the total active car stock. Full vehicle stock electrification would be expected to take place by mid-2040 when all ICE vehicles purchased before 2030 would probably retire.

2.1.3. Vehicle Efficiency

Vehicle characteristics (especially efficiencies) could be widely different depending on the size within each vehicle class. For example, a compact sedan's fuel efficiency would be significantly different from a van. To account for such differences, we split cars into three different classes of vehicles: subcompact hatchbacks, compact sedans, and vans/multi-use vehicles (MUVs). These classes and the market share of each are derived from the all-India vehicle sales data from Society of Indian Automobile Manufacturers (SIAM) in 2015 (SIAM, 2011). 2-wheelers are not split into sub-classes mainly because of non-availability of data.

For each vehicle category, we take the best-selling ICE vehicle or BEV model in India and use the manufacturer labeled fuel (i.e. electricity) consumption values for 2015. We assume that the vehicle efficiencies will improve between 2015 and 2030. Unfortunately, there is no study in India that forecasts vehicle efficiencies in the future. Therefore, the rate of improvement between 2015 and 2030 was taken from a study by the US National Research Council on assessing the potential for reducing GHG emissions from the light duty vehicles in the US between 2015 and 2050 (NRC, 2013). Given the globalized supply chain of the automobile manufacturing, we believe that such improvement rates would not be very different in India. Table 7 and Table 7 show the ICE and BEV efficiencies in 2015 and 2030.

Table 6: ICE Vehicle Efficiency (liters/km) in 2015 and 2030

	Model	Fuel	ICE Vehicles Efficiency (lit/km)	
			2015	2030
Two wheelers	Hero Splendor	Gasoline	0.0124	0.0074
Subcompact hatchbacks	Maruti Alto	Gasoline	0.0415	0.0249
Compact Sedans	Maruti DZire	Gasoline	0.0565	0.0297
Vans / MUVs	Mahindra Bolero	Diesel	0.0758	0.0397

Table 7: BEV Efficiency (kWh/km) in 2015 and 2030

Vehicle Type	Model	BEV Efficiency (kWh/km)	
		2015*	2030
2-Wheeler	Hero Electric Zion	0.013	0.012
Subcompact Hatchback	Mahindra E2O	0.08	0.069
Compact Sedan	Mahindra Verito	0.13	0.082
Van / MUV	Mahindra eSupro	0.22	0.11

* Estimated by dividing the manufacturer labeled battery capacity by the range.

Please note that the manufacturer labeled BEV consumption numbers match closely with our previous analysis of BEV efficiencies in India using drive-train simulations and real-world driving conditions (Saxena, Gopal, & Phadke, 2014).

We understand that the fuel efficiencies of the vehicles in the real world would be different from those labeled by manufacturers. Also, the rate of fuel economy improvement may be different in India than in the US. In order to assess the robustness of our findings on these uncertainties, we conduct a sensitivity analysis on vehicle fuel efficiencies in 2030.

2.1.4. Vehicle Kilometers Traveled

Based on the travel demand survey in the NCT in 2008, the average Vehicle Kilometers Traveled (VKTs) in a year by two-wheelers are 2,942 km/yr and that by cars are 2,893 km/yr. Unfortunately, we do not have a time-series data on VKTs nor we have data for any other region in India. Between 2015 and 2030, as the average per capita income is expected to double (in real terms), we expect that there will be a commensurate increase in the average VKTs in India. We have assumed the increase in average VKTs by cars to be 25% more than that in 2-wheelers. This trend is broadly consistent with other countries including China (Huo, Zhang, He, Yao, & Wang, 2012). Table 8 shows our assumptions on the per capita GDP of India (in constant 2005 dollars) and average VKTs per year in 2015 and 2030.

Table 8: GDP per capita and VKTs in 2015 and 2030

		2015	2030
Average VKTs (km/year)	2-Wheelers	2,942	5,886
	Cars	2,893	7,233
GDP per Capita (PPP Constant 2005 US $) *		4,000	9,000

* Source: (OECD, 2013)

By 2030, although we assume that average VKTs increase in India, they are still significantly lower than the current numbers in other industrialized and emerging economies such as US (19,801), Germany (12,446), and China (14,125).[1]

2.1.5. Vehicle Costs

We take the 2015 capital costs of ICE vehicles per manufacturer suggested retail prices and assume that vehicle costs change in the future. However, there is no study in India that forecasts the vehicle costs and therefore, like vehicle efficiency, we use the cost trend from (NRC, 2013), and apply that to project the ICE vehicle costs up to 2030. NRC (2013) also estimates the incremental manufacturing cost of BEVs over ICE vehicles. We use the same incremental cost estimates (as proportion of the ICE vehicle costs) to forecast the BEV costs in India by 2030. Table 9 shows our assumptions on vehicle capital costs in 2015 and 2030.

Table 9: Assumptions on Vehicle Capital Costs in 2015 and 2030 (Rs)

	2015		2030	
	ICE	BEV	ICE	BEV
Subcompact Hatchback	426,595	610,805	458,380	523,185

[1] Source: https://www.fhwa.dot.gov/policyinformation/statistics/2008/pdf/in5.pdf

Compact Sedan	525,720	752,830	564,980	623,285
MUV	626,730	897,390	673,465	742,950
2-Wheelers	50,000	70,000	53,725	59,958

As the ICE vehicle efficiencies improve significantly between 2015 and 2030, the capital cost is expected to increase slightly. The relative increase in the capital cost is much smaller than that in the efficiency improvement. BEV capital costs, on the other hand, are expected to reduce in the future mainly because of the expected advancements in the battery technology (improved energy density and economies of scale in production). Between 2015 and 2030, the incremental capital cost of BEVs over ICE vehicles drops over 75%.

We assume that the annual maintenance and spares cost is 5% of the capital cost. The fuel price for ICE vehicles is taken per the government approved prices in 2015: Rs 60/lit for gasoline and Rs 50/lit for diesel, which we believe are conservative. Marginal electricity price is assumed to be Rs 9/kWh based on the actual marginal electricity tariffs for residential customers in Mumbai and Delhi in 2015. Both fuel price and electricity price are held constant through 2030.

2.2.Power system modeling using PLEXOS

We model the Indian electricity grid using 5 nodes – one node each for every region viz. north, east, west, south, and north-east. In PLEXOS, we run two modules – capacity expansion and economic dispatch. The capacity expansion module takes 2030 as the terminal year i.e. the model is not assumed to have the foresight beyond 2030. The output of the capacity expansion module (total number of units in each region including the modeled additions until 2030) is used by the economic dispatch model. We run the economic dispatch model in two stages. The first stage is simulation of the day-ahead scheduling and market. In the day-ahead mode, the model takes the day-ahead renewable energy (RE) forecasts and expected maintenance outages and makes the unit commitment decisions for thermal power plants. These RE forecasts are revised up to three hours in advance in order to reduce the forecast errors significantly and potentially revise the unit commitment schedule, if necessary and feasible. The second stage is simulating the hourly real-time grid operation and power plant dispatch. In the real-time mode, the model takes the unit commitment decisions from the day-ahead mode (revised up to three-hours ahead) and does the economic dispatch considering the actual (i.e. forecasts of the 2030 real-time) RE generation and load (BEV and non-BEV). The unit commitment and dispatch decisions are made to minimize the total system cost (production as well as start and shutdown costs) subject to a number of operational constraints such as maximum ramping rates, minimum stable generation levels, minimum up and down times etc. Also, note that these are energy only simulations and do not include ancillary services such as reserves etc.

2.2.1. Electricity Generation Capacity

We create the following two scenarios for the installed electricity generation capacity in 2030.

(a) ***Business as Usual (BAU)***: This scenario serves as the baseline for this analysis and uses the generation capacity additions for all technologies as projected in the Government of India's 12th Plan (Planning Commission, 2012). Note that the 12th Plan has targets up to 2022; we do a linear extrapolation of these targets to 2030.

(b) ***NDC Compliant***: This scenario models the India's NDC at the Paris COP to increase the total installed capacity of solar PV projects to 100GW and wind projects to 60 GW by 2022; we linearly extrapolate these targets to 2030. We hold the nuclear and hydro capacities the same as the BAU scenario due to a range of non-economic constraints driving their construction and let PLEXOS's capacity expansion module optimize the coal and gas capacity additions in 2030.

The following table summarizes our scenarios and also shows the 2015 actuals.

Table 10: Assumptions on total (all-India) installed generation capacity by 2030 in GW

	2015 (Actual)*	2030 BAU	2030 NDC Compliant
Coal	165	415	Optimized by PLEXOS
Gas	19	19	Optimized by PLEXOS
Diesel	1.1	1.1	1.1
Nuclear	5.8	61	61
Hydro	41	83	83
Wind	22	60	110
Solar PV (incl distributed solar)	3.1	53	180
Other RE	8.0	20	20
Total	**265**	**714**	**#N/A**

Note: Totals may not match due to rounding off

* Source: (CEA, 2015a)

2.2.2. Wind and solar PV generation profiles

We forecast the hourly profiles of wind energy generation using the actual historical generation data for 2010 through 2013 from the states of Tamil Nadu, Karnataka, Maharashtra, and Gujarat. For estimating the hourly generation profile of solar PVs, we chose 100 sites spread over all 5 regions with best quality solar resource (measured in Direct Normal Irradiance and Global Horizontal Irradiance kWh/m2) using the national solar energy dataset for India developed by the National Renewable Energy Laboratory (NREL, 2013). Simulated hourly PV output profiles of the sites in each region were averaged to arrive at the regional solar PV generation profile. Please refer to Appendix 1 for more details.

2.2.3. Non-BEV electricity demand

We simulate the hourly demand curve for each region based on the historical hourly demand patterns in the country, growing urbanization, and the projected load growth based on the Central Electricity Authority's (CEA) 18th Electric Power Survey (EPS). One of the key problems in projecting the future demand was accounting for the load curtailment (which was as high as 6% by energy in 2013). To address that, we used a mixed approach. We used the current restricted load data for each region to assess the seasonal load pattern in a region; and used hourly load data of the key load centers that do not experience load shedding (such as Delhi, Chandigarh, Gujarat, Mumbai, Pondicherry etc.) and the load centers that have the load shedding data available (such as Maharashtra, Tamil Nadu etc.) to assess the diurnal demand pattern. For estimating the 2030 demand, we apply the regional demand growth rates from CEA's 18th EPS. Next, to account for the growing urbanization in the country, load shapes of the urban load centers (such as Delhi, Mumbai, Pondicherry etc.) are given an additional 20% weight relative to the state level load curves in each region. This would make the resultant 2030 load curve peakier than the current (2015) one. Finally, the regional load curve is uniformly adjusted so that the peak demand and total energy demand match CEA's projections for 2030 in their 18th EPS. Demand forecast and load shape assessment is an area where future work is needed using a combination of bottom up and top down approaches. Table 11 shows the projected energy demand, peak demand, and load factor for 2030 in each region.

Table 11: Projected non-BEV energy demand, peak demand, and load factors for 2030

Region	Energy Demand (non-BEV) (TWh/yr)	Peak Demand (non-BEV) (GW)	Load Factor (%)
Eastern	437	68	74%
North-Eastern	107	16	75%
Northern	1049	160	75%
Southern	937	153	70%
Western	951	153	71%
All-India	**3481**	**535**	**74%**

2.2.4. Generator Costs and Operational Parameters

Generator operational parameters such as unit size, heat rates, ramp rates, minimum stable level of the power plants have been estimated using the historical plant level hourly dispatch, outage and other performance data, regulatory orders on heat rates and costs, other relevant literature, and conversations with the system operators in India about actual practices. Our assumptions on operational parameters are listed in Appendix 1 and Appendix 2. Capital costs and fixed O&M costs for renewable technologies have been taken from India's Central Electricity Regulatory Commission's (CERC) tariff norms for 2014-2015. For coal based power projects, we have used CERC's interim order (2012) on benchmarking the capital costs of thermal projects (CERC, 2012). For gas, diesel, and hydro projects, we have used industry norms per our previous report (Abhyankar et al., 2013a). Capital and O&M costs of the nuclear projects have been taken from (Ramana, D'Sa, & Reddy, 2005). Given that most of the conventional technologies have already matured, their capital costs are not assumed to change until 2030 in real terms. For solar PVs, we use the capital cost trajectory projected in the Global PV Market Outlook 2015 by BNEF (BNEF, 2015). For Wind, given the historical trends, capital cost assumed to remain the same in real terms (Wiser & Bolinger, 2015). For more details, please refer to Appendix 1.

2.2.5. Fuel prices and availability

We take the 2015 fuel prices and use historical trends to project the fuel prices in 2030. Domestic coal availability for the power sector has been taken from the Ministry of Coal's projections in the 13th five-year plan up to 2017; the same trend has been projected up to 2030. We have assumed that the domestic gas availability for the power sector in the future remains the same as the current quantity. No quantity restrictions are assumed on imported fuels. For more details, please refer to appendix 1.

Power plant emission factors

Table 12 shows our assumptions of the CO2 emission factors from fossil fuel power plants. They have been taken from CEA's database of CO2 emissions from the power sector in India (CEA, 2016).

Table 12: CO2 emission factors from power plants

Fuel	Unit Size (MW)	CO2 Emissions kg/kWh
Coal	67.5	1.19
Coal	120	1.05
Coal	200-250	1.05
Coal	300	0.99
Coal	500 (Type 2)	0.97
Coal	600	0.97
Coal	660 (Type 2)	0.87

Coal	800	0.85
Gas (Open Cycle)	All sizes	0.66
Gas (Combined Cycle)	< 50	0.42
Gas (Combined Cycle)	50 – 100	0.41
Gas (Combined Cycle)	> 100	0.42
Diesel	All sizes	0.63

Data source: (CEA, 2016)

2.2.6. Transmission

India is already planning significant new investments in transmission expansion. Therefore, by 2030, we assume that there would be no constraints on transmission.

2.2.7. Smart charging

We allow for the shifting of charging events for the non-essential charging demand that is calculated in PEVI for each hour. Smart charging is subject to the daily energy constraint i.e. the amount of energy used to charge a vehicle should be exactly the same as the energy used by the vehicle during the day. In PLEXOS, we implemented the smart charging system by modeling the charger/vehicle system as flexible storage; the non-essential part of this hypothetical storage (in the form of car batteries) could be charged any time during the day so that the system cost is minimized. One of the implicit assumptions here is that daily BEV itineraries are decided at the start of each day and are not altered at any time during the course of the day. We intend to relax this constraint in our future work.

2.3. Estimating CO_2 emissions (per kilometer)

Per kilometer CO2 emissions from the ICE vehicles are estimated as follows:

$$\frac{g\ CO_2}{km}_{ICE} = Fuel\ Consumption\ (Gasoline\ or\ Diesel)\ per\ km\ \ x\ Emission\ Factor$$

Fuel consumption for ICE vehicles is taken from Table 6. Fuel emissions factor (8.78 kg CO_2 per gallon for gasoline and 10.21 kg CO2 per gallon for diesel) is taken from (US EPA, 2015).

For BEVs, the CO2 emissions per kilometer are calculated as follows:

$$\frac{g\ CO_2}{km}_{BEVs} = Electricity\ consumption\ per\ km\ x\ Temporally\ explicit\ grid\ emission\ factor$$

The BEV electricity consumption rates (kWh/km) are mentioned in Table 7. The temporally explicit grid emissions factor for BEV charging load is estimated by averaging the hourly grid emission factor for the national grid weighted by the hourly BEV charging load. The hourly grid emission factors are taken from the hourly power plant dispatch simulations in PLEXOS.

2.4. Estimating the Crude Oil Consumption

Total crude oil consumption in a year from ICE vehicles is estimated as follows:

$$Crude\ Oil\ Consumption/yr = Fuel\ Consumption\ per\ km\ \ x\ \ Vehicle\ Kilometers\ Traveled/yr\ \ x\ \ Crude\ Oil\ Conversion\ Factor$$

Where, Fuel Consumption per km is taken from Table 6 and Vehicle Kilometers Traveled is taken from Table 8. Based on US Energy Information Agency's assessments, Gasoline to Crude Oil Conversion Factor is assumed to be 2 while Diesel to Crude Oil Conversion Factor is assumed to be 3.[2]

3. Results

In this section, we present the key results of our analysis.

3.1. BEV owners can gain significantly

As shown in Table 9, between 2015 and 2030, the incremental capital cost of BEVs over ICE vehicles drops over 60-70%. For example, the incremental capital cost of subcompact hatchback cars is expected to drop from Rs 184,210 in 2015 to Rs 47,310 by 2030. In Figure 2, we compare the annualized incremental cost of BEVs (i.e. annualized incremental capital cost and total annual electricity cost) with the total annual fuel cost of ICE vehicles for subcompact cars. The annualized capital cost is estimated using a preferential interest rate of 6%.

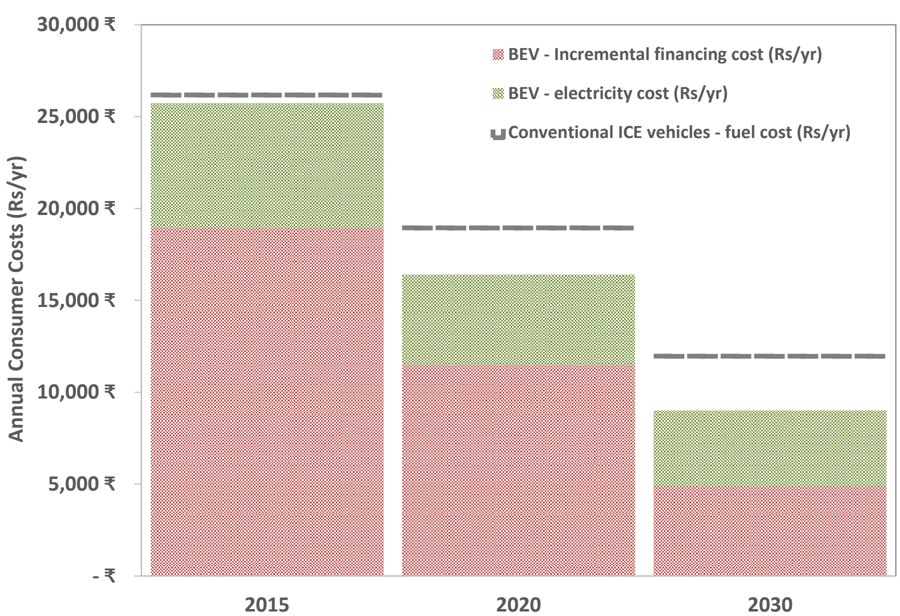


Figure 2: Annualized incremental cost of BEV and annual fuel cost of ICE vehicles for subcompact hatchbacks

[2] Source: https://www.eia.gov/tools/faqs/faq.cfm?id=327&t=9

Note that as the ICE vehicle efficiency increases, the annual fuel cost of ICE vehicles drops by over 65%. Despite such cost reduction, it can be seen that the total incremental cost of BEVs is lower than the annual fuel cost of ICE vehicles for all years. The difference in the ICE fuel cost and the total incremental cost of BEVs is the net BEV owners' benefit. By 2030, the net BEV owner's benefit is nearly Rs 3,000 per year; the difference in only the annual fuel costs of ICE vehicles and BEVs is about Rs 8,000/yr indicating a simple payback period of less than six years by 2030.[3] Note that due to deep reduction in the capital cost of BEVs, the net owner benefit increases significantly between 2015 and 2030. Also, the share of incremental capital cost in the total incremental BEV cost is as high as 75% in 2015 and drops to about 50% by 2030. Therefore, in the initial years, owner's benefit is highly sensitive to the interest rate assumption; BEV incentive program with preferential financing is crucial for early adoption. To demonstrate this, in Figure 3, we compare the total incremental cost of BEVs (incremental financing cost and electricity cost) with the annual fuel cost of ICE vehicles in the subcompact hatchback category for a range of interest rates (6% through 12%).

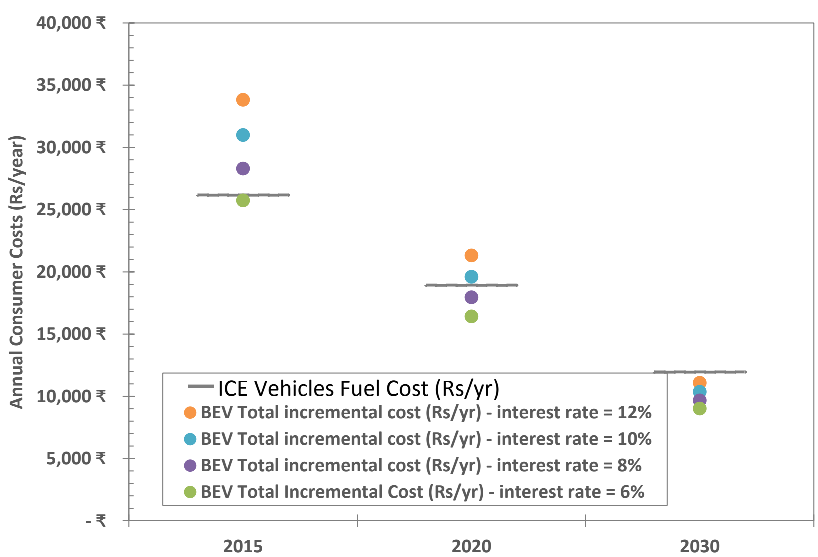


Figure 3: Sensitivity of BEV Total Incremental Cost on Interest Rate

As mentioned earlier, the net benefit of BEV owners is highly sensitive to the interest rate assumption. In 2015, given the incremental cost of BEVs, if the interest rate is over 6-7%, BEV owner's net benefit is negative (i.e. annual BEV costs are higher than ICE vehicle costs). However, by 2030, the BEV costs drop significantly, and even at high interest rates (12%), BEVs are cost-effective for owners.

[3] Simple payback period is estimated by diving the annual saving in operating costs by the incremental capital cost.

3.2.Additional load due to BEV charging is minor

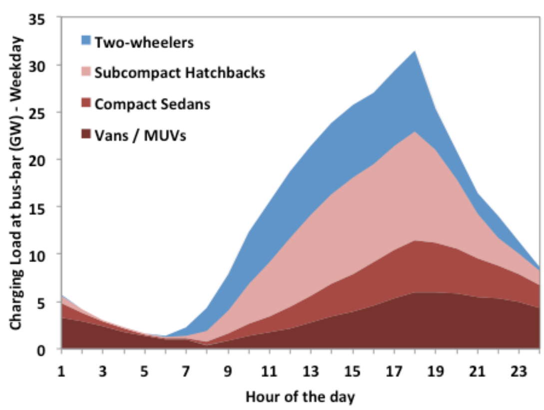
As shown in Table 13, despite aggressive vehicle electrification, the additional load added due to BEV charging by 2030 is less than 3% of the total electricity load in India. As mentioned previously, this is mainly because of the following three reasons: (a) In most urban areas of India, the rapid increase in electricity demand from numerous other end-uses (particularly air conditioners) will be very large over the next 15-20 years, and (b) the vehicle penetration by 2030 is dominated by 2-wheelers that require much less energy than cars, and (c) the overall vehicle penetration is expected to be significantly lower than the other industrialized or emerging economies.

Table 13: Annual energy consumption at bus-bar due to non-BEV electric load and BEV charging in India in 2030 (TWh/year)

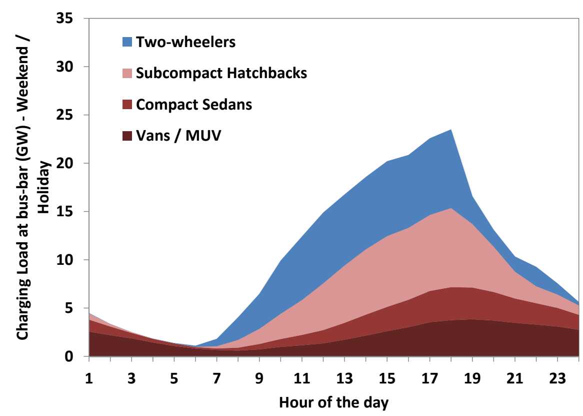
Non-BEV Electric load	**3,200**
BEV Charging Load	
Two-wheelers	11
Cars	61
Aggregate BEV Charging Load	**72**

Note: T&D loss is assumed to be 12%

Figure 4 shows the average hourly BEV charging load by 2030 during a typical weekday and a weekend/holiday. It can be seen that the total peak BEV charging load is little over 30GW, which is about 6% of the total peak load by 2030 (480 GW). Figure 5 shows the aggregate BEV charging load and average hourly load curve for the non-BEV load in May 2030.



(a) Typical weekday



(b) Typical Weekend/Holiday

Figure 4. Average Hourly BEV Charging Load (100% electrification of vehicle sales)

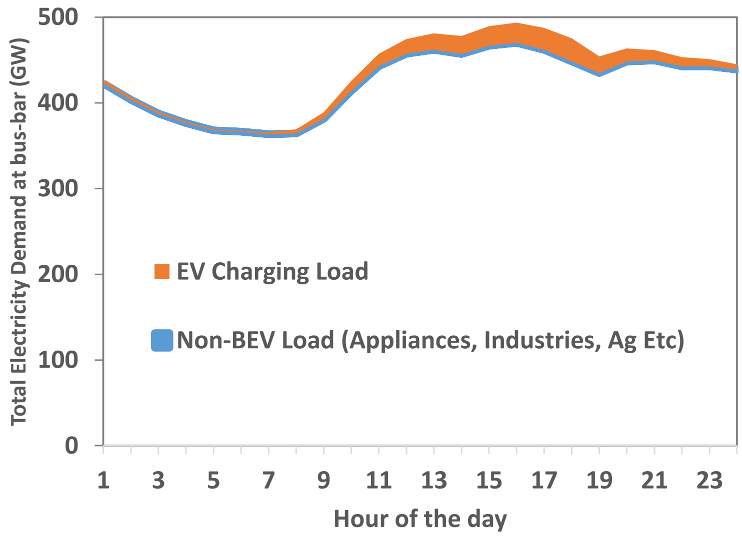


Figure 5: All-India average daily load curve and BEV charging load in May 2030

We find that the 2W BEVs charging load curve is shaped very differently from the results we see from BEV car charging in the US (Ecotality, 2013). This is due to two major factors. First, 2W are used for a wide variety of purposes and not necessarily the traditional commute. Hence, large numbers of 2W trips begin and end throughout the daytime hours. Since these vehicles are usually plugged in at the end of each trip, we see high charging demand from 10 AM to 6 PM. Second, 2Ws have a low battery capacity (1.5 kWh) and hence, frequently complete charging within an hour, even at Level 1 rates. Therefore, we see a substantial drop in demand from 6 PM to 7 PM as many 2W trips end in those hours.

In contrast, the daily BEV charging demand from cars and vans follow a similar pattern to that is seen in the US i.e. mostly associated with commuting (Ecotality, 2013). Most drivers will plug in their vehicle when they return home in the evening, while a significant share also charge at public locations during the day. Since most of the chargers in use are Level 1, vehicles with greater battery capacity draw power during more hours in the day – subcompacts can be fully charged from empty in less than 5 hours using a Level 1 charger, while it will take a van 13 hours to fill up from empty using the same charger.

Note that the BEV charging load on a holiday is lower than that for a weekday but the shape is not significantly different. This is primarily because majority of the BEVs are 2Ws, which may not be used for the traditional commute, as explained earlier. Overall, the charging demand from 2Ws in each daytime hour is the dominant share of all BEV demand mainly because of their large number. Moreover, the hourly charging profile has a strong correlation with the wind and solar

PV generation profiles shown in section 2.2.2 and Appendix 2; this makes the temporally explicit grid emission factors for BEV charging load lower than the non-BEV electric load.

3.3. BEV charging load can earn additional revenue for utilities

Although the additional load due to BEV charging is minor, that could still serve as a valuable additional revenue source for the financially distressed distribution utilities, as shown in Figure 6. Assuming a marginal electricity tariff of Rs 9/kWh, by 2030, BEV charging load could earn about Rs 80,000 Cr of additional revenue for utilities.[4]

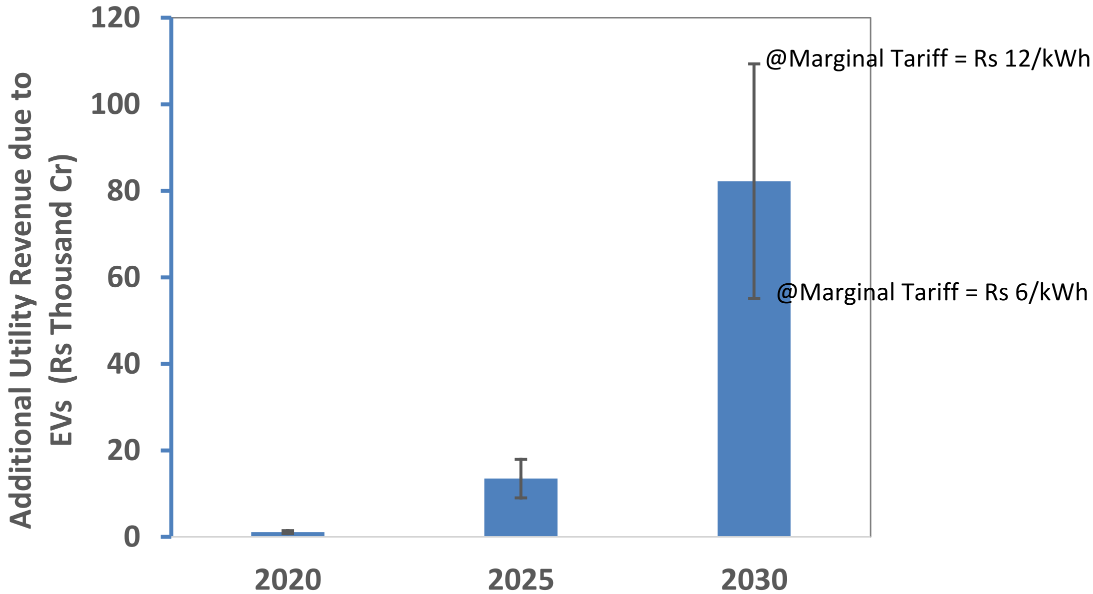


Figure 6: Additional utility revenue due to BEV charging load (Rs Thousand Crore)

Note that in 2014, the total utility financial deficit was Rs 62,000 Cr/yr, and the total government subsidy support to utilities was about Rs 36,000 Cr/yr (PFC, 2016).

Also, in 2014, the total revenue from the commercial sector was Rs 42,000 Cr/yr (PFC, 2016). Between 2015 and 2030, the commercial sector energy consumption is expected to nearly double; assuming the average commercial tariff remains the same in real terms, by 2030, the commercial sector revenue would also double (in real terms) i.e. Rs 84,000 Cr. In short, by 2030, the additional revenue due to BEV charging load would be comparable to that of the commercial sector.

The additional utility revenue is linearly proportional to the assumption on marginal tariff. Our assumption of the marginal tariff is based on the residential tariffs in Mumbai and Delhi.

[4] Cr stands for Crore. 1 Crore = 10 million (10^7).

However, in other regions of the country, marginal tariffs could be different. In Figure 6 we also show the additional revenue in 2030 with marginal tariff of Rs 6/kWh and Rs 12/kWh that changes the revenue to Rs 50,000 Cr and Rs 110,000 Cr respectively. Even with lower marginal tariff, the additional revenue can potentially help reducing the utility financial deficit.

Note that we have assumed that BEV owners will have access to public charging facilities, which could be a major challenge given the aggressive electrification levels. Deployment of such charging infrastructure could potentially be financed using the additional revenue from BEV charging. Also, it is likely that BEV adoption, especially in the initial years, would be limited in a few major urban centers resulting in a few hotspot regions. Although at the national level, the incremental BEV charging load is found to be minor, its impacts on the local distribution network, especially in potential hotspot regions, could be significant. The problem may worsen (or subside, depending on whether BEVs have smart charging) if the BEV hotspots coincide with the solar PV hotspots. Analyzing such local distribution system impacts is important and is part of our future works. For additional discussion of such local effects, please refer to (Waraich et al., 2013; Waraich, Georges, Galus, & Axhausen, 2014).

3.4.BEVs can reduce CO_2 emissions significantly

CO2 emissions due to BEVs depend largely on the grid emission factors, and therefore, on the electricity generation mix in the grid. Table 14 shows the results of the PLEXOS simulation for installed capacity and electricity generation (all-India) by technology, including coal and gas.

Table 14: Installed capacity and electricity generation by technology

	2015 Actual*		2030 BAU		2030 NDC Compliant	
	Installed Capacity (GW)	Electricity Generation (TWh/yr)	Installed Capacity (GW)	Electricity Generation (TWh/yr)	Installed Capacity (GW)	Electricity Generation (TWh/yr)
Coal	165	836	415	2441	361	2156
Gas	19	40	19	41	24	41
Diesel	1.1	1.4	1	0	1	0
Nuclear	5.8	36	61	453	61	398
Hydro	41	129	83	246	83	246
Wind	22	40 (approx.)	61	136	110	274
Solar PV (incl distributed solar)	3.1	5 (approx.)	53	93	178	297
Other RE	8.0	21 (approx.)	21	30	21	31
Total	***265***	***1109***	714	3440	839	3442
Share of non-fossil sources	***31%***	***21%***	**39%**	**28%**	**54%**	**36%**

* Source: (CEA, 2015a)

By 2030, the additional solar and wind capacity in the NDC Compliant scenario relative to the BAU is nearly 174GW. This results in avoiding investment in about 54GW of coal power plants but requires additional investment of about 5GW in gas-based power plants for flexibility.

Table 15 shows the temporally explicit (hourly weighted average) grid emission factors in 2030 for the non-BEV electric load as well as the BEV charging load. The grid emission factors are presented for the two scenarios of generation capacity described in section 2.2.1.

Table 15: Temporally explicit grid emission factors (kg/MWh) for the non-electric load and BEV charging load – 2015 actuals and 2030 projected

	2015 Actual*	2030 BAU	2030 NDC Compliant
All- India average grid emission factor	**820**	**683**	**638**
BEV Charging Load			
Vans	#N/A	686	650
Compact Sedans	#N/A	681	634
Subcompact Hatchbacks	#N/A	673	606
Two-wheelers	#N/A	670	593
Aggregate BEV charging load	#N/A	**673**	**604**

* Source: (CEA, 2016)
Note that the grid emission factors are different for each BEV type because their charging load profiles are different.

Two observations emerge from the table. First, even under the BAU scenario, significant decarbonization of the Indian grid is expected. This is mainly due to renewable capacity expansion already planned in the 12^{th} Plan and significant expansion of the nuclear and hydro capacity. Moreover, most of the new coal capacity in India is increasingly more efficient based on super-critical or ultra-super-critical technologies. In fact, from 2017 onward, the government has mandated that all new coal capacity addition to be only super-critical or ultra-super-critical. Second, the temporally explicit emission factors for BEV charging load (two-wheelers, in particular) are generally lower than the non-BEV electric load with the exception of Vans. This is mainly due to the fact that most of the BEV charging occurs during daytime hours (Figure 4); the grid emission factors during daytime are significantly lower because both wind and solar energy are available to the grid. In case of Vans, they take much longer to charge due to larger battery sizes and thus their charging extends into the early morning hours with limited generation from low-carbon sources.

Using these grid emission factors and equations described in section 2.3, Figure 7 shows the CO2 emissions per km for ICE vehicles as well as BEVs.

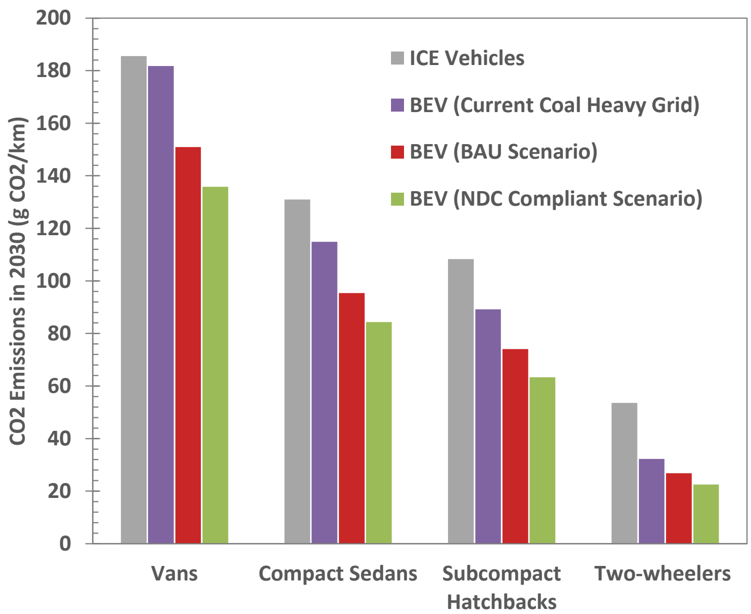


Figure 7: CO_2 emissions per km from ICE vehicles and BEVs in 2030

As shown in Figure 7, our study finds that BEVs have significantly lower end-use CO2 emissions per km than those by ICE vehicles. We find that in the NDC compliant scenario, on a gCO_2/km basis, BEVs can offer a reduction of nearly 35-37% in case of cars (Vans, Compact Sedans and Subcompact Hatchbacks) and nearly 50% in case of two-wheelers. Even if we assume that none of decarbonization measures in the BAU plan materialize and the grid in 2030 remains as coal heavy as it was in 2015, BEVs are still found to reduce the CO2 emissions per km by 5-12% in case of cars and over 35% in case of 2-wheelers.

Figure 8 shows total CO2 emissions by passenger vehicles (cars and 2-wheelers) in India up to 2050 if: (a) all passenger vehicles are ICE based, and (b) all vehicle sales beyond 2030 are BEVs.

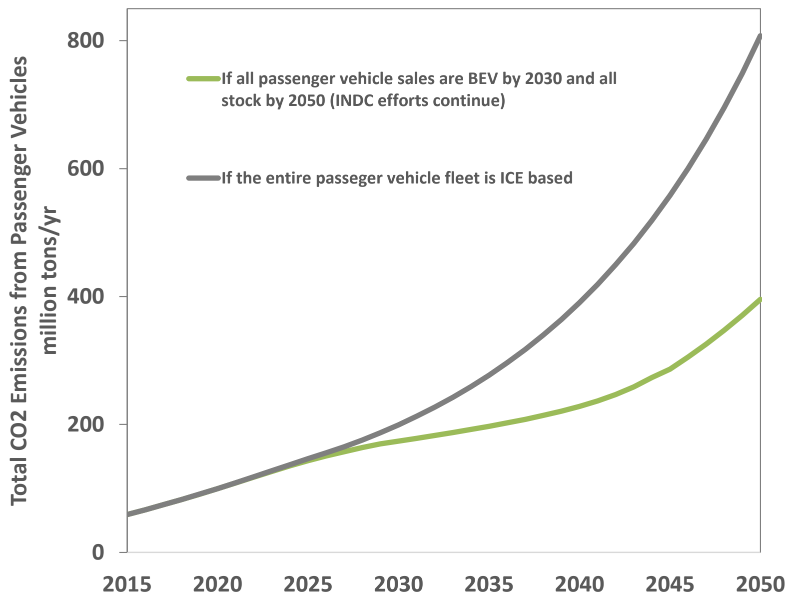


Figure 8: Total CO2 Emissions from Passenger Vehicles in India (million tons/yr)

If the NDC compliant efforts of grid decarbonization continue beyond 2030, passenger transport electrification alone can lower GHG emissions by ~400 million tons per year by 2050 (about 5% of total GHG emissions by 2050)[5]. However, if the clean power targets become more ambitious in future, even more emissions reductions are possible from transport sector.

3.5.BEVs can avoid crude oil imports

By 2030, BEVs can reduce the total crude oil consumption by 177 millon barrels/year (8% of total crude oil consumption by 2030).[6] By 2030 or so, it is projected that more than 80% of the crude oil consumption in India would be imported, implying that the entire reduction in crude oil consumption can potentially avoid oil imports (Planning Commission, 2014). Assuming a conservative crude oil price of $40/barrel, BEVs could reduce the oil imports by $7 billion/yr by 2030 (about Rs 50,000 Cr/year).

Figure 9 shows the total crude oil consumption by the passenger vehicle fleet (2-wheelers and cars) up to 2050 assuming the vehicle sales growth continues at the historical rate beyond 2030 as well. If all vehicle sales by 2030 and beyond are BEVs, all ICE vehicles purchased before 2030 retire by mid-2040 and total crude oil consumption by the passenger vehicle fleet becomes zero.

[5] India's total GHG emissions by 2050 are expected to be about 8 billion tons per year by 2050 (Gambhir, Napp, Emmott, & Anandarajah, 2014).

[6] In 2015, India's total crude oil consumption was 1,322 million barrels/yr. It is expected to increase to 2,246 million barrels/yr by 2030 and to 3,199 million barrels/yr by 2040 (IEA, 2015; Karali et al., 2017).

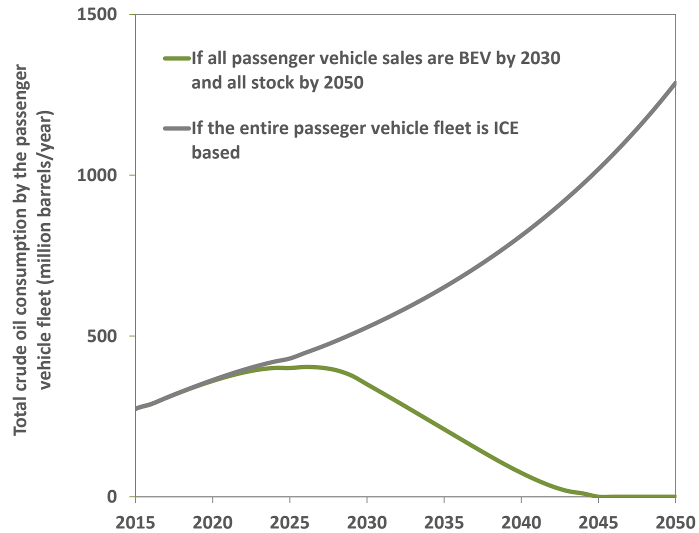
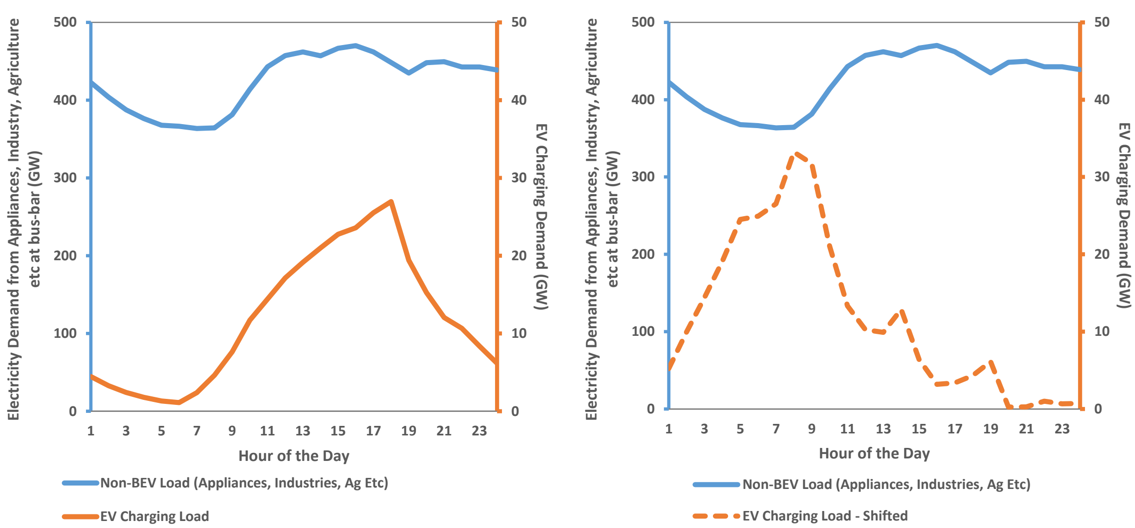


Figure 9: Total Crude Oil Consumption by the Passenger Vehicle Fleet (million barrels/yr)

By 2050, total avoided crude oil consumption would be as high as 1,287 million barrels/yr (28% of total crude oil consumption in 2050) and reduction in the oil import expenses by $51 billion/yr (Rs 350,000 Cr/yr).[7]

3.6.Smart charging and RE integration

BEV charging load can potentially be shifted to a different time of the day in order to reduce the total system cost. Such load shifting is called as smart charging. Figure 10 shows the average hourly BEV charging load with and without smart charging for the BAU scenario in May 2030.



(a) Fixed Charging

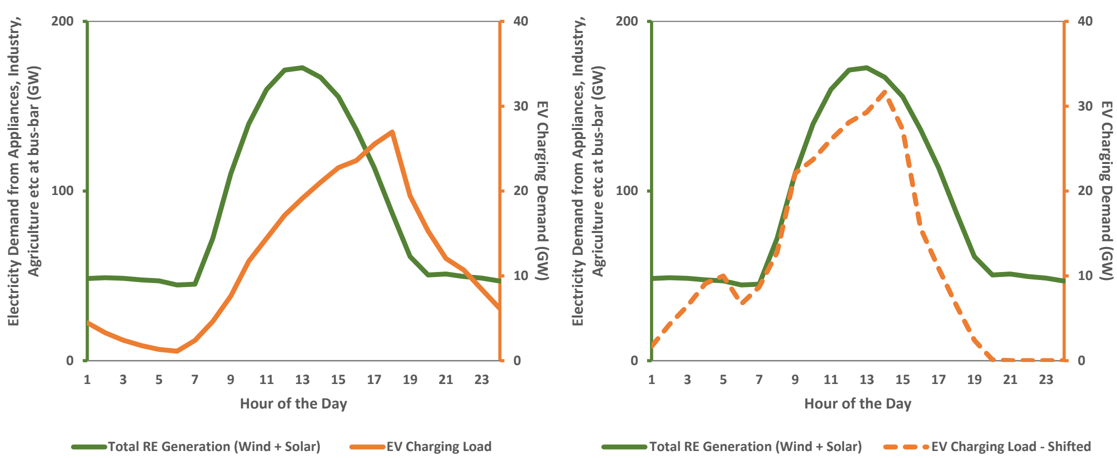
(b) Smart charging

[7] Based on IEA (2015) and Karali et al. (2017), we project that by 2050, the total crude oil consumption in India would be 4,556 million barrels/yr.

Figure 10: Average hourly load curve and BEV Charging Load – BAU Scenario (May 2030)

A large part of the charging load gets shifted to the early morning when the non-BEV electricity load is the lowest and most of the electricity generation is coal based i.e. least cost. Although this would increase the charging load's temporally explicit grid emission factor relative to the fixed load case, the CO2 emissions per km would still be lower than the ICE vehicles. Also, note that such large load shifting is made possible by the large number of two-wheelers with small batteries that make up the fleet. Since a two-wheeler can be fully charged within an hour and has high fuel efficiency, two-wheeler owners can move their charging to almost any hour of the day without affecting their trips.

Figure 11 shows the BEV charging profiles with and without smart charging in case of the NDC compliant scenario for May 2030. The figure also shows the average hourly total RE generation (solar and wind).



(a) Fixed Charging

(b) Smart charging

Figure 11: Average hourly RE generation and BEV Charging Load – NDC Compliant Scenario (May 2030)

The BEV charging load shifts almost entirely to the day-time in order to match the solar generation curve. This is primarily because there is significant solar generation during the day that requires the coal power plants to operate inefficiently at their technical minimum levels or curtail renewable energy; with smart charging, most of the BEV charging load shifts in order to avoid such curtailment or inefficient operation. Also, since most of the BEV charging occurs during the solar generation hours, its temporally explicit grid emission factors are lower than the fixed (non-smart) charging case.

Table 16 shows the impact of smart charging on generation capacity investments and average cost of generation.

Table 16: Generation Capacity Expansion (GW) and Average Cost of Generation (Rs/kWh)

		BAU Scenario		NDC Compliant	
		Fixed BEV Charging	Smart BEV Charging	Fixed BEV Charging	Smart BEV Charging
Installed Capacity (GW)	Coal	415	415	361	345
	Gas	19	19	24	19
Average Cost of Generation (Rs/kWh)		2.93	2.90	3.04	2.99

In the BAU scenario, smart charging does not have any impact on the generation investments but it would lower the average cost of generation by 0.7%. In the NDC compliant scenario, smart charging can enable cost-effective grid integration in three ways. First, since the BEV charging load follows the RE generation (especially solar PV), significant RE curtailment could be avoided during the day. Second, smart charging would reduce the net load ramps[8] that the conventional capacity has to meet – especially around 6 or 7 PM when the solar PV generation is dropping and the evening electricity load is increasing. And thirdly, smart charging can provide significant load reduction during the evening hours. So, by 2030, about 16 GW of Coal generation capacity and 5 GW of Gas capacity (Rs 100 Thousand Cr of total investment) could be avoided. As a result, with smart charging the reduction in the average generation cost would be 1.6% in the NDC compliant scenario. Furthermore, there are several other ancillary services that smart charging can offer including the last mile voltage or reactive power support through Vehicles to Grid (V2G) mechanisms, which would be assessed in our future work.

4 Conclusion

In this report, we have assessed the impact on a range of stakeholders of electrification of all passenger vehicle sales (cars and two-wheelers) in India by 2030. Specifically, we have addressed the following questions: (a) how does the total vehicle ownership cost of BEVs compare with the conventional vehicles, (b) what is the additional load due BEV charging, (c) what is the impact on the power sector investments, costs, and utility revenue, (d) how can smart BEV charging help renewable energy grid integration, (e) what is the impact on the crude oil imports, and (f) what is the impact on the GHG emissions. We conduct the analysis using three simulation-optimization models that are soft-linked: (a) PEVI, which is an agent based BEV travel and charging demand model that simulates BEV driving and charging behavior, (b) PLEXOS, which is an industry standard simulation software for least-cost investment planning and economic dispatch of the

[8] Net load ramp is hour to hour (or any time block) change in the load after integration renewable energy i.e. load minus RE generation. The conventional generation capacity has to meet the net load in any system.

power system, and (c) Economic and Environmental Impacts model, which is a spreadsheet based tool that assesses the impact on emissions, oil imports, and utility finances.

We use historical data to project the future BEV sales and stock. We use a comprehensive travel demand survey in the New Delhi Metropolitan region and assume that by 2030, the travel demand pattern in rest of the country is the same. We then use the manufacturer labeled fuel efficiency numbers for ICE as well as BEVs (2015) and adjust them to reflect the technology improvements by 2030 based on a vehicle technology assessment in the US. Using the assumptions on travel demand in 2030, total BEV penetration and efficiency, and agent based modeling of the charging behavior, PEVI estimates the BEV charging load for each hour of the year. Using official government data and historical trends, we project hourly electricity demand in the country from sources other than BEVs. We then simulate the 2030 power system in India using certain assumptions on operational constraints and by creating the following two scenarios for the generation capacity mix: (a) Business as Usual (BAU), which includes the new electricity generation investments that have been identified in India's 12th five year plan (up to 2022), extrapolated to 2030, and (b) NDC Compliant Scenario, which includes the aggressive RE targets committed to by India in its NDC (100 GW solar and 60 GW wind by 2022), extrapolated to 2030. In PLEXOS, we simulate least cost generation capacity expansion and hourly economic grid dispatch for each scenario so that the electricity demand (non-BEV as well as BEV) is fully met. We then use the capacity expansion and hourly power plant operation results to (a) estimate the temporally explicit grid emission factors, which are in turn used to assess the BEV emissions, (b) assess how smart BEV charging could reduce the overall system cost, (c) assess the total BEV charging load and the impact on utility finances. We also conduct sensitivity analysis to assess the robustness of our findings given the uncertainties in a few key parameters.

Between 2015 and 2030, the incremental capital cost of BEVs over ICE vehicles is expected to drop over 75%. As a result, we find that BEV owners benefit significantly when they switch from ICE vehicles i.e. the total incremental cost of BEVs is significantly lower than the annual fuel cost of ICE vehicles. Also, the share of capital cost in the total incremental BEV cost is as high as 75% in 2015 and drops to about 30% by 2030. Therefore, in the initial years, BEV owner's benefit is highly sensitive to the interest rate; BEV incentive program with preferential financing is, thus, crucial for early adoption. Such incentive programs could be run by a third party and given the significant benefits to BEV owners as well as power sector at large, they may not need any financial or fiscal support from government; they may be financed entirely from power sector revenue.

We find that despite aggressive vehicle electrification, the additional load added due to BEV charging by 2030 is less than 3% of the total electricity load in India (by energy). This is mainly because of the following three reasons: (a) In most urban areas of India, the rapid increase in electricity demand from numerous other end-uses (particularly air conditioners) will be very large over the next 15-20 years, and (b) the vehicle penetration by 2030 is dominated by 2-wheelers that require much less energy than cars, and (c) the overall vehicle penetration is expected to be significantly lower than the other industrialized or emerging economies.

Although the additional load due to BEV charging is minor, that could still serve as a valuable additional revenue source for the financially distressed distribution utilities. By 2030, BEV charging load could earn about Rs 80,000 Cr of additional revenue for utilities, which approximately equals the total utility financial deficit and the total government subsidy support to utilities in 2014, combined. One of the important assumptions in this study is the access to a public charging infrastructure to all BEV owners, which could be a major challenge given the aggressive electrification levels. Deployment of such charging infrastructure could potentially be financed using the additional revenue from BEV charging. Also, it is likely that BEV adoption, especially in the initial years, would be limited in a few major urban centers. Although at the national level, the incremental BEV charging load is found to be minor, its impacts on the local distribution network, especially in the potential hotspots, could be significant. The problem may worsen (or subside, depending on whether BEVs have smart charging capability) if the BEV hotspots coincide with the solar PV hotspots and may require significant distribution system upgrades. Analyzing such local distribution system impacts is important and is part of our future works.

Our study finds that BEVs have significantly lower end-use CO2 emissions per km than those by ICE vehicles. We find that in the NDC compliant scenario, on a gCO_2/km basis, BEVs can offer a reduction of nearly 35-37% in case of cars (Vans, Compact Sedans and Subcompact Hatchbacks) and nearly 50% in case of two-wheelers. Even if we assume that none of decarbonization measures in the BAU plan materialize and the grid in 2030 remains as coal heavy as it was in 2015, BEVs are still found to reduce the CO2 emissions per km by 5-12% in case of cars and over 35% in case of 2-wheelers. If the NDC compliant efforts of grid decarbonization continue beyond 2030, passenger transport electrification alone can lower GHG emissions by ~400 million tons per year by 2050 (5% of India's total GHG emissions by 2050). If the clean power targets become more ambitious in future, even more emissions reductions are possible from transport sector.

BEVs can also avoid significant crude oil imports in India: by 2030, BEVs can avoid importing 177 millon barrels/yr (8% of total crude oil consumption in 2030), and by 2050, nearly 1,287 million barrels/yr (28% of total). Assuming a conservative crude oil price of $40/barrel, the total reduction in the oil import bill would be about $7 billion/yr by 2030 and $51 billion/yr by 2050.

With smart charging, BEVs can potentially reduce the total cost of electricity generation. In the BAU scenario, smart charging does not have any impact on the generation investments but it would lower the average cost of generation by 0.7%. In the NDC compliant scenario, smart charging can enable cost-effective grid integration in three ways. First, since the BEV charging load follows the RE generation (especially solar PV), significant RE curtailment could be avoided during the day. Second, smart charging would reduce the net load ramps that the conventional capacity has to meet – especially around 6 or 7 PM when the solar PV generation is dropping and the evening electricity load is increasing. And thirdly, smart charging can provide significant load reduction during the evening hours. So, by 2030, about 16 GW of Coal generation capacity and 5 GW of Gas capacity (Rs 100 Thousand Cr of total investment) could be avoided. As a result, with smart charging, the reduction in the average generation cost would be 1.6% in the NDC compliant scenario. Furthermore, there are several other ancillary services that smart charging can offer including the last mile voltage or reactive power support through Vehicles to Grid (V2G) mechanisms, which would be assessed in our future work. Note that deploying the public charging infrastructure for BEVs and enabling smart charging would involve additional costs. Based on the experience of the appliance level demand response and smart control technologies, the additional cost of enabling smart charging, especially for private BEV chargers, would be minor (Shah, Abhyankar, Phadke, & Ghatikar, 2015). The infrastructure cost for deploying the public charging infrastructure could involve substantial capital investments, especially by electric utilities. However, quantifying such additional investments is outside the scope of this paper and would be evaluated in our future work.

Appendix 1: Assumptions on Power System Modeling

5.1 Hourly Solar and Wind Generation Forecast by Region

5.1.1 Wind Energy Generation Profiles

India's current wind installed capacity is more than 21GW and has been growing consistently over the last 10 years or so. Indian wind energy generation is highly seasonal and peaks during monsoon. For Financial Year (FY) 2030, hourly profiles of wind energy generation have been forecasted using the actual historical generation data for the FYs 2010 through 2013 from the states of Tamil Nadu, Karnataka, Maharashtra, and Gujarat. These states together cover over 80% of the existing wind installed capacity and over 75% of the total wind potential in India (CWET, 2014; Phadke, 2012). Hourly wind generation data was sourced from the websites of the respective state load dispatch centers. We understand that the reported wind generation does not take into account the curtailment. Therefore, actual data may not represent the true profiles of wind generation. Unfortunately, the data on exact amount and timing of curtailment is not available. Secondly, industry experts suggest that wind energy curtailment was quite limited until the FY 2012-2013 (Phadke, Abhyankar, & Rao, 2014).

The following chart shows the seasonal averages of the wind energy generation (as a share of the installed capacity) in the key states mentioned above.

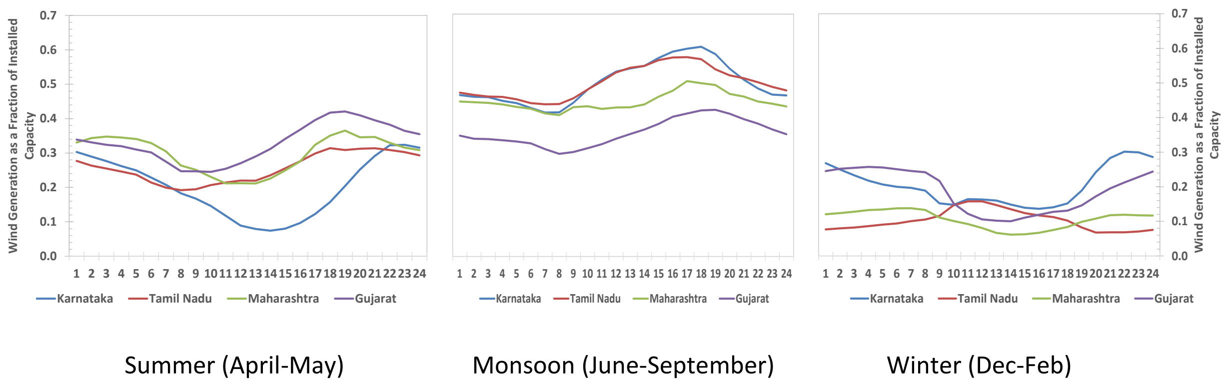


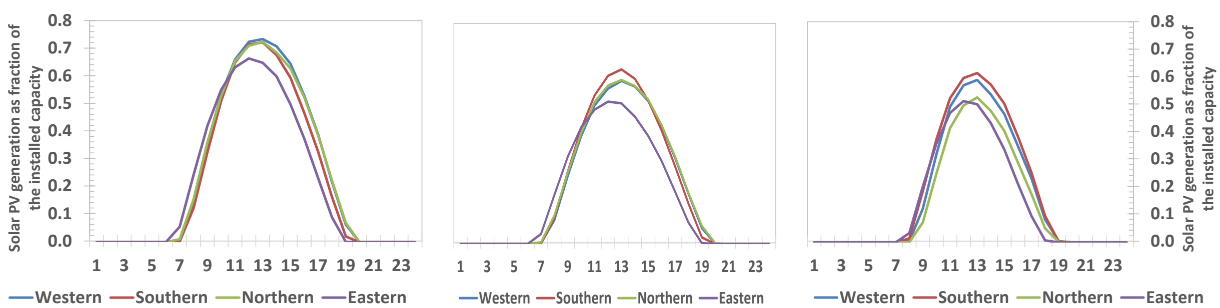
Figure 12: Average daily wind generation curve (of existing capacity) in key states for key states

It can be seen that there is significant seasonal variation in wind generation in all states. Wind generation peaks in monsoon (June through September) and drops significantly in the winter. However, the diurnal pattern of wind generation in a season is very similar across all states. In Monsoon and Summer, the wind generation peaks late afternoon or early evening which matches with the overall demand patterns in these seasons.

For future wind capacity addition, we used the wind energy potential numbers in each state from our previous study assessing the wind energy potential in India (Phadke, 2012). For estimating the hourly wind generation profile for a future year (2030, in this case), the approach in other studies has been to use time-series data from meso-scale models. But in this study, we are scaling the actual generation data for the current year, which assumes that the additional capacity will be installed in the same regions, and hence will have the same profiles. However, in reality, capacity addition will occur in different areas, which is likely to reduce the overall variability of the wind generation at the regional level due to geographic diversity of the wind installations. However, given that verified hourly wind resource data was not available in the public domain, we could not use wind resource data from undeveloped sites. Thus, wind variability in this analysis would be high and the capacity value conservative; and could be seen as the worst-case scenario of the future wind capacity addition. More detailed analysis (for example using time-series meso-scale resource data) is needed to improve the profiles of wind generation used in this analysis.

5.1.2 Solar Energy Generation Profiles

Unlike wind, total grid connected solar PV capacity in India is only 3 GW (2015) albeit it is increasing rapidly given the dropping costs and favorable regulatory and policy environments. The largest capacity of 1.5 GW is operational in the state of Gujarat. However, several studies have shown practically infinite solar energy potential in India. For estimating the hourly generation profile, we chose 100 sites spread over all 5 regions with best quality solar resource (measured in DNI and GHI kWh/m2) using the national solar energy dataset for India developed by the National Renewable Energy Laboratory that contains hourly irradiance data for every 5kmx5km grid in India. The solar irradiance data was then fed into the System Advisor Model (SAM) also developed by the National Renewable Energy Laboratory to get the solar PV output at the chosen 100 sites. The hourly PV output profiles of the sites in each region was averaged to arrive at the regional solar PV generation profile. The average generation profiles for each season are shown in the charts below.



Summer (April-May) Monsoon(June-September) Winter (Dec-Feb)

Figure 13: Average daily solar generation curves for each region

As can be seen from the charts that the solar resource peaks in the summer and drops in winter. However, the seasonal variation is not as dramatic as that in case of wind. It may appear that there is not much difference in the average resource quality of the western, northern and southern regions; however, resource quality would vary significantly at the individual site level. Most of India's best quality solar resource is concentrated in the western and the northern region. Note that averaging of the solar profiles over multiple sites may underestimate the total variability in solar PV generation. On the other hand, as explained in the previous section on wind energy, we assume that the future solar capacity is added at the sites selected for estimating the hourly generation profile. Therefore, it may not fully capture the benefits of geographic diversity and may overestimate the variability to some extent. A comprehensive

GIS based analysis for site selection would correct these errors; however, that is outside the scope of this research and hence not considered.

5.2 Operational Parameters of Generators

Table 24 in Appendix 2 summarizes our assumptions on the operational characteristics (unit size, heat rates, ramp rates, minimum stable level, etc.) of the power plants. The values have been estimated using the actual hourly dispatch data, actual outage and other performance data, regulatory orders on heat rates and costs, other relevant literature, and actual practices in India. Currently, the combined cycle (gas) plants in India are not operated in the open cycle mode (gas turbine only; no waste heat recovery). However, by 2030, we assume that the gas turbines in the combined cycle plants could be operated independently in open cycle mode, which enhances the system flexibility considerably.

5.3 Hydro Capacity and Energy Model

Hydro capacity is modeled using a fixed monthly energy budget. Based on the historical dispatch and minimum flow and spill constraints we estimated the capacity factors of the hydro power plants for every month. Subject to such monthly capacity factor constraints, reservoir based hydro power plants are assumed to be optimally dispatched. The following table shows the monthly capacity factors for hydro plants in each region:

Table 17: Monthly Capacity Factors of Hydroelectric Projects for Each Region

	East	North-East	West	South	North
January	18%	25%	30%	28%	24%
February	18%	23%	27%	32%	29%
March	19%	22%	26%	40%	36%
April	25%	34%	26%	31%	40%
May	18%	49%	26%	27%	62%
June	27%	61%	23%	27%	64%
July	28%	80%	27%	31%	67%
August	27%	83%	47%	37%	67%
September	32%	67%	49%	54%	71%
October	26%	60%	38%	39%	40%
November	16%	40%	26%	29%	29%
December	8%	26%	21%	24%	26%
Annual Average	***22%***	***47%***	***30%***	***33%***	***46%***

Data sources: (CEA, 2015a, 2015b)

Hydro capacity factors depend on a variety of factors including high recharge season (such as summer or monsoon), irrigation and minimum flow requirements, etc.

More than 50% of India's current hydro capacity is run of the river; output of the run-of-the-river plants is assumed to be flat subject to the monthly capacity factor constraint. India has limited pumped storage capacity; they are modeled using a weekly energy balance i.e. the head and tail storage ponds return to their initial volumes at the end of each week. We ran a sensitivity case with daily energy balance but given the small pumped storage capacity, it does not make a large difference to the overall results.

5.4 Costs

The following tables show the assumptions on capital cost and fixed O&M costs for each technology. The current capital costs of renewable technologies have been taken from the Central Electricity Regulatory Commission's (CERC) tariff regulations 2015. CERC's tariff regulations for the conventional projects do not mention the capital cost norms. For coal based power projects, we have used CERC's interim order (2012) on benchmarking the capital costs of thermal projects (CERC, 2012). For gas, diesel, and hydro projects, we have used industry norms per our previous report (Abhyankar et al., 2013a). Capital and O&M costs of the nuclear projects have been taken from (Ramana et al., 2005).

The following table shows the current year capital and O&M costs for all technologies considered in this analysis.

Table 18: Capital cost (overnight; excluding interest during construction) and fixed O&M cost of the generating plants (2015Rs)

Generation Technology	Capital Cost Rs Cr/MW (2015)	Fixed O&M Cost Rs Cr/MW/yr (2015)	Fixed O&M Cost as % of Capital Cost
Coal (>600 MW units)	5.37	0.14	2.7%
Coal (500 MW units)	5.08	0.16	3.1%
Gas CCGT (Combined cycle)	4.80	0.15	3.1%
Gas CT (Open Cycle)	4.20	0.15	3.5%
Diesel	3.60	0.13	3.5%
Nuclear	5.71	0.11	2.0%
Hydro (<200 MW)	8.00	0.32	4.0%
Hydro (>200 MW)	8.00	0.20	2.5%
Small Hydro (between 5 and 25MW) - excluding Himachal Pradesh, Uttaranchal and North-Eastern States	5.93	0.17	2.8%
Small Hydro (between 5 and 25MW) - Himachal, Uttaranchal and North-Eastern States only	7.54	0.21	2.8%
Biomass (for rice straw and juliflora based projects with water cooled condenser)	6.10	0.45	7.3%
Wind (Onshore)	6.19	0.11	1.7%
Solar PV	5.87	0.13	2.2%

Data Sources: (Abhyankar et al., 2013a; CERC, 2012, 2014, 2015; Ramana et al., 2005)

Note that the capital cost of coal units shown above does not include the additional investment needed to meet the new norms for Particulate Matter, SOx, and NOx emissions (2015); such investments may increase the capital cost of the coal units by over 10% or so.

The economic life of all generation assets has been assumed to be 25 years and the weighted average cost of capital is assumed to be 12.8% (i.e. weighted average of the 14% Return on Equity (ROE) and 10% interest rate assuming a debt to equity ratio of 70:30).

The solar PV cost in CERC regulations matches up with the prices quoted in the latest solar PV reverse auctions in India. In the state of Madhya Pradesh, a reverse auction concluded in July 2015 received a winning bid of Rs 5.05/kWh (Business Standard, 2015). Using CERC's capital cost and O&M cost norms, WACC of 12.8%, and assuming a capacity factor of 21%, the levelized cost of electricity for a solar PV plant comes to Rs 5.07/kWh.

Given that most of the conventional technologies have already matured, their capital costs are not assumed to change until 2030. Renewable technologies especially solar PV still have high learning rates and thus their costs would reduce between 2015 and 2030. Our assumptions for such reduction are shown in the following table.

Table 19: Wind and Solar PV Capital Cost Reduction in Future

	2015 Capital Cost Rs Cr/MW	Average annual price reduction (%)	2030 Capital Cost Rs Cr/MW
Wind	6.19	-	6.19
Solar PV	5.87	4.7%	2.85

For solar PVs, we used the capital cost trajectory projected in the Global PV Market Outlook 2015 by BNEF (BNEF, 2015). Based on their capital cost projections, we estimated the average annual reduction in PV prices to be 4.7% between 2015 and 2020. We apply the same annual reduction up to 2030. Lawrence Berkeley National Lab's PV market assessment in the US reports similar cost reductions (Barbose, Weaver, & Darghouth, 2014). For wind, we use the historical capital cost data in the US from LBNL's wind technologies assessment report (Wiser & Bolinger, 2015). Although there have been significant annual fluctuations in the wind capital cost, the capital cost has not changed much over the last 10 years or so.[9] Therefore, going forward, we have assumed that wind capital cost would stay the same until 2030.

5.5 Fuel Availability and Prices

Domestic gas and coal availability is constrained in India. Coal availability for the power sector has been taken from the Ministry of Coal's projections in the 12th five-year plan up to 2017; the same trend has been projected up to 2030. Domestic gas availability is highly constrained too and several gas-based power plants are stranded because of non-availability of gas. We have assumed that the domestic gas availability for power sector in future remains the same as the current quantity. If the system needs more

[9] Wind Power Purchase Agreement (PPA) prices have dropped significantly in the recent years though; in 2014, the average levelized wind PPA price in the US was $23/MWh including the Production or Investment Tax Credits (Wiser & Bolinger, 2015). If the tax credits are excluded, the levelized price would be about $40/MWh (approximately Rs 2.5/kWh).

natural gas, it will have to be imported (LNG) at international prices. We have not assumed any restrictions on imported coal and gas, and other fuels such as diesel and biomass.

Table 20: Fuel Availability and Calorific Value Assumptions

Fuel	Max Availability in FY 2030	Gross Calorific Value
Domestic Coal	1071 Million Tons/yr	4000 kCal/kg
Imported Coal	Unlimited	5400 kCal/kg
Domestic Gas	29 bcm/yr	9000 kCal/m^3
Imported LNG	Unlimited	9000 kCal/m^3
Diesel	Unlimited	10000 kCal/lit
Biomass	Unlimited	3000 kCal/kg

Data source for coal and gas availability: (Planning Commission, 2012)

Domestic coal price data have been taken from Coal India Limited's (CIL) annual reports as the average price of coal sold by CIL in that year (CIL, 2011, 2015).[10] Historical trends in the imported coal prices have been taken from the BP Statistical Review (Asian marker price) (BP, 2015); current international. Domestic natural gas price has been taken from the Ministry of Petroleum and Natural Gas' orders in various years/months. Imported LNG price for the current year (2015) has been taken from the media reports on the international LNG market, while the historical trend in the imported LNG price in India has been taken from (Sen, 2015). The fuel prices are assumed to increase at the long-run (10-year) compounded average growth rate. However, note that the historical fuel prices are listed in nominal dollars (or rupees, as the case may be). In order to assess the price trend in real terms, we deflated the nominal prices using the annual inflation rate (Wholesale Price Index (WPI)); the WPI data was sourced from (OEA, 2015). The following table shows the current fuel prices, long-run growth nominal and real growth rates, and the projected 2030 fuel prices expressed as 2015 dollars or rupees.

Table 21: Fuel Price Assumptions

Fuel	Fuel Price in 2015 (FOB)	Escalation in Nominal Price (10-yr CAGR) %	Inflation adjusted (real) escalation rate % p.a.	Fuel Price in 2030 (FOB)
Domestic Coal (Rs/Ton)	1948	7.5%	1.4%	2400
Imported Coal ($/Ton)	77.89	6.9%	0.7%	86
Domestic Gas ($/mmbtu)	4.66	8.8%	2.7%	6.9
LNG ($/mmbtu)	11	6.2%	0.1%	11

Data Sources: *Ibid*

[10] Coal India Limited controls more than 80% of India's total coal production and about 80% of its coal is sold to the power sector.

Note: All price and cost numbers refer to 2015 real values.

Note that these are the FOB (free on board) prices and do not include the fuel transportation and LNG regasification etc. costs. Those costs depend on the locations of the plant and the fuel sources. Domestic coal transportation costs have been taken from regulatory proceedings and tariff orders of the state and central generation utilities. Imported coal plants are assumed to be located on the shore and therefore would not incur any domestic transportation charge except in cases of northern and eastern regions. The following table shows the coal transportation costs to each of the regions:

Table 22: Average Coal Transportation Costs to Each Region

	Domestic Coal (Rs/Ton)	Imported Coal	
		International transportation ($/Ton)	Domestic transportation (Rs/Ton)
North	1200	30	1500
West	1500	30	-
South	1800	30	-
East	1000	30	1500

Data source: Authors' estimates, Regulatory filings

Note: All price and cost numbers refer to 2015 real values.

Similarly, imported LNG based plants are not assumed to incur domestic gas pipeline charges, except in cases of northern and eastern regions; all LNG imports are assumed to incur a regasification cost of $0.5/MMBTU. In case of domestic gas, we have assumed two sources viz. (a) Bombay high field (off the western coast) near Mumbai and, (b) KG-D6 field off the eastern coast near Andhra Pradesh. The following table shows the domestic gas and LNG transportation charges from these sources to each of the regions. The following table shows the gas transportation costs to each of the regions:

Table 23: Average Gas Transportation Costs to Each Region

	Domestic Gas ($/MMBTU)		Imported LNG ($/MMBTU)		
	Bombay High	KG D-6	International transportation	Regasification	Domestic Pipeline
North	1.5	2.0	1.0	0.5	1.5
West	0.5	1.5	1.0	0.5	0
South	1.5	0.5	1.5	0.5	0
East	#N/A	1.5	1.5	0.5	1.5

Data source: Authors' estimates, PNGRB website

Note: All price and cost numbers refer to 2015 real values.

5.6 Transmission

In 2013, southern regional grid in India was integrated with the northern regional grid. Additionally, there have been significant transmission investments planned in the near future. Going forward, we have assumed no constraints on transmission primarily to assess the transmission transfer capability requirements between the regions in future.

Appendix 2: Assumptions on Operational Characteristics of Generating Plants

Table 24: Assumptions on Operational Characteristics of Generating Plants

Generator Technology	Region	Generator_Name	Average Unit Size (MW)	Min Stable Factor (%)	Gross Heat Rate (GJ/MWh)	Start Cost ($)	Shutdo wn Cost ($)	Min Up Time (hrs)	Min Down Time (hrs)	Max Ramp Up (MW/min.)	Max Ramp Down (MW/min.)	Auxiliary Consump tion (%)	Planned Mainte nance Rate (%)	Forced Outage Rate (%)
Biomass+Cogen	East	ER_Biomass	20	20	16	100	100	1	1	0.5	0.5	10	10	10
Biomass+Cogen	North	NR_Biomass	20	20	16	100	100	1	1	0.5	0.5	10	10	10
Biomass+Cogen	South	SR_Biomass	20	20	16	100	100	1	1	0.5	0.5	10	10	10
Biomass+Cogen	West	WR_Biomass	20	20	16	100	100	1	1	0.5	0.5	10	10	10
Coal	East	ER_Old_<210	87	55	12	8741	8741	24	24	0.87	0.87	10.6	12.3	32.9
Coal	East	ER_Old_210/250	220	55	11.2	22000	22000	24	24	2.2	2.2	9	2.8	11.9
Coal	East	ER_Old_500/600	516	55	10.8	51579	51579	24	24	5.16	5.16	6.5	4.9	11.8
Coal	East	ER_Old_660	660	55	10	66000	66000	24	24	6.6	6.6	8.1	5	11.8
Coal	East	ER_Old_Other	390	55	11	39000	39000	24	24	3.9	3.9	10.5	0.9	18.6
Coal	East	ER_SuperCritical	660	55	9	66000	66000	24	24	6.6	6.6	8	5	5
Coal	North_East	NER_Old	30	0	12	3000	3000	24	24	0.3	0.3	10.6	0	100
Coal	North	NR_Old_<210	114	55	12.2	11378	11378	24	24	1.14	1.14	10.6	13.3	14
Coal	North	NR_Old_210/250	222	55	11.4	22238	22238	24	24	2.22	2.22	9	3.6	8.4
Coal	North	NR_Old_500/600	531	55	10.8	53077	53077	24	24	5.31	5.31	6.5	5.5	5
Coal	North	NR_Old_660	660	55	9.7	66000	66000	24	24	6.6	6.6	8.1	5	5
Coal	North	NR_Old_Other	348	55	10.8	34750	34750	24	24	3.48	3.48	10.5	1.2	19.2
Coal	North	NR_SuperCritical	660	55	9	66000	66000	24	24	6.6	6.6	8	5	5
Coal	South	SR_Old_<210	99	55	12.2	9925	9925	24	24	0.99	0.99	10.6	3.7	10.9
Coal	South	SR_Old_210/250	215	55	11.4	21455	21455	24	24	2.15	2.15	9	5.6	5.7
Coal	South	SR_Old_500/600	512	55	10.8	51176	51176	24	24	5.12	5.12	6.5	3.7	3.5
Coal	South	SR_Old_660	660	55	9.7	66000	66000	24	24	6.6	6.6	8.1	5	3.5
Coal	South	SR_Old_Other	300	55	10.8	30000	30000	24	24	3	3	10.5	8.2	8.6
Coal	South	SR_SuperCritical	660	55	9	66000	66000	24	24	6.6	6.6	8	5	5
Coal	West	WR_Old_<210	106	55	12.2	10603	10603	24	24	1.06	1.06	10.6	6.1	22.9
Coal	West	WR_Old_210/250	220	55	11.4	21968	21968	24	24	2.2	2.2	9	6	7.2
Coal	West	WR_Old_500/600	505	55	10.8	50500	50500	24	24	5.05	5.05	6.5	3.6	4.3
Coal	West	WR_Old_660	774	55	9.7	77429	77429	24	24	7.74	7.74	8.1	0	15.4
Coal	West	WR_Old_Other	312	55	10.8	31200	31200	24	24	3.12	3.12	10.5	1.3	10.8
Coal	West	WR_SuperCritical	660	55	9	66000	66000	24	24	6.6	6.6	8	5	5
Diesel	East	ER_Diesel	17.2	0	13.5	100	100			17.2	17.2	1	5	5

Generator Technology	Region	Generator_Name	Average Unit Size (MW)	Min Stable Factor (%)	Gross Heat Rate (GJ/MWh)	Start Cost ($)	Shutdown Cost ($)	Min Up Time (hrs)	Min Down Time (hrs)	Max Ramp Up (MW/min.)	Max Ramp Down (MW/min.)	Auxiliary Consumption (%)	Planned Maintenance Rate (%)	Forced Outage Rate (%)
Diesel	North_East	NER_Diesel	60	0	13.5	100	100			17.2	17.2	1	5	5
Diesel	North	NR_Diesel	13	0	13.5	100	100			13	13	1	5	5
Diesel	South	SR_Diesel	50	0	13.5	100	100			50	50	1	5	5
Diesel	West	WR_Diesel	17.5	0	13.5	100	100			17.5	17.5	1	5	5
Gas_CCGT	East	ER_CC_GT	25	10	12	250	250	1	1	2.5	2.5	1	5	5
Gas_CCGT	East	ER_CC_ST	11	40	14	1100	1100	6	6	0.04	0.04	5	10	10
Gas_CCGT	North_East	NER_CC_GT	21	10	12	214	214	1	1	2.14	2.14	1	5	5
Gas_CCGT	North_East	NER_CC_ST	11	40	14	1100	1100	6	6	0.04	0.04	5	10	10
Gas_CCGT	North	NR_CC_GT	79	10	12	794	794	1	1	7.94	7.94	1	5	5
Gas_CCGT	North	NR_CC_ST	106	40	14	10589	10589	6	6	0.39	0.39	5	10	10
Gas_CCGT	South	SR_CC_GT	85	10	12	852	852	1	1	8.52	8.52	1	5	5
Gas_CCGT	South	SR_CC_ST	84	40	14	8380	8380	6	6	0.31	0.31	5	10	10
Gas_CCGT	West	WR_CC_GT	155	10	12	1552	1552	1	1	15.52	15.52	1	5	5
Gas_CCGT	West	WR_CC_ST	112	40	14	11250	11250	6	6	0.41	0.41	5	10	10
Gas_CT	East	ER_CT	50	10	12	0	0	1	1	5	5	1	5	5
Gas_CT	North_East	NER_CT	50	10	12	0	0	1	1	5	5	1	5	5
Gas_CT	North	NR_CT	50	10	12	0	0	1	1	5	5	1	5	5
Gas_CT	South	SR_CT	50	10	12	0	0	1	1	5	5	1	5	5
Gas_CT	West	WR_CT	50	10	12	0	0	1	1	5	5	1	5	5
Hydro_Large	East	ER_Hydro_<=100	50	0	0	0	0			5	5	1	5	5
Hydro_Large	East	ER_Hydro_>100	150	0	0	0	0			15	15	1	5	5
Hydro_Large	North_East	NER_Hydro_<=100	29	0	0	0	0			2.9	2.9	1	5	5
Hydro_Large	North_East	NER_Hydro_>100	139	0	0	0	0			13.9	13.9	1	5	5
Hydro_Large	North	NR_Hydro_<=100	60	0	0	0	0			6	6	1	5	5
Hydro_Large	North	NR_Hydro_>100	163	0	0	0	0			16.3	16.3	1	5	5
Hydro_Large	South	SR_Hydro_<=100	29	0	0	0	0			2.9	2.9	1	5	5
Hydro_Large	South	SR_Hydro_>100	118	0	0	0	0			11.8	11.8	1	5	5
Hydro_Large	West	WR_Hydro_<=100	44	0	0	0	0			4.4	4.4	1	5	5
Hydro_Large	West	WR_Hydro_>100	154	0	0	0	0			15.4	15.4	1	5	5
Hydro_Small	East	ER_SmallHydro	20	0	0	0	0			20	20	1	5	5
Hydro_Small	North_East	NER_SmallHydro	20	0	0	0	0			20	20	1	5	5
Hydro_Small	North	NR_SmallHydro	20	0	0	0	0			20	20	1	5	5
Hydro_Small	South	SR_SmallHydro	20	0	0	0	0			20	20	1	5	5
Hydro_Small	West	WR_SmallHydro	20	0	0	0	0			20	20	1	5	5
Pumped Storage	East	ER_Hydro_PS	163	0	10	0	0			16.3	16.3	1	5	5
Pumped Storage	North_East	NER_Hydro_PS	142	0	10	0	0			14.2	14.2	1	5	5
Pumped Storage	North	NR_Hydro_PS	142	0	10	0	0			14.2	14.2	1	5	5

Generator Technology	Region	Generator_Name	Average Unit Size (MW)	Min Stable Factor (%)	Gross Heat Rate (GJ/MWh)	Start Cost ($)	Shutdown Cost ($)	Min Up Time (hrs)	Min Down Time (hrs)	Max Ramp Up (MW/min.)	Max Ramp Down (MW/min.)	Auxiliary Consumption (%)	Planned Maintenance Rate (%)	Forced Outage Rate (%)
Pumped Storage	South	SR_Hydro_PS	130	0	10	0	0			13	13	1	5	5
Pumped Storage	West	WR_Hydro_PS	142	0	10	0	0			14.2	14.2	1	5	5
Run of River	East	ER_Hydro_ROR	48	0	0	0				4.8	4.8	1	5	5
Run of River	North_East	NER_Hydro_ROR	63	0	0	0				6.3	6.3	1	5	5
Run of River	North	NR_Hydro_ROR	68	0	0	0				6.8	6.8	1	5	5
Run of River	South	SR_Hydro_ROR	21	0	0	0				2.1	2.1	1	5	5
Run of River	West	WR_Hydro_ROR	46	0	0	0				4.6	4.6	1	5	5
Nuclear	East	ER_Nuclear	410	70	10	100000	100000	96	96	0.1	0.1	10	10	10
Nuclear	North	NR_Nuclear	410	70	10	100000	100000	96	96	0.1	0.1	10	10	10
Nuclear	South	SR_Nuclear	410	70	10	100000	100000	96	96	0.1	0.1	10	10	10
Nuclear	West	WR_Nuclear	410	70	10	100000	100000	96	96	0.1	0.1	10	10	10

References

Abhyankar, N., Phadke, A., Sathaye, J., Bharvirkar, R., Johnson, A., Deshmukh, R., … Rao, A. (2013a). *Modeling Clean and Secure Energy Scenarios for the Indian Power Sector in 2030*. Lawrence Berkeley National Laboratory.

Abhyankar, N., Phadke, A., Sathaye, J., Bharvirkar, R., Johnson, A., Deshmukh, R., … Rao, A. (2013b). *Modeling Clean and Secure Energy Scenarios for the Indian Power Sector in 2030.* Lawrence Berkeley National Laboratory.

Axsen, J., Kurani, K. S., McCarthy, R., & Yang, C. (2011). Plug-in hybrid vehicle GHG impacts in California: Integrating consumer-informed recharge profiles with an electricity-dispatch model. *Energy Policy*, *39*(3), 1617–1629. https://doi.org/10.1016/j.enpol.2010.12.038

Barbose, G., Weaver, S., & Darghouth, N. (2014). Tracking the Sun VII: An Historical Summary of the Installed Price of Photoboltaics in the United States from 1998 to 2013. *Lawrence Berkeley National Laboratory, Berkeley, CA*.

BNEF. (2015). *2015 PV Market Outlook*. Bloomberg New Energy Finance.

Bose, R. K. (1998). Automotive energy use and emissions control: a simulation model to analyse transport strategies for Indian metropolises. *Energy Policy*, *26*(13), 1001–1016. https://doi.org/10.1016/S0301-4215(98)00045-7

BP. (2015). *BP Statistical Review of World Energy 2015*. British Petroleum.

Business Standard. (2015, July 16). Solar power tariff touches new low of Rs 5.05. Retrieved from http://www.business-standard.com/article/companies/solar-tariffs-reach-new-low-of-rs-5-05-115071501204_1.html

Campanari, S., Manzolini, G., & Garcia de la Iglesia, F. (2009). Energy analysis of electric vehicles using batteries or fuel cells through well-to-wheel driving cycle simulations. *Journal of Power Sources*, *186*(2), 464–477. https://doi.org/10.1016/j.jpowsour.2008.09.115

CEA. (2015a). *Executive Summary - Power Sector (March-15)*. New Delhi: Central Electricity Authority (Ministry of Power - Government of India). Retrieved from http://cea.nic.in/reports/monthly/executive_rep/mar15.pdf

CEA. (2015b). *Load Generation Balance Report 2015-16*. Central Electricity Authority (Government of India).

CEA. (2016). *CO2 Baseline Database for the Indian Power Sector*. Central Electricity Authority (Ministry of Power - Government of India). Retrieved from http://cea.nic.in/reports/others/thermal/tpece/cdm_co2/user_guide_ver11.pdf

CERC. Benchmark Capital Cost (Hard cost) for Thermal Power Stations with Coal as Fuel, Pub. L. No. L-1/103/CERC/2012 (2012).

CERC. Central Electricity Regulatory Commission (Terms and Conditions of Tariff) Regulations, 2014, Pub. L. No. 1/144/2013/CERC (2014).

CERC. (2015). *Central Electricity Regulatory Commission (Terms and Conditions for Tariff determination from Renewable Energy Sources) (Third Amendment) Regulations, 2015*. New Delhi: Central Electricity Regulatory Commission (Government of India).

CIL. (2011). *Annual Report 2010-11*. New Delhi: Coal India Limited.

CIL. (2015). *Annual Report 2014-15*. New Delhi: Coal India Limited.

CWET. (2014). *Wind Power Installed Capacity (MW) in India*. Centre for Wind Energy Technology (Ministry of New and Renewable Energy - Government of India). Retrieved from http://www.cwet.tn.nic.in/html/information_yw.html

Das, A., & Parikh, J. (2004). Transport scenarios in two metropolitan cities in India: Delhi and Mumbai. *Energy Conversion and Management*, *45*(15–16), 2603–2625. https://doi.org/10.1016/j.enconman.2003.08.019

DHI. (2012). *National Electric Mobility Mission Plan (NEMMP) 2020.* Department of Heavy Industry, Government of India. Retrieved from http://dhi.nic.in/NEMMP2020.pdf.

Doucette, R. T., & McCulloch, M. D. (2011). Modeling the CO2 emissions from battery electric vehicles given the power generation mixes of different countries. *Special Section on Offshore Wind Power Planning, Economics and Environment*, *39*(2), 803–811. https://doi.org/10.1016/j.enpol.2010.10.054

Economic Times. (2016, March). India aims to become 100% e-vehicle nation by 2030: Piyush Goyal. Retrieved September 22, 2016, from http://economictimes.indiatimes.com/industry/auto/news/industry/india-aims-to-become-100-e-vehicle-nation-by-2030-piyush-goyal/articleshow/51551706.cms

Ecotality. (2013). *The EV Project: Quarter 2, 2013 Quarterly Report*. U.S. Department of Energy.

EPRI and NRDC. (2007, July). Environmental Assessment of Plug-In Hybrid Electric Vehicles Volume 1: Nationwide Greenhouse Gas Emissions. Retrieved from http://www.epri.com/abstracts/pages/ProductAbstract.aspx?productId=000000000001015325

Gambhir, A., Napp, T. A., Emmott, C. J. M., & Anandarajah, G. (2014). India's CO2 emissions pathways to 2050: Energy system, economic and fossil fuel impacts with and without carbon permit trading. *Energy*, *77*, 791–801. https://doi.org/10.1016/j.energy.2014.09.055

Gopal, A., Saxena, S., Witt, M., Park, W., Criden, M., Phadke, A., … Jacobson, A. (2014). *Assessing and Accelerating Electric Vehicle Deployment in India*. Technical Report for the Electric Vehicles Initiative of the Clean Energy Ministerial. Retrieved from http://www.cleanenergyministerial.org/Portals/2/pdfs/EVI-LBNL_India_May2014report.pdf

Guttikunda, S. K., & Mohan, D. (2014). Re-fueling road transport for better air quality in India. *Energy Policy*, *68*, 556–561.

Hadley, S. W., & Tsvetkova, A. A. (2009). Potential Impacts of Plug-in Hybrid Electric Vehicles on Regional Power Generation. *The Electricity Journal*, *22*(10), 56–68. https://doi.org/10.1016/j.tej.2009.10.011

Hawkins, T. R., Gausen, O. M., & Strømman, A. H. (2012). Environmental impacts of hybrid and electric vehicles—a review. *The International Journal of Life Cycle Assessment*, *17*(8), 997–1014. https://doi.org/10.1007/s11367-012-0440-9

Huo, H., Zhang, Q., He, K., Yao, Z., & Wang, M. (2012). Vehicle-use intensity in China: Current status and future trend. *Energy Policy*, *43*. https://doi.org/10.1016/j.enpol.2011.09.019

IEA. (2015). *India Energy Outlook 2015* (World Energy Outlook Special Report). International Energy Agency.

Jansen, K. H., Brown, T. M., & Samuelsen, G. S. (2010). Emissions impacts of plug-in hybrid electric vehicle deployment on the U.S. western grid. *Journal of Power Sources*, *195*(16), 5409–5416. https://doi.org/10.1016/j.jpowsour.2010.03.013

Karali, N., Gopal, A., Sharpe, B., Delgado, O., Bandivadekar, A., & Garg, M. (2017). *Improved heavy-duty vehicle fuel efficiency in India: Benefits, costs and environmental impacts*. forthcoming: Lawrence Berkeley National Laboratory.

Kempton, W., & Letendre, S. E. (1997). Electric vehicles as a new power source for electric utilities. *Transportation Research Part D: Transport and Environment*, *2*(3), 157–175.

Kennedy, C. A., Ibrahim, N., & Hoornweg, D. (2014). Low-carbon infrastructure strategies for cities. *Nature Climate Change*, *4*(5), 343–346. https://doi.org/10.1038/nclimate2160

Lopes, J. A. P., Soares, F. J., & Almeida, P. M. R. (2011). Integration of electric vehicles in the electric power system. *Proceedings of the IEEE*, *99*(1), 168–183.

Lund, H., & Kempton, W. (2008). Integration of renewable energy into the transport and electricity sectors through V2G. *Energy Policy*, *36*(9), 3578–3587.

MacPherson, N. D., Keoleian, G. A., & Kelly, J. C. (2012). Fuel Economy and Greenhouse Gas Emissions Labeling for Plug-In Hybrid Vehicles from a Life Cycle Perspective. *Journal of Industrial Ecology*, *16*(5), 761–773. https://doi.org/10.1111/j.1530-9290.2012.00526.x

McCarthy, R., & Yang, C. (2010). Determining marginal electricity for near-term plug-in and fuel cell vehicle demands in California: Impacts on vehicle greenhouse gas emissions. *Journal of Power Sources*, *195*(7), 2099–2109. https://doi.org/10.1016/j.jpowsour.2009.10.024

McCleese, D. L., & LaPuma, P. T. (2002). Using monte carlo simulation in life cycle assessment for electric and internal combustion vehicles. *The International Journal of Life Cycle Assessment*, *7*(4), 230–236. https://doi.org/10.1007/BF02978878

MORTH. (2015). *Road Transport Yearbook 2013*. New Delhi: Ministry of Road Transport and Highways, Government of India.

NRC. (2013). *Transitions to Alternative Vehicles and Fuels*. Washington, D.C.: National Academies Press. Retrieved from http://www.nap.edu/catalog/18264

NREL. (2013). *The National Solar Radiation Database (System Advisor Model's Solar Resource Files)*. National Renewable Energy Laboratory (NREL), Golden, CO.

OEA. (2015). *Wholesale Price Index (WPI) data 2006-2015*. Office of the Economic Advisor to the Government of India (Ministry of Commerce and Industry).

OECD. (2013). Economic Outlook No 93 - June 2013 - Long-term baseline projections. Retrieved from http://stats.oecd.org/Index.aspx?DataSetCode=EO93_LTB#

Parks, K., Denholm, P., & Markel, T. (2007). *Costs and Emissions Associated with Plug-in Hybrid Electric Vehicle Charging in the Xcel Energy Colorado Service Territory* (No. NREL/TP-640-41410). National Renewable Energy Laboratory (NREL), Golden, CO. Retrieved from http://www.osti.gov/scitech/biblio/903293

PFC. (2016). *The Performance of State Power Utilities for the years 2012-13 to 2014-15*. New Delhi: Power Finance Corporation Ltd (A Government of India Undertaking).

Phadke, A. (2012). Reassessing wind potential estimates for India: economic and policy implications. Retrieved from http://escholarship.org/uc/item/7551z3z3.pdf

Phadke, A., Abhyankar, N., & Rao, P. (2014). *Empirical Analysis of the Variability of Wind Generation in India: Implications for Grid Integration*. Lawrence Berkeley National Laboratory.

Phadke, A., Abhyankar, N., & Shah, N. (2013). Avoiding 100 New Power Plants by Increasing Efficiency of Room Air Conditioners in India: Opportunities and Challenges. Presented at the 7th

International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL), 7th International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL),Coimbra, Portugal. Retrieved from http://www.superefficient.org/Resources/~/media/Files/EEDAL%20Papers%20-%202013/031_Shah_finalpaper_EEDAL13.pdf

Planning Commission. (2012). *Report of the Working Group on Power and Energy for Twelfth Plan (2012-17)*. The Planning Commission of India.

Planning Commission. (2014). *The Final Report of the Expert Group on Low Carbon Strategies for Inclusive Growth*. New Delhi: Planning Commission(Government of India).

Rahman, S., & Shrestha, G. B. (1993). An investigation into the impact of electric vehicle load on the electric utility distribution system. *IEEE Transactions on Power Delivery*, *8*(2), 591–597.

Ramana, M. V., D'Sa, A., & Reddy, A. K. N. (2005). Economics of Nuclear Power from Heavy Water Reactors. *Economic and Political Weekly*, *40*(17), 1763–1773.

RITES. (2005). *Integrated Multi-Modal Public Transport Network for the National Capital Territory of Delhi*. Transport Department, NCT of Delhi.

RITES, (first), & MVA Asia. (2008). *Transport Demand Forecast Study and Development of an Integrated Road cum Multi-modal Public Transport Network for NCT of Delhi: Traffic Survey Results Report*. Transport Department, NCT of Delhi.

Rotering, N., & Ilic, M. (2011). Optimal charge control of plug-in hybrid electric vehicles in deregulated electricity markets. *IEEE Transactions on Power Systems*, *26*(3), 1021–1029.

Saxena, S., Gopal, A., & Phadke, A. (2014). Electrical consumption of two-, three- and four-wheel light-duty electric vehicles in India. *Applied Energy*, *115*, 582–590. https://doi.org/10.1016/j.apenergy.2013.10.043

Sen, A. (2015). *Gas Pricing Reform in India: Implications for the Indian gas landscape* (No. OIES PAPER: NG 96). The Oxford Institute for Energy Studies. Retrieved from http://www.oxfordenergy.org/wpcms/wp-content/uploads/2015/04/NG-96.pdf

Shah, N., Abhyankar, N., Phadke, A., & Ghatikar, G. (2015). Considerations in Standardization for Demand Ready Air Conditioners in India. Presented at the India Smart Grid Week, Bangalore. Retrieved from http://www.researchgate.net/profile/Rish_Ghatikar/publication/274719318_Considerations_in_Standardization_for_Demand_Response_Ready_Air_Conditioners_in_India/links/5528073a0cf2e089a3a28cb9.pdf

SIAM. (2011). India Vehicle Sales by Month and Type. Society of Indian Automobile Manufacturers.

US EPA. (2015). Emission Factors for Greenhouse Gas Inventories. Retrieved April 4, 2016, from https://www.epa.gov/sites/production/files/2015-12/documents/emission-factors_nov_2015.pdf

Waraich, R. A., Galus, M. D., Dobler, C., Balmer, M., Andersson, G., & Axhausen, K. W. (2013). Plug-in hybrid electric vehicles and smart grids: Investigations based on a microsimulation. *Transportation Research Part C: Emerging Technologies*, *28*, 74–86.

Waraich, R. A., Georges, G., Galus, M. D., & Axhausen, K. W. (2014). Adding Electric Vehicle Modeling Capability to an Agent-Based Transport Simulation. *Data Science and Simulation in Transportation Research*, 282–318.

Wiser, R., & Bolinger, M. (2015). *2014 Wind Technologies Market Report* (No. LBNL-188167). Berkeley, CA: Lawrence Berkeley National Laboratory (US Department of Energy).

Lawrence Berkeley National Laboratory is a member of the national laboratory system supported by the U.S. Department of Energy through its Office of Science. It is managed by the University of California (UC) and is charged with conducting unclassified research across a wide range of scientific disciplines.

This work was funded by the 21st Century Power Partnership through the U.S. Department of Energy's Office of International Affairs under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

Lawrence Berkeley National Laboratory
One Cyclotron Road
Berkeley, CA 94720
http://www.lbl.gov/

Lawrence Berkeley National Laboratory Disclaimer

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.