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Dhar, Subash; Pathak, Minal; Shukla, Priyadarshi

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Electric vehicles and India's low carbon passenger transport: a long-term co-benefits assessment

Subash Dhar [a, *], Minal Pathak [b], Priyadarshi R. Shukla [c]

[a] UNEP DTU Partnership, Technical University Denmark, DTU – Dept. Management Engineering, UN City, Marmorvej 51, 2100, Copenhagen Ø, Denmark
[b] CEPT University, Kasturbhai Lalbhai Campus, University Road, Ahmedabad, India
[c] Indian Institute of Management, Vastrapur, Ahmedabad, India

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ABSTRACT

Electric vehicles have attracted the attention of India's policy makers as clean technology alternatives due to their multiple advantages like higher efficiency and lower air pollution in short to medium term and reduced CO_2 emissions as electricity gets decarbonized in the long-run under low carbon scenarios. This paper uses an energy system model ANSWER-MARKAL to analyse the role of electric vehicles (EV) in India. The modelling assessment spans the period 2010 to 2050 and analyses future EV demand in India under three scenarios: i) a 'Reference' scenario which includes the continuation of existing EV policies as outlined in India's Intended Nationally Determined Contribution (INDC); ii) a 'EV policy' scenario which, in line with India's INDCs, follows targeted supply-side push policies for EVs, but without the budget constraints; and iii) a 'low carbon' scenario which uses an exogenous price for CO_2 in line with the global target of 2 °C temperature stabilization. The scenarios analysis delineates penetration of EVs and their co-benefits as well as co-costs. The co-benefits relate to local air quality, national energy security and CO_2 emissions in India whereas the co-costs (risks) are related to sourcing of raw materials for batteries and battery reprocessing and disposal.

The findings show that: i) in the reference scenario, the EVs 2-wheelers will achieve a significant share by 2050. Electric 4-wheelers though would have a small share even in 2050; ii) EV push policies though lead to significant diffusion of electric 2- wheelers in India by 2030. These policies enhance diffusion of electric 4-wheelers only if financial incentives are sustained in the long-term, iii) the application of global carbon price on the Indian economy in the 2° C stabilization scenario increases competitiveness of EVs and results in near total share of electric 2-wheelers by 2030 and a sizable share of electric 4-wheelers by 2050. The high and rising carbon price in low carbon scenario cause deep decarbonisation of electricity and enables EVs to deliver deep cut in CO_2 emissions. The results show asymmetry in the impacts of national and global policies on co-benefits from EV. The EV supply-push policies deliver moderate benefits vis-à-vis air pollution and energy security indicators but make insignificant contribution CO_2 emissions reduction. On the other hand, the global carbon price in the global 2° C stabilization scenario delivers sizable co-benefits vis-à-vis all three indicators. This asymmetry reveal important policy insights: i) the policy sequencing is vital to gain co-benefits, ii) EV technology push policies are good for creating early domestic market for a clean vehicle technology but they may not deliver sizable co-benefits vis-à-vis CO_2 emissions which are global externalities, and iii) implementing strong climate policies early would lead to EVs delivering high co-benefits, in case of India, vis-à-vis all three indicators.

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1. Introduction

1.1. Changing transport landscape

India's transport landscape is undergoing major transformation. This is shaped by diverse initiatives at the national and subnational levels, across transportation demands, vehicle technologies and

* Corresponding author. Tel.: +45 4533 5261.
E-mail address: sudh@dtu.dk (S. Dhar).

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fuels. Infrastructure investments including high speed rail and dedicated freight corridors are significant initiatives that will alter the trends in freight and intercity passenger transport in coming decades. A number of cities are investing in mass transit including metros and Bus Rapid Transit (BRT) systems. The mix of vehicles and fuels is evolving with penetration of cleaner technologies and fuels. Electrification of transport is aided by increasing share of rail for intercity, urban passenger transport and freight transport.

The dynamics of the transport sector also include rapid increase in vehicle population and demand for passenger transport. Between 2001 and 2011, the share of households owning cars increased by 88% and 2-wheelers by 79% (Dhar et al., 2015). Despite the growth in vehicle ownership, the car ownership was only 15.7 cars per 1000 persons and the 2-wheeler ownership was 81.7 per 1000 persons in 2010. This is low compared to a much higher level of vehicle ownership in most of the developed countries (World Bank, 2014). The expected increase in population and GDP in future and the low levels of vehicle ownership portends a major increase in population of vehicles in the future and consequently demand taken by road transport. National Transport Development Policy Committee (NTDPC) projections show that travel demand served by road transport would increase to 163,111 billion passenger kilometres (bpkm) by 2031, nearly 17 times from 2011 (NTDPC, 2014). The International Energy Agency is not as aggressive about demand growth and expects that demand for energy from transport would increase to 174 Million Tonnes oil equivalent (Mtoe) by 2030 (IEA, 2013), nearly 3 times from 2011. Despite the wide variations in expectations for future, the growth in energy use from transport sector looks inevitable and undoubtedly this means increasing challenges for energy security, local environment, safety, traffic congestion and greenhouse gas emissions. The government is keen on addressing these challenges and has implemented a number of policies with the objective of reducing environmental impacts of transport. These include measures that directly address externalities from vehicle use and include fuel quality standards, fuel economy standards, policies to encourage the use of low carbon fuels and technologies (Refer Table S2, Supplementary Materials Policies for an overview of transport policies). In addition, a number of national policies that change the modal composition of transport demand are also under implementation. These include investments in public transport, urban development policies and policies to encourage rail and water transport. For instance, sustainable transport is one of the thrust areas in the Smart Cities Mission of the Government of India that envisages developing 100 smart cities to serve as model cities in the country. India's Intended Nationally Determined Contribution (INDC) which specifies a decarbonization target of 33–35% with respect to GDP between 2005 and 2030 also takes into consideration the ongoing policies and programs within transport sector and sees them as a key lever to meet its emissions intensity reduction target (UNFCCC, 2015a).

1.2. Passenger transport trends

Contemporary research has shown that per capita mobility in India is highly correlated with per capita income (Dhar and Shukla, 2015) which is also consistent with the observed data across countries (Schafer and Victor, 2000). The overall demand for passenger transport in India increased from 1560 bpkm in 1990 to 6962 bpkm in 2010 driven by rising income as well as rising population.

Transport policies in India have given precedence to motorised transport relative to non-motorised transport (Tiwari, 2013). Even where transport project design had a focus on non-motorized transport, implementation has been piecemeal and symbolic (Mahadevia et al., 2012). Vehicle ownership, especially 2-wheelers, has therefore seen a significant increase, between 2001 and 2011. In 2011, the 2-wheeler population crossed the 100 million mark and 2-wheelers catered to nearly 30% of the total passenger transport demand. The number of 4-wheelers was nearly 20 million however the growth was faster than 2-wheelers between 2001 and 2011. The growing fleet of vehicles is dependent on oil (petrol and diesel) and given India's high dependence on oil imports, there are associated risks of prices and supplies. Transport is also a growing source of CO_2 emissions. In 2010, nearly 14% of energy related CO_2 emissions were attributed to transport sector (GoI, 2015a).

The growing population of vehicles in urban areas has led to congestion and severe air pollution. In an assessment carried out by the Central Pollution Control Board, half of the 164 cities studied had high or critical levels of PM_{10} while more than half had moderate or critical levels of NOx (Pathak and Shukla, 2015). Increasing motorisation has also contributed to impacts on human health (Dholakia et al., 2014) and increasing accidents (Ghate and Sundar, 2013).

1.3. Global experience with electric vehicles

Electric vehicles have gained market share across countries following varied incentives (Refer Supplementary Materials Table S1 & S4 for a snapshot of policies across countries that support EVs or creating favourable enabling conditions). These incentives have been provided with a belief that EVs can deliver broader developmental benefits and also help in reducing CO_2 emissions. Studies show that electric vehicles can improve energy efficiency (Yagcitekin et al., 2015), reduce air pollutant emissions (Nanaki and Koroneos, 2013), increase penetration of renewables (Andersen et al., 2009) and reduce CO_2 emissions in the long term (Sims et al., 2014). The experiences vary across countries e.g., in a country with energy inefficient and CO_2 intensive power generation sector the shift to EVs may neither improve efficiency nor reduce CO_2 emissions. This paper assesses the future of EVs in India under varied scenarios including a low carbon emissions scenario corresponding to the stabilization of global temperature rise to 2° C (UNFCCC, 2015b).

1.4. Policy landscape and status for EVs in India

India's Intended Nationally Determined Contribution (INDC) enlists electric vehicles as a focus area under transport mitigation actions. Part of the country's National Electric Mobility Mission Plan 2020 (GoI, 2012), the Faster Adoption and Manufacturing of Hybrid and Electric vehicles (FAME India) is aimed at accelerating the diffusion of hybrid and electric vehicles through financial incentives (GoI, 2015b) India has also announced CO_2 emission standards for vehicles (See Table S1, Supplementary Material Policies) and though the present electricity system in India is coal dependent electricity generation in low carbon scenarios in India would shift towards energy efficient and lower carbon emitting technologies (Shukla et al., 2015). This vision of future is also evident in India's INDC communicated to the UNFCCC (UNFCCC, 2015a) which includes ambitious targets for renewable and nuclear power generation. Clean electricity would create favourable enabling conditions for EVs.

EVs have however negligible presence currently in India. The domestic manufacturing of electric 2-wheelers (E2Ws), electric 3-wheelers (E3Ws) and electric cars (E4Ws) has recently begun in the country. There were nearly two dozen domestic manufacturers of electric 2-wheelers in 2014. Electric 3-wheelers are assembled by manufactures in the informal sector using batteries and components imported from China. A few automobile companies are engaged in the production of electric cars. Electric buses are not manufactured in the country; however, some Indian cities have introduced imported buses on pilot basis.

1.5. Research questions

EVs have zero tailpipe emissions and hence can potentially mitigate adverse impacts on air quality from passenger transport. Indian government has instituted policies that enable EVs through incentives such as the capital subsidies under the FAME program. The paper analyses the extent to which these EV friendly policies can address the economic barriers facing electric vehicles.

India is a part of global efforts to limit the global temperature rise to 2° C. The paper analyses how a 2° C goal for climate stabilization along with EV polices can help in the diffusion of EVs.

Transport sector is the largest consumer of oil in India. Since India imports over three fourth of its oil demand, the oil imports have serious implications for national energy security. Due to high oil dependence transport sector also accounts for nearly 10% of CO_2 emissions and is a major source for air pollutants. The paper analyses the multiple co-benefits of EVs vis-à-vis CO_2 emissions reduction, energy security and air pollution. Besides the co-benefits, EVs can also have co-costs and risks such as from the large scale demand for batteries. The battery demand would require raw materials (e.g., rare earths) and also produce hazardous waste at the end of life. The analyses in the paper also consider the risks from large scale demand for batteries.

The answers to these questions are quite relevant for policy makers since the analysis informs whether the incentives that government is providing can achieve the objective of increasing penetration of EVs and achieve the desired outcomes in terms of improvement in local environment, energy security and reduction in CO_2 emissions.

2. Methodology

The questions addressed in this paper require an analysis of how the EV specific incentives together with global climate stabilization target affect diffusion of EVs in India and to what extent the EV diffusion impact the local environment quality, CO_2 emissions and other sustainability indicators such as national energy security. The assessment span has a long-time horizon (till 2050) since the climate policy is a key policy driver and climate change is a long term phenomena. Since policies to support EVs are largely in the form of financial incentives (Table 1) they can be evaluated using financial modelling. The financial modelling can reveal whether EVs are attractive for investors by examining key financial ratios (e.g., Net Present Value, Internal Rate of Return, etc.) and can also provide information on subsidy burden for the government from EV related incentives. Financial modelling however cannot analyse the impacts on environment or how internalising environmental externalities can change technology choices and neither can it analyse the interactions between changes in electricity markets and EVs. A wide range of energy system models have coverage of both electricity and transport sector (Refer Supplementary Materials Methodology, Table S5) and can perform a techno economic analysis (Connolly et al., 2010). The current study uses MARKAL/TIMES family of energy system models for the analysis which are also well suited for analysis of climate policies as well as the assessment of co-benefits for energy and environment.

2.1. ANSWER MARKAL model

The penetration of EVs in the long term would depend on rate of technological change, discount rates, capital cost of EVs versus other vehicle technologies and the price of electricity relative to other forms of energy (e.g., oil, gas, biofuels) used by competing vehicles. ANSWER MARKAL is an optimisation model suitable for analysing the national energy system (Loulou et al., 2004) and has been used extensively for sectoral analysis (Shukla et al., 2009), analysis of renewable energy policies (Shukla et al., 2010) and analysis of climate scenarios (Shukla et al., 2008) for India. The model structure allows a rich characterisation of the electricity sector and includes both generation and distribution of electricity and therefore is suitable for EVs as large scale diffusion of EVs will entail changes in grid infrastructures. The model has a full accounting of CO_2 emissions and therefore embedded CO_2 emissions in electricity can also be accounted.

The demand for transportation is defined exogenously for each time period and within each vehicle category i.e., 2-wheeler, 4-wheelers, etc. In each vehicle category a variety of technologies are available (See Figure S1 in Supplementary Materials Methodology for an illustration for 4-wheelers). The model solves for the entire time period with full information of costs and optimises the overall system costs. In each vehicle category the technologies chosen reflect the least cost pathway. Capacity constraints are however put for some cases to reflect resource constraints (e.g., availability of biomass) or infrastructure constraints (e.g. availability of Compressed Natural Gas (CNG) due to absence of a city gas distribution). In case of a strong climate policy (e.g., in the 2° C Scenario), a constraint is put on level of carbon emissions and the model optimises technologies that have the lowest marginal abatement costs and if a carbon price is exogenously provided then the model will choose technologies that can provide the highest mitigation.

The model also includes emissions coefficients of local pollutants (e.g., NOx, SO_2, Particulates, etc.) for each vehicle technology and this enables assessment of local pollutant loads. All these features make the model quite well suited for evaluation of co-benefits for energy security and local environment.

2.2. Demand for passenger transport

EV technologies, due to their limitations in driving range, are more suitable at present for urban driving where trip lengths are shorter as compared to intercity travel. Hence, the passenger transport demand in this paper is separated between urban and intercity transport. The demand projections are based on Dhar and Shukla (2015) which uses a combination of top down and bottom up methods for demand assessment. The top down method links mobility to income, measured as per capita GDP (Schafer and Victor, 2000) and estimates the aggregate demand for mobility as a first step. In the next step the bottom up method is used to estimate urban transport demand (Dhar and Shukla, 2015). The bottom up method is based on transport planning theory which links demand for urban passenger transport to design, density and diversity (Ewing and Cervero, 2001).

3. Scenarios

Scenarios have been commonly used for analysing climate policy and provide a structured approach of analysing policy relevant questions however scenarios are neither predictions nor forecasts. A scenario provides a possible description of how the future can unfold based on a set of clear and internally consistent set of assumptions about key driving forces (e.g. economic growth, population, technological change, fuel prices, etc.). In this paper three possible futures for EVs are analysed. The first scenario is identified as the reference scenario and assumes the implementation of current and announced policies. The second scenario is identified as the EV scenario and has more ambitious EV policies

Table 1
Policy instruments in reference and EV scenario.

Policy instrument	Reference scenario	EV scenario
Economic Instruments for EV		
Excise Duty/Import Duty	A duty of 12% applies to EV and hybrid cars. This is at par with small gasoline or diesel cars (engine capacity less than 1500 cc and length less than 4 m). Batteries, motors and other parts for EV have no preferential treatment.	Considers full duty exemption till 2025 on cars and batteries. Post 2025 tax rates increased and tax parity is achieved by 2040.
Sales Tax (VAT)	No concessions for VAT	Considers half the VAT of reference scenario to factor for the positive local environmental benefits till 2025 and thereafter an increasing tax rate with tax parity by 2040 Overall lower capital cost compared to reference scenario.
Infrastructures for EV		
Charging infrastructures	The reference considers no specific investment into charging infrastructures and as a result EV makes use of spare capacity of grids. Therefore a maximum share constraint of 20% put on 2 W and cars by 2035.	An intelligent electric grid which can allow usage of EV both as storage and source of electricity combined with a higher capacity grid. As a result a 10% higher investment on transmission & distribution is assumed. Maximum share of EVs among 2 Ws and cars is increased to 40% by 2035.

Source: Adapted from Shukla et al. (2014).

and does not assume budgetary constraints for the same. The third scenario is the 2° C scenario which includes the implementation of climate policy in combination with EV policies.

3.1. Reference scenario storyline

The reference scenario considers rapid economic growth accompanied by decoupling of economic growth from CO_2 emissions. The CO_2 emission intensity with respect to GDP is expected to reduce at least by 35% between 2005 and 2030 in line with the India's INDC. The scenario also includes FAME India program since it is one of the key strategies for CO_2 mitigation and would also boost domestic manufacturing capabilities for electric vehicles (GoI, 2012).

The reference scenario storyline includes the business-as-usual dynamics and policies as outlined in India's INDC and the National Action Plan on Climate Change (NAPCC) (GoI, 2008). More specifically, this includes implementation of sustainable transport actions outlined in the submissions on Sustainable Habitat and the National Solar Mission within the NAPCC. The key points for the socio—economic transitions are described here.

3.1.1. Economic growth

Indian economy is expected to be one of the fastest growing economies in future (IEA, 2013). India's GDP growth is projected at an annual growth rate of 7.1% between 2010 and 2050. The medium term projections are consistent with Government of India projections of 8% till 2032 (GoI, 2011). The reference scenario storyline assumes that this GDP growth is also accompanied by major changes in sectoral contributions. The share of agriculture sector is expected to go down from 17.3% of GDP in 2010 to 4% by 2050, however contribution of transport is expected to increase marginally from 5.6% in 2010 to 6.4% in 2050.

3.1.2. Demographic transition

The population growth follows the medium variant projections from UN Populations division (United Nations, 2013) and reaches 1.62 billion in 2050 from 1.20 billion in 2010. The increase in population would be accompanied by an increasing urbanisation and by 2050, 50% of population would live in urban areas (United Nations, 2014).

The household sizes have shown a reducing trend in the past (Census of India, 2011), however higher than developed countries. For example, average household size for urban areas was 4.52 in 2010 as compared to around 2.5 observed in EU (EC, 2013), US (US-DoT, 2011) and several other developed countries. The household size is therefore expected to reduce further and in 2050, the average household in urban areas is estimated as 2.76 (Dhar and Shukla, 2015).

3.1.3. Passenger transport demand

The overall demand for passenger transportation is expected to increase from 6962 bpkm in 2010 to 31,872 bpkm in 2050. This reflects both an increase in per capita mobility by about 3.3 times (Dhar and Shukla, 2015) and an increase in population during the period. The growth is higher in urban areas where the travel demand would increase from 1049 bpkm in 2010 to 5932 bpkm in 2050 i.e., by 5.7 times whereas intercity transport demand grows from 5914 bpkm in 2010 to 25,941 bpkm in 2050 i.e., by 4.4 times (Dhar and Shukla, 2015).

The demand for motorised urban transport is largely met by 2-wheelers, cars, buses, 3-wheelers, metros (rail) and non-motorised transport. The ownership of two-wheelers is expected to increase from 127 vehicles per 1000 persons in 2010 to 330 in 2050 in the urban areas. Similarly the ownership of cars is going to increase from 29 vehicles per 1000 persons in 2010 to 183 in 2050 in the urban areas. The aggregate demand met by 2-wheelers and cars would increase 10 times from 300 bpkm in 2010 to 3064 bpkm in 2050. Public transport is deficient in most towns and cities and this demand is met by para-transit modes (3-wheelers and cycle-rickshaws). The government is keen to strengthen public transport in cities and has taken a programmatic approach for the same. Around 50 cities are being provided central grants and assistance in debt funding for building metro projects. Public transport is therefore expected to play an increasing role within the cities in future and as a result the demand met by public transport would increase from 272 bpkm in 2010 to 2308 bpkm in 2050. Public transport is however expected to lose share to private modes in long term (Fig. 1) due to growing ownership of cars and 2-wheelers. 3-wheelers (and other para transit modes) are expected to lose share to both public transport and private vehicles.

More than 80% of intercity transport demand is catered by road based transport (Fig. 1). Government of India is keen to achieve a greater share for rail transport by increasing travel speed of rails and building a network of high speed rails. The increase in share of rail would entail substantial investments (NTDPC, 2014) which would not be feasible from domestic sources (Dhar and Shukla, 2015)and therefore growth in rail is pegged at the same level as the overall growth in demand. In the intercity road passenger transport, cars and 2-wheelers are projected to enhance share at the expense of bus transport. The demand met by cars is projected to increase nearly 10 times from 463 bpkm in 2010 to 4751 bpkm in

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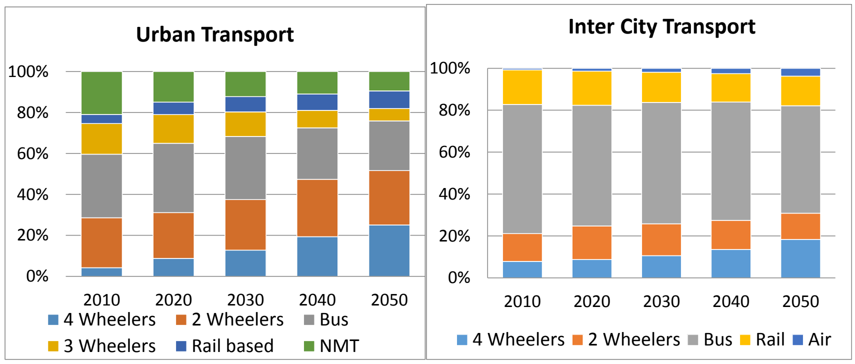

Fig. 1. Modal share: urban and intercity passenger transport.

2050. The projected demand growth of 2-wheelers on the other hand is relatively lower and grows from 784 bpkm to 3247 bpkm in 2050.

3.1.4. Technologies and policies for electric vehicles

Electric vehicles have gained attention of policy makers and automobile manufacturers globally (Shukla et al., 2014). However, as shown in several other studies, factors influencing EV market share include high battery costs (Wu et al., 2014), financial incentives, charging infrastructure, and local production (Sierzchula et al., 2014). The government has recently announced demand incentives for electric vehicles under the Faster Adoption and Manufacturing of Electric Vehicles (FAME) program (GoI, 2015b). The demand incentives on electric 2-wheelers are in the range of USD 27 to USD 437 whereas for cars these will range from USD 166 to USD 2000. However to limit the subsidy burden, the number of vehicles that can receive the subsidy is capped. The policy also envisages support for charging infrastructure, and an investment of USD 1.5 M is allocated for the same (Table 1).

Consumers in India perceive charging time, driving range, battery replacement costs, top speed and acceleration as key barriers for EVs (GoI, 2012). A further analysis of these barriers using techniques such as decomposition (Painuly, 2001) or logical framework approach (Boldt et al., 2012) reveal battery as the root cause of most of these barriers. The costs of battery packs have however declined considerably from nearly USD 1000/kWh in 2007 to nearly USD 300/kWh in 2015 (Nykvist and Nilsson, 2015). Battery technologies are also undergoing multiple transformations which would be able to address the cost, driving range and speed related barriers. Presently, lithium ion (Li-ion) battery is the preferred option for EVs due to its multiple advantages including high energy density, long cycle life and high charging and discharging rate capability (Huat et al., 2015). The driving range for battery variants based on Li-ion can stretch driving range beyond 200 km for cars at a cost less than USD150/kWh in future (Bruce et al., 2012). The driving range can be stretched to reach around 400 km with technologies based on Zn-air and Li-S at similar costs (ibid). Driving range can also be addressed through well distributed infrastructures for charging or replacement of discharged batteries. The reference scenario has internalised these technology and policy stories as technology assumptions for electric vehicles (Shukla et al., 2014). EVs based on advanced battery technologies can achieve a faster reduction in costs however would require large investments in R&D, demonstration projects and transfer of technology. In the reference scenario these are not fully realised and hence the costs reductions are moderate.

EV technologies available currently show a wide variation in their costs and performance. EV 2-wheelers for example with a low payload capacity and with a limited driving range can be obtained at low costs whereas EV-2 wheeler variants comparable to conventional 2-wheelers are relatively more expensive (Table 2).

To handle this technology diversity, the reference scenario assumes that the less expensive EVs with driving range limitations (e.g. electric 2-wheelers based on lead acid batteries) can play a role within cities where trip lengths are shorter. However these technologies will not be feasible for inter-city transport. Therefore, these less expensive technologies are limited to urban transport demand. Advanced and more expensive technology options, e.g. those with a higher driving range are made available for both urban and inter-city transport.

Besides EV 2-Wheelers and EV 4-Wheelers, EV 3-Wheelers have shown a rapid growth in recent years and they have taken share from both the cycle rickshaws and 3-wheelers powered by diesel, gasoline and CNG. The price of cheaper electric 3-Wheelers is below USD 600 which is much below the cost of conventional 3-wheelers. The electric 3-Wheelers have therefore been assumed to replace all the conventional 3-wheelers post 2020.

3.2. EV scenario

EV scenario includes the continuation of INDC targets for EVs as outlined in reference scenario. In addition, this scenario assumes that national and local governments recognize the benefits of EVs for improved air quality in cities, energy security, integration of renewable electricity technologies, etc. The scenario therefore assumes significant policy support for electric vehicles (Table 1) which increases the competitiveness of EVs vis-à-vis conventional vehicles. The scenario does not impose quantitative limits such as those specified in NEMMP 2020 (GoI, 2012) e.g., limiting subsidy to one million EV 2-Wheelers. The scenario however considers that financial support will be gradually phased out and completely withdrawn by 2035.

The scenario also assumes a global push for electric vehicles that lead to a higher R&D expenditures and therefore faster and greater improvements in battery capacities, component costs, and economies of scale in production which lead to reduction in cost of EVs. Electric vehicles in this scenario have capital costs which are in 2020 nearly 30% lower compared to the reference scenario. India could be at forefront of research in EV technologies since it does not have a high oil endowment and has a large domestic market that can help in gaining experience in technology.

3.3. 2° C scenario

Electricity cleaning is integral to transforming EVs as an efficient and clean option however this requires policies beyond EVs. India's

Table 2
EV 2-wheeler technologies currently available in the Indian market.

	Lead acid battery		Lithium-ion battery
Payload	Low	High	High
Efficiency	18.7 km/kWh	35 km/kWh	56 km/kWh
Approximate cost	USD 550	USD 700	USD 2400
Driving Range	Less than 100	Less than 100	200
Manufacturing	Local	Local	Imported

INDC communicated to the UNFCCC (UNFCCC, 2015a) includes ambitious targets for renewable and nuclear power generation. The Paris Agreement reiterated the global commitment to the goal of limiting the temperature increase to "well below 2 degrees Celsius and to limit the temperature increase to 1.5 degrees Celsius" (UNFCCC, 2015b) and therefore strengthens the global consensus for implementation of INDCs. This scenario is accordingly aligned with the global 2 °C temperature stabilization scenario which also includes a carbon price. The CO_2 price trajectory is along a pathway which assumes a strong climate regime post 2020. The CO_2 price trajectory therefore starts from USD 13.9 per tCO_2 in 2020 and then increases steadily to reach USD 200 per tCO_2 in 2045 (Lucas et al., 2013).

4. Results and discussion

4.1. Share of electric vehicles

4.1.1. Electric 2-wheelers

In the reference scenario EVs based on lead acid batteries (Table 2) would become viable from 2020 onwards however more expensive EVs based on Lithium-ion batteries with driving range and payload capacity comparable to conventional two-wheelers become viable only after 2030 (Fig. 2).

In the EV scenario, the incentives for electric vehicles (Table 1) leads to nearly 30% share of 2-wheeler demand in the cities in 2020. The driving range limitations are expected to be overcome and EVs become comparable to conventional 2-wheelers and therefore EVs become competitive against the conventional 2-wheelers.

In the 2 °C stabilization scenario, enhanced R&D in battery technologies will make electric 2-wheelers comparable to conventional 2-wheelers in terms of driving range and payload by 2030. As a result, nearly all 2-wheelers are either full electric or hybrid by 2030 (Fig. 2). Electric 2-wheelers benefit from a high carbon price and the cleaning of electricity which transforms EV as a clean option both for local environment and CO_2 mitigation.

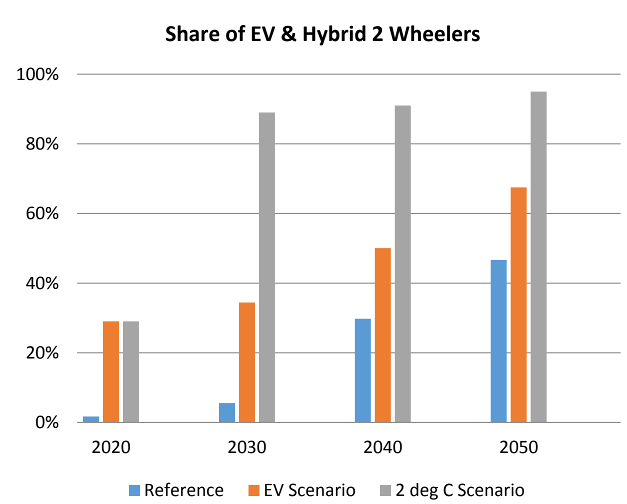

Fig. 2. Share of electric and hybrid 2-wheelers.

4.1.2. Electric 4-wheelers

Cars are a fast growing mode of transport and there has been a rapid increase in car ownership within both urban and rural areas (Dhar et al., 2015). Internal combustion engines fuelled by petrol or diesel have dominated historically, however during the last decade CNG has emerged as an alternative fuel due to development of city gas distribution infrastructure in several cities (Dhar and Shukla, 2010). Fully electric 4-wheelers and hybrid cars currently have a negligible market share. In the reference scenario, small electric cars with a price below USD 15,000 would become competitive after 2040 onwards however cars with a larger battery, payload capacity and a longer driving range do not become competitive within the horizon period. In 2050 the demand catered by EV 4-wheelers is 635 bpkm.

Small electric cars become viable in the EV scenario from 2030 onwards however their diffusion is limited by driving range, payload limitations and subsidy burden. Since no subsidy supports for EVs is considered beyond 2035, EV growth slows down and the share of EVs declines in 2040. However, by 2050, further reductions in battery costs (battery costs are considered as USD 130 per kWh in 2050) bring in EV as a major option (Fig. 3). In 2050 the demand catered by EV 4-wheelers is 2835 bpkm.

In the 2 °C stabilization scenario a high carbon price gives a further boost to EV 4-wheelers post 2030. The high carbon price offsets withdrawal of subsidies post 2030 and the share of EV 4-wheelers steadily increases (Fig. 3). In 2050 the demand catered by EV 4-wheelers is 4413 bpkm.

4.2. Electricity demand

Electricity demand for transport has traditionally been dominated by rail based intercity transport. In 2010, demand for electricity from transport was 11.6 TWh out of which 82% was from intercity rail. The remaining demand was from metro systems in cities and for transportation of petroleum products through pipelines. In future demand for electricity from rail based transport would increase due to expansion of rail networks, increase in rail services, creation of dedicated freight corridors, and high speed rails networks. The demand for electricity by 2050 in the reference scenario would be around 231 TWh (Fig. 4). Thirty four percent of this demand would be from intercity rail transport. The remainder demand for electricity would be for public transport in cities (metros, trams, and electric buses), pipelines and electric vehicles. In the reference scenario, the demand for electricity from electric vehicles would account for 36% of overall demand from transport by 2050.

In the EV scenario the demand for electricity would grow faster relative to reference scenario due to rapid diffusion of EV 2-wheelers and EV 4-wheelers. The overall demand for electricity from transport in 2050 would be 400 TWh (Fig. 4), 73% higher than the reference scenario. The share of electric vehicles on electricity demand from transport would increase to 63% by 2050.

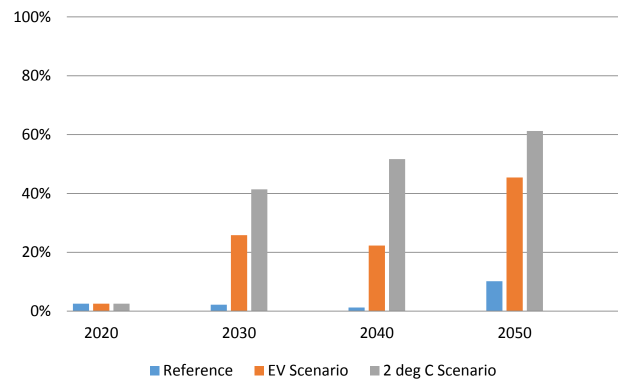

Fig. 3. Share of electric, hybrid and fuel cell 4-wheelers.

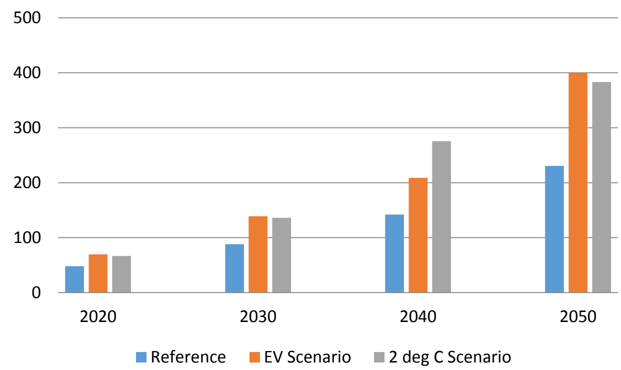

Fig. 4. Electricity demand in transport (TWh).

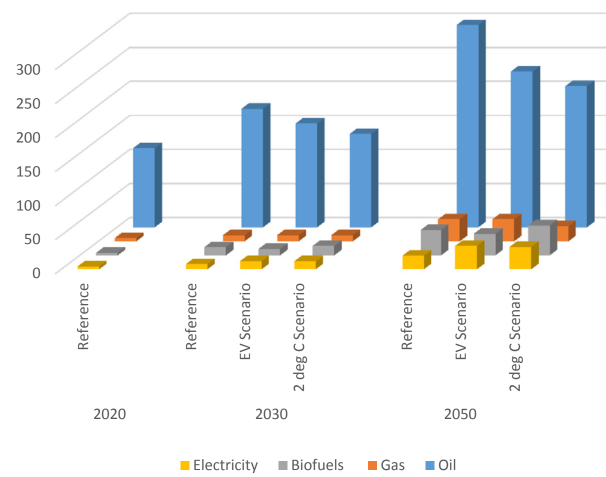

Fig. 5. Energy demand in transport (Mtoe).

In 2 °C scenario since the share of EVs is higher (Figs. 2 and 3), the demand for electricity is also higher initially. However by 2050, even with a higher share of EVs (including hybrid and fuel cell vehicles) relative to reference and EV scenarios, the demand for electricity is 383 TWh, a little less than EV scenario. This is on account of a higher share of hybrid vehicles and relatively efficient but expensive EVs.

It has been argued that a greater penetration of electric vehicles can imbalance the electricity supply and thereby burden the electricity grids (Saxena et al., 2014). The power and energy shortages in India have been quite high in the past (CEA, 2014). The share of electricity demand from transport sector of overall electricity demand was only 1.2% in 2010. The highest demand for electricity from transport sector is in the EV scenario, where the share of electricity would increase over time and reach to around 6% in 2050. The EV growth would entail limited and gradual capacity additions for electricity generation and therefore not put sudden strains (Fig. 4) on the grid. On the other hand technology to use battery storage provided by EV together with smart grids are emerging (Klemeš et al., 2012) and therefore higher penetration of EVs may even help to integrate renewables and to augment decentralised generation.

4.3. Energy security

In the reference scenario the overall demand for energy increases by 6.9 times between 2010 and 2050. The dependence on oil continues despite some penetration of natural gas and bio fuels. Electricity becomes a significant option post 2020 (Fig. 5).

The higher penetration of EV brings down the demand for final energy in the EV scenario and 2 °C scenario (Fig. 5). The benefits for energy security also accrue from the diversification of fuel mix away from oil towards electricity which allows for greater flexibility in terms of fuel choices. In the EV scenario, in 2050, the dependence on oil is reduced to 70% whereas in 2° C scenario it is even lower at 67%, compared to 77% in the reference scenario.

The diversification towards EVs however entails energy security risks in terms of sourcing of rare earth materials for batteries. The energy security risks in the long term may be addressed through global and national R&D efforts for efficiency improvements in batteries (Saw et al., 2016); The battery demand as a result may grow slower than growth in EVs (See section 4.6). Technologies that allow for extraction of heavy metals for recycling from spent batteries in a cost-effective and sustainable manner (Ku et al., 2016; Xin et al., 2016) can also mitigate this. In addition, technological advancements may lead to disruptive innovations in battery technologies that may go beyond the lithium-ion technology (Crabtree, 2015) for alternate and more accessible materials.

4.4. Local air pollutants

$PM_{2.5}$, a key local pollutant, will further increase till 2020 in reference scenario and the increasing two-wheeler and four wheeler population would be a key driver for this (Dhar and Shukla, 2015). Therefore air quality in cities is expected to deteriorate in the short-term due to an increase in pollution loads. In the medium term, implementation of stricter emission standards (See Supplementary Materials Policies, Table S2) is however expected to lead to a reduction in local pollutants (e.g. $PM_{2.5}$) from 2030 onwards assuming that the emissions from other sectors such as construction, power generation, brick klins, etc also witness a similar trend.

In EV scenario the emissions of air pollutants begin to reduce rapidly i.e., starting 2020 and this helps in arresting the growth of air pollution in the short term and contributing to declining emissions of air pollutants in the medium term. In the 2 °C scenario the benefits for local air quality can be further enhanced, e.g., emissions of $PM_{2.5}$ will fall below half of the current levels by 2030 (Fig. 6). $PM_{2.5}$ emissions would increase at the power plant however since, these would be located outside dense urban areas where the health impacts would be lower. Also, electricity generation will be cleaner in future due to more stringent environmental regulations for power plants and increasing penetration of cleaner technologies for power generation.

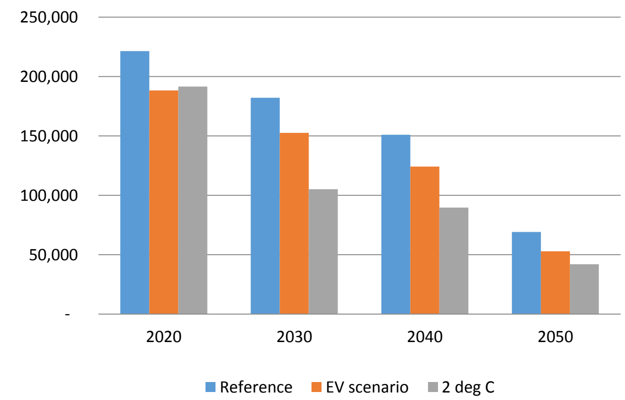

Fig. 6. PM 2.5 emissions (in t).

4.5. CO_2 emissions

CO_2 emissions in the reference increase by 6.6 times from transport sector between 2010 and 2050, lower than the increase in energy demand. Decoupling between energy and CO_2 emissions, in reference scenario, is due to the diversification of fuel mix towards biofuels and natural gas and reduction in CO_2 intensity of electricity. The CO_2 intensity of the grid reduces from 0.80 Mt CO_2/GWh in 2010 (CEA, 2012) to 0.64 Mt CO_2/GWh in 2050.

In the EV scenario the CO_2 intensity of electricity is similar to the reference scenario and therefore reduction in CO_2 emissions is low (Fig. 7). In the 2 °C scenario, the CO_2 emission intensity of electricity is reduced to 0.06 Mt CO_2/GWh in 2050. This results in a significant reduction in CO_2 emissions relative to reference and EV scenarios. In addition, penetration of more efficient vehicles reduces the energy demand in this scenario.

4.6. Battery demand

EVs will take up a significant share of two-wheeler and car market in the EV and 2° C scenario (Figs. 3 and 4). The demand for electric vehicles is from different vehicle types with very different battery capacities. The battery capacities for EV scenario calculated on the basis of investments into different vehicle types made in the model (Fig. 8) indicate a progression towards more efficient batteries since the demand for batteries does not increase at the same rate as increase in demand for EVs. The demand for batteries from EV 2-wheelers is almost similar to the demand from cars. The demand for the batteries in the short term i.e., till 2020 might be a challenge in the EV scenario since the vehicle are not as efficient. The growing battery market will however be a challenge in terms of battery reprocessing and disposal. In future, cost-effective recycling of spent materials and material recovery may be a feasible option (Xin et al., 2016). In the short and medium term, this can be addressed through policy interventions such as national policies for battery disposal and recycling including extended producer responsibility (Gies, 2015).

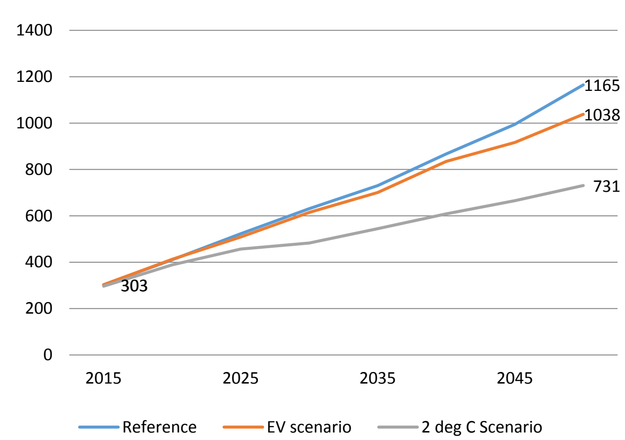

Fig. 7. CO_2 emissions from transportation (tCO_2).

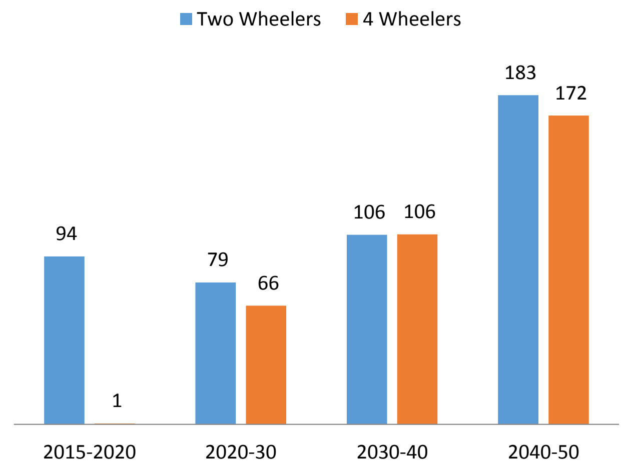

Fig. 8. Battery power demand (GWh) in EV scenario.

5. Conclusions and policy implications

The EV scenarios assessment shows that direct financial incentives to EV buyers and support to upfront investments in infrastructure can help increase the share of EVs in India in the short to medium term (2030). In the long-run however, EVs can be competitive vis-à-vis conventional vehicles under a low carbon (i.e. 2 °C temperature stabilization) scenario. Given India's large and growing two-wheeler market, there exists a significant potential for scaling up share of electric two-wheelers in the short-term. This would also be an opportunity for India to develop domestic EV industry and create an enabling environment, including charging infrastructure, which can facilitate diffusion of larger EVs. Similar findings are reported for China where e-bikes have replaced car trips and are reported to act as intermediate links in the transition process from bicycle to bus and bus to car (Cherry et al., 2016).

The scenarios assessment shows that the policies that push EVs deliver energy security and air pollution co-benefits. However, the advantages of EV over Internal Combustion Engine Vehicles in mitigating climate change and local air pollutants in congested cities will depend strongly on the electricity mix and charging strategies (Jochem et al., 2016).

EVs benefit CO_2 mitigation provided the electricity is decarbonized e.g., in the 2 °C scenario wherein entire national electricity supply is significantly decarbonized. Generating cleaner electricity however will take time, to allow the turnover of the existing fossil-based electricity generation. In the immediate future, the policies to shift to electric vehicles will deliver local pollution benefits in rapidly growing cities in India. Targeted policies for supporting electric vehicles complimented with a strong climate regime can enhance the local pollution benefits. Air quality benefits are vital for the cities and therefore city policymakers would incentivise EVs in the self-interest by pushing local policies for stricter emission standards, prioritizing parking for EVs, building charging infrastructures at parking slots, and giving priority to EV in traffic. As cities expand their bus fleets, a higher share of investments can be used for purchasing electric buses.

Enhanced electricity demand for EVs is a common concern given the current supply-demand gap in India's electricity system. The modelling analysis in this paper shows that this concern is misplaced. A high share for electric vehicles happens in EV and 2 °C scenario, however the demand for electricity even in the long-term (i.e., by 2050) does not exceed 6% of overall demand for electricity. Therefore a transition to EV will not require major changes to the energy supply. Also, there will be adequate time for the electricity sector to adjust to the increase in electricity demand since the higher EV penetration such as under low carbon scenario will happen after the year 2030.

EVs can benefit to soften the electricity supply-demand mismatch. The diffusion of EV would create a capacity for energy storage which together with smart grids can be used for enhanced integration of renewables with the grid. This can reduce the cost of smart grid which according to a study on the US electricity grid can increase the costs for consumers can by 8.4–12.8% (EPRI, 2011).

EVs' market share in India is still small. In terms of sales, the EVs in the Indian market are exhibiting a pattern similar to China's where E2Ws have a higher market penetration than E4Ws. E3Ws have achieved commercial success using cheap technology from China. EV policies and incentives announced by the Government of India, which are referred to in India's INDCs, can make EV 2-wheelers competitive by 2020; however for EV 4-wheelers, these may not be sufficient. The size of 2-wheeler market is going to be much larger than the 10 Million two-wheelers sold in 2010 and therefore the policy of limiting to 1 million electric vehicles will not be adequate to make EVs a major option. In case of EV 4-wheelers the incentives will make the difference only by 2030 as global decline in battery costs further brings down the costs.

The reference scenario results indicate that EV policies as outlined in India's INDC would require additional policies to support the domestic EV market both on the supply and demand side. The demand for batteries for instance, especially for lithium ion batteries in the medium term, would require sourcing lithium. India does not have substantial lithium resources and therefore would need to establish a reliable supply-chain to create domestic battery industry that supports EV industry. Technological advancements may reduce the amount of lithium required per kWh of battery production (Oliveira et al., 2015), however, this is an important consideration in the immediate and medium-term. High EV penetration will also warrant investments and policies for creation of facilities for the collection and recycling of the batteries. Policies to promote private and public initiatives to address these needs are vital to support the rising EV stock in the country. Electric vehicles can perform adversely vis-à-vis conventional vehicles if they lead to creation of fossil based electricity generation and public policies must include measures to mitigate these (Choma and Ugaya, 2015). Studies on user behaviour can be useful to assess and develop charging infrastructure at suitable locations to attract potential EV users (Fang et al., 2015).

EV would contribute to energy security by reducing the demand for energy from transport and secondly by diversifying the fuel mix. The energy demand reduces since EV technologies have lower direct energy consumption and their energy efficiency shall rise relatively quickly compared to more mature internal combustion engine technologies. In the reference scenario, oil (diesel and petrol) will continue to remain the mainstay of transport (meet 70% demand) even in 2050. Our assessment shows that under EV policy-support scenario as well as 2 °C stabilization scenarios, EV penetration in India will rise rapidly and will this will reduce dependence on imported oil.

Similar to observed trend in China (Günther et al., 2015), CO_2 emissions from transport in India will remain high even in the EV scenario in the absence of sustainability measures. These could include measures that reduce the transport demand (e.g. reducing the number and length of trips through urban design), cause modal shift away from road transport (e.g., to rail and non-motorised transport) and facilitate penetration of substitutes for oil (e.g., biofuels). But in 2 °C stabilization scenario, CO_2 emissions as well as emissions of local pollutants from transport decline sizably due to cleaner and low carbon production of electricity. The scenarios assessment in this paper shows that EVs are clean technologies. They are promising options within the clean transport portfolio of the future which can concurrently deliver low carbon as well as energy security and air quality co-benefits in India.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2016.05.111.

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