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Long Term Energy and Emission Implications of Global Shift to Electricity-Based Public Rail Transit System

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A report on Long Term Energy and Emission Implications of Global Shift to Electricity-Based Public Rail Transit System.

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ABOUT THE AUTHORS

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His research is focused on Indian and global energy and climate change mitigation policy issues- carbon dioxide emission stabilization pathways, low carbon and sustainable energy policies, modelling energy demand, and water-energy nexus within the integrated assessment modelling framework of the Global Change Assessment Model (GCAM). Vaibhav's recent work includes analyzing nuclear energy scenarios for India, Indian HFC emission scenarios, climate policy-agriculture water interactions, transportation energy scenarios, model evaluation, investment implications for the global electricity sector, and modelling the building sector energy demand scenarios for India. Vaibhav has been actively involved in global model comparison exercises like Asian Modelling Exercise (AME) and Energy Modelling Forum (EMF).

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ABSTRACT

Transportation sector service demands are growing with rising incomes across the world and managing energy and emission mitigation challenges from this sector have been identified as a global priority. With high reliance on light-duty vehicles in the present, the future of global transportation system is also geared towards private modes. Public transportation has been argued as an alternative strategy for meeting the rising transportation demands of the growing world, especially the poor, in a sustainable and energy efficient way. The present study analyzes an important yet under-researched question− what are the long-term energy and emission implications of an electric rail based passenger transport system? We analyze a suite of electric rail share scenarios with and without climate policy. In the reference scenario, the transportation system will evolve towards dominance of fossil based light-duty vehicles. We find that an electric rail policy is more successful than an economy wide climate policy in reducing transport sector energy demand and emissions. Economy wide emissions however can only be reduced through a broader climate policy, the cost of which can be reduced by hundreds of billions of dollars across the century when implemented in combination with the transport sector focused electric rail policy. Moreover, higher share of electric rail enhances energy security for oil importing nations and reduces vehicular congestion and road infrastructure requirement as well.

1. INTRODUCTION

Transport sector was highlighted in the Kyoto Protocol as one of the key sectors to be tackled for meeting ambitious global greenhouse gas emission reduction targets (Chapman, 2007). In 2005, the transport sector accounted for 23% of global carbon dioxide (CO_2) emissions from fossil fuel combustion with road sector largely dominating (OECD/ITF, 2010). Between 1990 and 2007, global transport sector CO_2 emissions increased by approximately 46%, more than the rise in total emissions of 38%, indicating that emission growth in transport sector is significantly higher than other sectors (IEA, 2009). At the same time, energy consumption in the transport sector increased by 45% (IEA, 2009). Contrary to what was the global priority highlighted in the Kyoto Protocol, carbon intensity of energy consumed in the transport sector has not decreased between 1990 and 2007.

Private vehicles for road transport meet the bulk of passenger transportation service demand. In 2005, this category comprised 55% of the total passenger service demand of almost 34000 Billion passenger kilometers. Public road transportation was the next with 26% share in passenger travel demand, followed by air with 11% share, while rail services contributed less than 6% (Electris et al., 2009). Per capita passenger service demand is much higher in the high income regions like the USA and Western Europe, compared to developing regions like Africa, China and India where the bulk of future transportation service demand growth will occur (Kyle and Kim, 2011). A vast difference can be observed in the regional patterns, with the richer countries more dependent on private modes while non-motorized and public transportation modes being dominant in the developing nations.

Reducing emissions from the transportation sector has been seen as a more costly option due to distributed emission sources, high dependence on liquid hydrocarbon fuels where emission mitigation options are limited, and low responsiveness of passenger service demand to fuel price increases (Kyle and Kim, 2011). Different strategies for reducing energy demand and emissions from the transportation sectors have been discussed and debated by researchers and policy makers. Land use and urban planning has strong implications for travel demand, modal choices and transport energy consumption, and efforts on this front can significantly reduce emissions (van Wee, 2002; Brommelstroet and Bertolini, 2008; Bartholomew and Ewing, 2009; Limtanakool et al., 2006). Some of the important objectives of optimal land use and urban planning are to reduce average daily travel distances for official and personal travel, and promote infrastructure for better access to secure and reliable public transportation service. Reduced average travel distances and an efficient public transport system has positive implications for reducing global and local emissions. Electric, biofuel and hybrid vehicles can provide multiple benefits like lower fuel combustion, lower operating costs, lower noise pollution, and longer operating life, and can be very effective for reducing direct emissions from the transportation sector (Litman, 2007; Bayindir et al., 2011; Zheng et al., 2012; Kyle and Kim, 2011). Biofuels policies for mitigating transportation sector emissions, proposed by many governments, can have multiple benefits such as improving energy security and rural employment generation along with emission mitigation. Adverse effects of bio-energy use on food security, forest ecosystem and environment are a concern, however (Ryan et al., 2006; Escobar et al., 2009; Sorda et al., 2010; Alavalapati et al., 2011). Improving vehicle fuel efficiency, which varies widely across regions, has been highlighted as one of the key strategies to reducing vehicular emissions in a cost effective way (An and Sauer, 2004). Schipper (2011) and Litman (2005) however argue that this strategy is overvalued.

Shifting towards a higher share of public and mass rapid transportation system has been proposed and discussed as another important strategy for mitigating emissions from the transport sector (Hensher, 2007; GEF-STAP, 2010; The World Bank, 2012). UITP (2009) shows that cities where modal share of private motorized vehicles is above 75% produce 2.5 tons more CO_2 per passenger per year, or more than four times, than cities where the share of public transport, cycling and walking together is more than 55%. However, in developing countries, where most of the future transportation growth and infrastructure investments will occur, it is expected that the future share of public transport and non-motorized transport will decrease (GEF-STAP, 2010).

Rail based urban passenger transport system is an important element in the public transportation strategy of many countries and cities (Priemus and Konings, 2001; Phang, 2002; Cascetta and Pagliara, 2008), including many cities in Brazil, Canada, China, India and the USA.[1] Multiple benefits of urban rail systems, especially that based on electricity-such as reliable and safe transportation service to commuters, higher energy efficiency compared to other modes of travel, reduced local air pollution and improved energy security by reducing oil dependence- make it an attractive investment option.

Tirachini et al. (2010) show that for transport from peripheral areas to the city center, a rail mode may have a lower total cost than bus service if it is able to operate at faster speeds. Currently, high standard bus service is the most cost effective means. The higher the speed difference the lower is the overall cost of rail. This highlights the developments in fast growing countries and cities of the world, as in China and India. As roads become more and more congested due to increased traffic, city based rail systems can provide large savings in commuting time.

Electric rail technology is increasing its presence in many urban centers around the world. Energy intensity per passenger km in 2005 was lowest for electric rail across regions and all modalities including private and public road, non-electric rail, and air. Electric rail was the most energy efficient transport choice available with double the efficiency of non-electric rail (Electris et al., 2009). Electric rail systems support the scenario of a low carbon society that

[1] http://www.world-metro.org/en/ ;http://www.lightrailnow.org/news/n_newslog002.htm ; http://www.lightrail.com/ ; http://indiatoday.intoday.in/story/metro-rail-intra-city-commuting/1/160680.html

envisions a higher share of public transportation modes for sustainable urban transport planning (IIMA et al., 2009).

The highlighted benefits of an electric rail based transportation system are many. The benefits and importance of such a system from the energy and climate change mitigation perspective are further analyzed in this paper. Could electric rail based urban passenger transportation systems, which are being planned across the urban centers of the world play an important role in mitigating global carbon dioxide emissions? What are the long term energy and emissions implications of an electric rail based transportation system? What is the economic value of including an electric rail push policy as a part of broader economy-wide emission mitigation effort? We address these important yet under-researched questions within an integrated assessment energy and climate change modeling framework. We model scenarios related to high share of electric rail in meeting passenger service demands to find its impact under the business as usual as well as under a climate policy scenario. The next section describes the modeling framework followed by the scenario design. The results and discussions are presented next, and finally the conclusions are presented. It should be noted that the aim of the analysis is to investigate the impact of higher share of electric rail technology on global energy and emission mitigation efforts and not how such high shares are to be achieved. We provide potential motivations for the increased investment in public electric rail systems from a global perspective. The realistic implementation of such efforts will depend on the transportation policies of each country as well as local governments.

2. METHODOLOGY

2.1 Integrated Assessment Modelling Framework

We use the Global Change Assessment Model (GCAM) for exploring the implications of a higher share of electric rail in global passenger transportation service. GCAM is an integrated assessment model that has a particularly rich representation of the overall energy system. It accounts for GHG emissions from the energy sectors, as well as from agriculture and land use change. GCAM disaggregates the world into 14 regions, and represents economic markets for fossil fuels, renewables, as well as biofuels, synthetic fuels and agricultural commodities. GDP, population and prices drive energy service demands in the end-use sectors; services are provided through the suite of end-use and energy conversion technologies. Additional information on GCAM can be found in Edmonds and Reilly (1983), Edmonds *et al.* (1996), Clarke and Edmonds (1993), Kim *et al.* (2006), Clarke *et al.* (2008), and Chaturvedi et al. (2013).

Transportation sector is one of the three end-use energy sectors modeled in GCAM, along with industry and buildings. Within the transportation sector, energy consumption is modeled for three transport services - freight, international shipping, and passenger. Within passenger transport, which is the focus of our study, there are a variety of modes (light-duty vehicles, trains, buses, airplanes) that compete for service. Within each mode, alternative vehicle technologies (e.g electric, biofuel, hydrogen fuel cell, and fossil-fuel based vehicles) compete for service.

More broadly, transportation service demand in GCAM is dependent on the GDP, population, and the price of transportation service aggregated across all modes. The transportation service price of a given mode is dependent on fuel price, vehicle fuel intensity, vehicle non-fuel price (representing the capital cost, maintenance cost and others such as insurance cost), and load factor. Additionally, GCAM includes the value of time spent in transit as part of the service cost in competing alternative modalities. The fuel price, and the variable component of the service price, is determined endogenously while all other parameters are exogenous to the model. The market share captured by each modality is determined by a logit formulation and the cost of each mode for providing transport services (Clarke and Edmonds, 1993). Fuels supplied to vehicle technologies include refined liquid fuels, natural gas, electricity and hydrogen. Detailed structure of the transportation sector in GCAM and the relevant algebraic relationships can be found in Kim *et al.* (2006) and Kyle and Kim (2011).

The present study focuses on the implications of modal shift towards electric rail based passenger transportation system. It is important thus to discuss the modal choices available for passengers in GCAM. The freight transportation sector is not discussed here. The modal choices available can be broadly categorized into road, rail and air transport modes. Light-duty vehicles (LDVs) and buses constitute road transport; rail and high-speed rail have been modeled separately in rail-based transport, while airplanes represent air-based transport. A given mode can use different fuels, depending on economics. Both road-based modes can use refined liquids, gas, electricity or hydrogen; high-speed rail is based solely on electricity; rail (includes intercity rail, subways, and metro rails) can use refined liquids, electricity, or coal (still used in small amounts in China); and finally air transportation is also completely dependent on refined liquids. All these modes compete within the model to meet the transportation service demand of a growing and wealthier global population.

For meeting the study objectives, we analyze first a reference and a climate policy scenario without the rail push policy to establish a baseline for comparison to a suite of electric rail share scenarios under both the reference and climate policy scenarios. The scenario design is described in the next section. These exogenously imposed electric rail targets are met by reducing the cost of this mode through a subsidy. Our analysis does not intend to find the 'efficient' level of targets, or targets that maximize social welfare in the aggregate sense. Such analysis would need to incorporate many other dimensions within a dynamic analysis including the activities and associated externalities of all the other production and consumption sectors of the economy, which is a much broader issue. The present analysis focuses on the important issue of energy and emission implications of an important passenger transportation technology and does not propose the social welfare maximizing combination of transportation technologies. At present, the model does not have such capability, but the motivation of this analysis is to encourage dialogue on alternative futures of transportation and climate change policies.

2.2 Scenario Design

A combination of emission mitigation policy and electric rail push policy scenarios (12 scenarios) have been modeled in this study. The targets for electric rail penetration are expressed in terms of the share in total passenger transportation service including road, rail and air. Climate policy aims at stabilization of carbon dioxide emissions at 380 ppmv CO_2 in 2095.Table 1 describes the 12 scenarios-

Table 1: Scenario Descriptions

Scenario name	Scenario description	2020 target share	2035 target share	2050 and onwards target share
Ref_Base	No climate policy or electric rail targets. Penetration of electric rail decided endogenously within the model.	3.3%	3.3%	3.3%*
Ref_10%Rail	10% electric rail share without climate policy	5%	7.5%	10%
Ref_20%Rail	20% electric rail share without climate policy	10%	15%	20%
Ref_30%Rail	30% electric rail share without climate policy	15%	20%	30%
Ref_40%Rail	40% electric rail share without climate policy	20%	30%	40%
Ref_50%Rail	50% electric rail share without climate policy	25%	35%	50%
CP_Base	Climate policy scenario without electric rail target. Penetration of electric rail decided endogenously within the model.	3.3%	3.3%	3.5%
CP_10%Rail	10% electric rail share with climate policy	5%	7.5%	10%
CP_20%Rail	20% electric rail share with climate policy	10%	15%	20%
CP_30%Rail	30% electric rail share with climate policy	15%	20%	30%
CP_40%Rail	40% electric rail share with climate policy	20%	30%	40%
CP_50%Rail	50% electric rail share with climate policy	25%	35%	50%

* Rail penetration increases in absolute terms, however in terms of share it remains same in the Reference scenario and increases marginally in the Climate policy scenario

The reference scenario is not a frozen technology scenario, and costs and efficiencies of all technologies change over time leading to change in the penetration of different technologies for meeting end-use energy service demands. The rail share scenarios also have reference cost assumption but an additional push for electric rail technology through subsidy. The climate policy scenarios target a 380 ppmv CO_2 concentration target, which corresponds to a 2 degree Celsius temperature rise. A carbon price is imposed in this scenario, which leads to changes in the relative cost of fuels, penetration of low carbon technologies, and alternative fuel mixes. Under any of the rail push scenarios, it has been assumed that the target share is composed fully of electric rail, while fossil fuel based rail is phased out.

3. RESULTS

3.1 Reference scenario and the impact of climate policy on transportation sector

3.1.1 Reference Scenario

Transportation sector globally consumes almost a quarter of total final energy across the century. In the Reference scenario, global population grows from 6.46 Bn in 2005 to a peak of 9.19 Bn in 2070, and declines thereafter to 8.87 Bn in 2095. Global GDP grows by a factor of eight between 2005 and 2095. Corresponding to the increase in global population and GDP, total passenger service demand grows from 37 Tr-pkm (Trillion passenger kilometer) in 2005 to 140 Tr-pkm in 2095(Fig. 1a). Almost all of this demand is concentrated in the developing and transition economies[2] of the world, where both income and population increase lead to six-fold increase of transportation service demand across the century. The per capita service demand of developing and transition economies increases from 3000 pkm in 2005 to 13000 pkm in 2095, but is far less than the per capita demand of developed regions[3]in 2005 at21000 pkm that increases to 30000 pkm in 2095.

In reference scenario, passenger modal share is dominated by LDVs (light duty vehicles: this include private cars, taxis and two wheelers), with relatively lower share of public transportation modes like buses and rail (Fig. 1b). LDVs take a large share in high-income developed countries and account for more than 70% in meeting transportation service demands. In the developing and transitioning regions, however, bus services play an important role in meeting passenger transportation needs throughout the century along with LDVs. Nevertheless, bus share decreases from 40% in 2005 to less than 20% in 2095 as incomes rise and people shift towards private modes due to rising value of time and the demand for increased transit speed and convenience of private modes.

Reference scenario transport sector final energy consumption is dominated by fossil fuels and there is little penetration of alternative fuels like electricity and gas. Most of the LDVs and almost all buses consume fossil fuels, and this is true across all regions. After 2050, the share of low carbon LDVs increases to 20% of global passenger service. Due to increased penetration of alternative fuels like electricity, and also a lower rate of increase in air travel, the final energy intensity of passenger transportation services in the developed economies declines at a faster rate compared to the developing economies.

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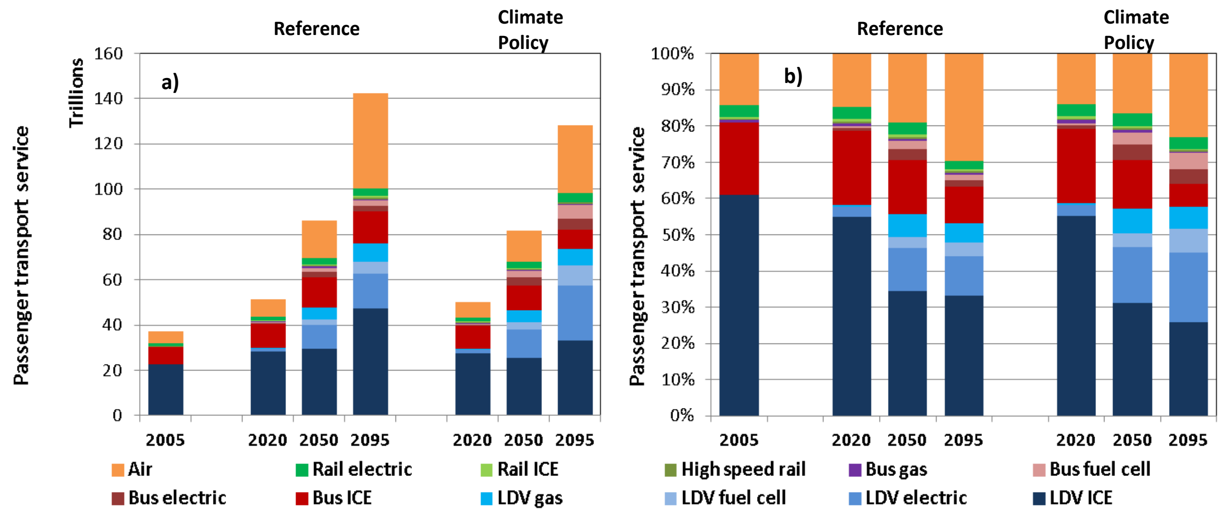
[2] Developing and transitioning economies in our paper include GCAM regions Africa, China, Eastern Europe, Former Soviet Union, India, Korea, Latin America, Middle East and Southeast Asia.

[3] Developed regions in our paper include GCAM regions Australia and New Zealand, Canada, Japan, USA and Western Europe.

Figure 1: Global Passenger Service Under Reference and Climate Policy Scenario



3.1.2 Climate Policy

A carbon tax is imposed on fossil fuels in the climate policy scenarios. The carbon tax changes the relative price of fossil fuels and other energy carriers affecting the choice of technologies throughout the value chain from conversion to end-use. There are multiple implications of a climate policy that are discussed below.

First, the climate policy leads to decrease in the passenger service demand due to increasing cost of transportation service, and this decline is significantly higher in the developing and transition economies due to lower incomes. By the century end, global passenger transportation service demand in the climate mitigation policy scenario declines by 10% compared to reference scenario (Fig. 1a). Thus higher transportation cost induced by carbon tax leads to contraction in transportation activity.

Second, final energy consumption is also reduced under a climate policy, mainly due to reduction in energy service demand as a response to a carbon price(Fig. 2a).Global passenger transportation final energy consumption reduces by 9% in 2050 and 17% in 2095 relative to the reference scenario.

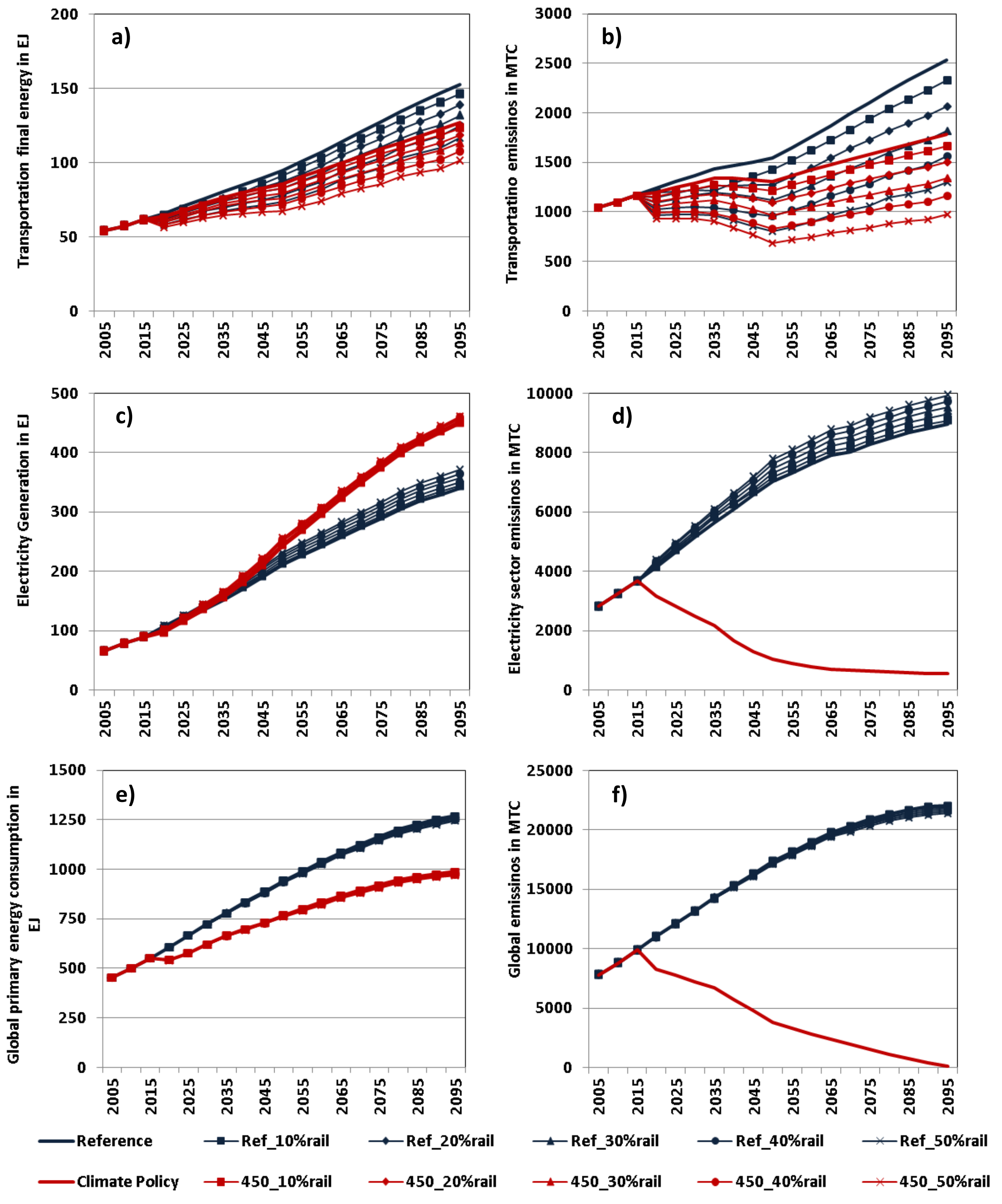
Third, a carbon tax spurs higher share of low carbon transportation technologies(Fig. 1b). The total share of electric and hydrogen LDVs and buses is 27% in 2050 and 35% in 2095. The share of natural gas based vehicles also increases due to carbon tax, further decreasing the carbon intensity of passenger service as carbon intensity of natural gas is much lower than that of oil. Interestingly, electric vehicles take a high share of 14-18% in 2095 for some regions (Australia_New Zealand, Canada, Eastern Europe, Japan, Korea, Middle East, USA and Western Europe) while for all the other regions the share ranges from 5% (China) to 10% (Latin America).

Fourth, the production of biofuels and its share in refined liquids increases as a result of climate policy. Relative to the Reference scenario, the production of biofuels under the climate policy world increases by 40% in 2030 and by 100% in 2050 and onwards. However, as there is a significant decline in total refined liquids production due to climate policy, the share of biofuels increases significantly. Share of biofuels in refined liquids is 5% in 2095 under the Reference world, while under the climate policy world it increases to 10% by 2050 and 17% by 2095. Though oil is used across all the sectors (industrial, buildings and transport), a large part of oil is still used for meeting transportation needs, and hence biofuel based or biofuel blended oil is also another low carbon transportation technology that will be important under a climate policy world.

Fifth, although there is a shift towards low carbon vehicles, the modal share is still dominated by LDVs as the climate policy does not induced a shift towards public transportation modes(Fig. 1b). Existing infrastructure and bias towards LDVs remain. A carbon tax, in itself, is not sufficient to make public transportation more competitive. Greater public transportation service induced through targeted subsidies is discussed in the next section.

Finally, a climate policy leads to significant reduction in emissions in the overall economy, mainly through emissions reductions from the electricity sector (Fig. 2d & 2f). However, even the stringent climate policy leads to only 30% direct emission reduction from the transportation sector by 2095 (Fig. 2b). This 30% reduction is due to the reduction in final energy demand as a consequence of reduction in passenger service, and shift towards low carbon electric, biofuel and hydrogen vehicles as discussed above.

Figure 2: a) Global transportation sector final energy consumption, b) Global transportation sector emissions, c) Global electricity generation, d) Global electricity sector emissions, e) Global primary energy consumption, and f) Global emissions for all scenarios



3.2 Implications of an Electric Rail Share Policy

3.2.1 Impact of rail policy on transportation sector

The motivation behind promoting an electric rail based transportation system is energy efficiency of passenger transport service, as well as reduction in direct carbon dioxide emissions from the transportation sector, which is otherwise difficult to achieve through a carbon tax policy. Here we present the results of five different rail share scenarios, ranging from 10% to 50% target share in total passenger service demand from year 2050 and onwards.

An electric rail share policy is successful in achieving both the objectives of higher energy efficiency and reduced emissions. In 2095, the lowest target of 10% global share of electric rail results in a 4% decline in total final energy consumption in the transportation sector compared to the reference scenario. The highest target of 50% rail share results in decline in total final energy of 20%. Direct emissions from the transportation sector emissions decline by 49% in the Ref_50%Rail scenario by 2095 compared to the reference scenario, an achievement significantly higher than that due to a carbon tax alone.

The rail share policy, as intended, leads to a significant shift in modal share across all the regions of the world. This is evident in both developed as well as developing regions. In developed regions, almost all the increase in electric rail service corresponds to a decrease in LDV service. In the developing regions, the increase in electric rail is largely due to decline in LDV service, but also a decline in bus service. The decline is not only in fossil fuel based LDVs, but across all fuels. Fossil based road vehicles in 2095 decrease from 49% share in the reference scenario to 25% share in the Ref_50%Rail scenario. Corresponding decrease in low carbon vehicles[4]is from 18% to 9%. This significant modal shift is mainly responsible for the reduction in final energy consumption and direct emissions from the transportation sector.

Higher share of electric rail leads to increased production of electricity and hence shifts away from refined liquid fuel production. Global electricity generation increases by about 9% under the Ref_50%Rail scenario compared to reference scenario(Fig. 2c), while the total global primary energy consumption declines by 1% in 2095 under the Ref_50%Rail scenario (Fig 2e). The impact of a rail policy is negligible on its impact on the total economy-wide energy consumption and emissions.

As the share of electric rail technology increases, emissions shift from the transportation sector to the electricity generation sector with marginal impact on total carbon emissions (Fig. 2b, 2d & 2f). Total emissions in the Ref_50%Rail scenario in 2095 decline only by 1% compared to the reference scenario, as electricity sector emissions increase by 11%. Increased electricity production, however, has varying implications for carbon emissions for each

[4] Low carbon road vehicles include vehicles that run on non-fossil fuels. In GCAM this includes electric and hydrogen vehicles.

region as the electricity generation mix varies across countries. The carbon intensity of electricity generation can range from 14 MTC/EJ for Latin America to 35 MTC/EJ for India by 2095 in the reference scenario. The same amount of increase in electricity generation results in greater emissions for countries with higher carbon intensity of electricity generation than those with lower intensities. For instance, under the Ref_50%Rail scenario in 2095, electricity production in both China and Latin America increases by 3 EJ compared to the Reference scenario; however, emissions in China increased by 112 MTC, whereas in Latin America, emissions increased by 66 MTC.

3.2.2 Is rail policy an alternative to climate policy?

To what extent is an electric rail policy and a climate policy comparable or variant in reducing final energy demand and emissions from the transportation sector? The objective of a climate policy is economy wide emission reduction. Clearly the electric rail policy alone cannot achieve this. In terms of the whole economy, emissions under the electric rail policy scenarios are reduced by only 1-3% in 2095, much less than nearly 100% reduction imposed in an economy wide climate policy (Fig. 1f).

The objectives of an electric rail policy are reducing energy consumption and direct emissions from the transportation sector. As is the case above, the climate policy does not address the objectives of the rail policy. As compared to the reference scenario, an electric rail policy by itself reduces direct emissions from the transportation sector by 8-49% in 2095and reflects a 4-20% decline in the transportation final energy consumption in 2095 under range of rail share scenarios. On the other hand, the stringent 380 ppmv CO_2 climate policy reduces direct transportation emissions by 30% (Fig. 2b) and transportation energy consumption by 17% (Fig. 2a). An aggressive electric rail policy could have greater impact on transportation emissions reduction than a stringent climate policy.

An electric rail policy is successful in meeting the energy and emission reduction challenges for the transportation sector, while the climate policy is successful in mitigation energy and emissions for the whole economy. By design an electric rail policy in and of itself does not significantly reduce the total economy wide GHG emissions. It is, however, very effective at reducing energy and emissions from the transport sector. Hence, these policies are not alternatives to each other, but can have positive complementarities that should be explored.

3.3 Electric Rail Share Policy Complemented with a Climate Policy Regime

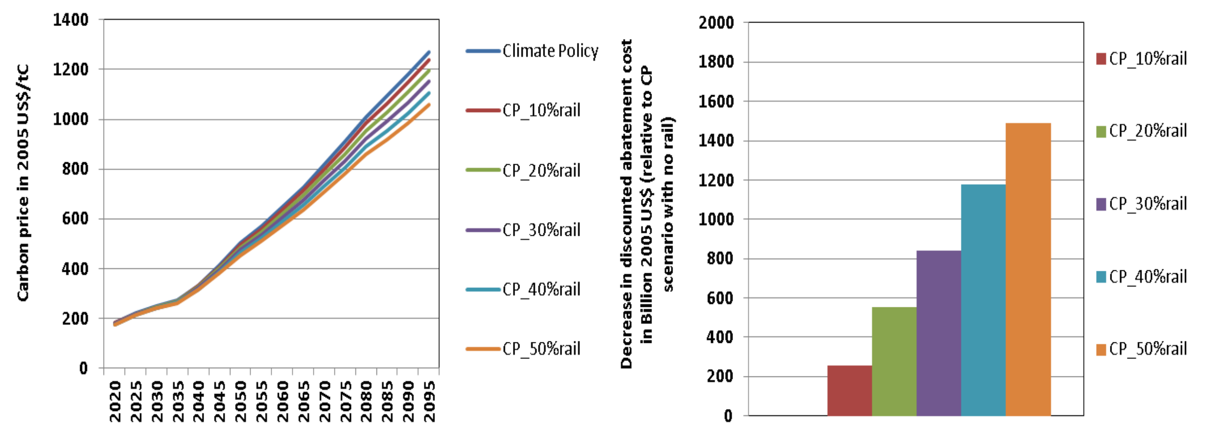
A more effective means to ensure lower energy consumption and emissions from the transportation sector is to complement transport policies with carbon mitigation policies to minimize emissions leakage to the electric power sector.

Final energy consumption in the transportation sector declines by 17-44% in 2095 under the combined climate and rail share scenarios relative to the reference scenario (Fig. 2a). The corresponding decline in direct transportation emissions is 30-62% (Fig. 2b). Higher electric rail share leads to significant shift in emissions to the electricity sector, where electricity generation is decarbonized. 807 MTC of emissions are shifted out of the transportation sector in 2095 in the CP_50%Rail scenario compared to climate policy with no rail targets scenario. This substantial decrease in direct transportation sector emissions does not lead to an increase in overall economy-wide emissions, which are constrained to the same level due to a climate policy.

Many more cost effective options are available for emissions reductions from the central station electric power generation. While not specifically explored in this study, an electric rail policy in conjunction with a limited carbon policy focused more narrowly on the electric power sector could be one alternative and potentially effective approach to reducing global carbon emissions.

An important benefit of higher electric rail share under climate policy is the reduced carbon price and policy cost. Reducing direct emissions from the transportation sector is difficult as carbon taxes and increased fuel costs have limited leverage on reducing transportation demand and encouraging vehicle technology substitutions. Emission mitigation occurs where it is cheapest to do so, and emissions reduction from the transportation sector is more expensive compared to lower cost opportunities in other parts of the economy. By combining an electric rail policy with the climate policy, emissions can be shifted to the electricity sector where these can be decarbonized at a lower cost. The benefits of this approach gets reflected in the lower carbon prices and policy cost. The additional costs of increased electric rail shares or savings due to reduced road infrastructure were not included the analysis.

Figure 3: Global carbon price and total discounted policy cost under climate and electric rail policy scenarios



Carbon price under electric rail share scenarios declines by 3% to 17% in 2095 depending on the extent of rail share relative to the climate policy with no rail policy (Fig. 3a). The corresponding decline in total discounted policy cost is 2% to 9% (Fig. 3b). Total discounted cost reduction is 250-1490BnUS$ (in 2005 prices) in the CP_10%Rail and CP_50%Rail scenarios. This reduction in the abatement cost represents the potential value of an electric rail policy for addressing climate change.

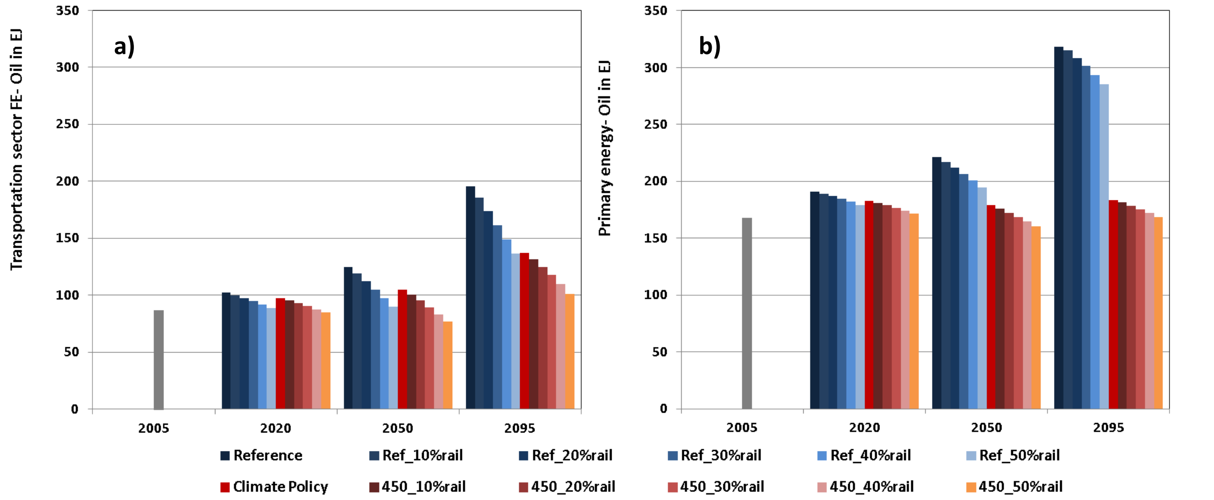
4. DISCUSSION AND ANCILLARY BENEFITS

4.1 Impact on energy security, global oil consumption and prices

An important ancillary benefit of the shift away from petroleum-based vehicles is higher energy security for most regions of the world, mainly the oil importing regions. The transportation sector is predominantly dependent on oil irrespective of the region. Reduced reliance on oil is observed in both the transport sector and economy-wide.

Oil consumption declines significantly in the transportation sector with shift towards electric rail (Fig. 4a). In 2095, oil consumption declines by 5-30%in the rail scenarios without climate policy and 4-26% with climate policy. Decline in oil prices follows the reduction in oil demand. Oil prices under both reference and climate policy scenarios fell by 10% in 2095 in the 50% rail share scenarios.

Figure 4: a) Global oil consumption in the transportation sector, and b) Global primary energy-Oil



It is evident that a shift away from oil enhances energy security for many nations. The greater reliance on electricity enhances the flexibility and diversity of energy use since alternative fuels can be utilized in the production of electricity. At the same time, the significant decline in transportation oil demand leads to downward pressure on oil prices, which reduces the cost of oil consumption in other sectors of the economy. These feedbacks and secondary effects are captured in GCAM. Although oil consumption for transportation is reduced significantly, lower oil prices leads to its increased use other sectors of the economy, such as for electric power and industry, and therefore, the total global oil consumption may not be reduced as significantly. Global primary oil consumption declines by 1-10% depending on the rail share scenario under both reference and climate policy (Fig. 4b).

4.2 Reducing congestion and infrastructural implications

Road congestion is a major issue in many urban centers around the world and is likely to become an increasing concern with rising demand for LDV service. The high growth in passenger service implies many more cars and buses on roads, which will need to be accommodated by increasing the carrying capacity of roads through investments in building road infrastructure. Increased road stress, health impact of local pollutant, and decreased reliability of transport service (timeliness) are some of the critical negative outcomes of road congestion. One strategy to curb road congestion is promoting urban rail systems as has been done in many mega-cities. A discussion of road and rail infrastructure needs for reducing congestion is provided below.

The number of LDVs in the above scenarios are calculated using an average LDV load factor of 1.7 passengers/vehicle and average distance travelled by a LDV equal to 20000 km/yr. Globally, LDV service increases from 13 trillion veh-km in 2005 to 45 trillion veh-km in 2095. The corresponding number of LDVs grows from about670 Mn in 2005 to2230 Mn vehicles in 2095, more than three times the numbers operating today.

The number of buses globally also increases by 2.5 times from 20Mn in 2005 to 52 Mn in 2095 using a load factor of 19 passenger/vehicle and annual service of 20000 km/yr. The growth is driven by India to a large extent with 12Mn buses in 2095, a growth of almost five-fold across the century.

IEA (2013) in its detailed analysis of transportation sector states that an increase of 22 Tr vehicle-kms between 2010 and 2050 will correspond to 25 Mn paved lanes-km globally. Assuming the same relationship for LDV growth, the GCAM reference scenario will require 17 Mn new paved lane-km between 2005 and 2050 and 19 Mn new paved lane-km between 2050 and 2095for accommodating the growing passenger road transport demand. Within the 2005 to 2050 time frame, the greatest additions are 2.9 Mn lane-km for USA, 2.8 Mn lane-km for Middle East, 2.4 Mn lane-km for Southeast Asia, and 1.9 Mn lane-km for India. In the second half of the century (2050 to 2095), Africa requires massive investments in road infrastructure with an additional requirement of 4.7 Mn lane-km, on top of the 1.7 Mn lane-km required between 2005 and 2050.Infrastructure needs of this magnitude require huge investments, without which implies significant road congestion across all regions with increased time spent in transit and loss of productivity.

In the 50% rail share policy, rail service increases 52-fold from 14 Bn-km in 2005 to over 712 Bn-km in 2095. The need for new global road infrastructure throughout the 21 century declines from 36 Mn lane-kms to 11 Mn lane-kms under the most ambitious electric rail policy of the Ref_50%Rail scenario. Increased rail shares also imply greater needs for rail infrastructure. However, options for longer rail cars with higher load factors could help reduce the capital infrastructure requirement for passenger rail service. Such strategies are difficult to implement in road travel as it implies behavioral changes such as large scale carpooling in place of independent travel. Moreover, higher travel speeds for rail implies greater reliability of transport service, and the shift of road to rail transport has the ancillary benefit of reduced road congestion and potential increased reliability of the overall transport system. Careful planning would be required to encourage co-evolution and benefit to both road and rail networks.

5. CONCLUSIONS

An energy efficient and low carbon transportation system is critical for meeting climate mitigation policy goals. Most of the present transportation needs, as well as those of the future, are expected to be met by light-duty vehicles, which provide more comfort as compared to existing public transportation systems. However, from the point of view of overall systemic efficiency and energy intensity, public transportation system is the preferred option. Electric rail based dedicated transportation corridors for meeting urban and peri-urban transportation needs is establishing itself as a reliable and secure model in many major cities across the world. The present study focuses on the long-term energy and emission implications of an electric rail based transportation system, where in a major share of travel service needs are met by electric rail. We analyze a suite of scenarios with varying share of total passenger service met by electric rail modality under both reference and climate policy for exploring the energy and carbon emissions implications.

Under the reference scenario, light-duty vehicles would meet the bulk of transportation service demands across regions. A larger share of passenger transportation system under the reference scenario is fossil based, though low carbon technologies, mainly electric vehicles, also gain share by the end of century. Under a climate mitigation policy, the end-use technology mix changes substantially towards more electric and hydrogen based LDVs and buses. The share of fossil-fueled based transportation decreases. A climate policy leads to significant economy-wide carbon emission reductions, but direct emissions from the transportation sector are only marginally impacted. An emission mitigation policy in itself does not lead to shift towards less energy and carbon intensive public transportation system like electric rails. The market in itself would not achieve high public transportation share and hence additional policy and investment would be required for achieving this.

A targeted policy focusing on higher share of electric rail, whether implemented under reference scenario or climate policy scenario, is successful in decreasing transportation sector final energy consumption by 5-20% and carbon emissions by 8-49%. Total economy-wide carbon emissions decrease only by 1-3%. Under scenarios with higher share of electric rail, carbon emissions shift from the transportation sector to electricity production with increasing demand for electricity from passenger rail modality. Electricity sector carbon emissions increase by as much as 11% under the Ref_50% rail scenario. Greater use of electricity for transport services, however, allows more flexible and cost effective means for carbon emissions reduction from central station power generation.

Higher electric rail share leads to reduction in long-term carbon price by 3-17% and total discounted abatement cost by 2-9% across the century. The reduction in total discounted abatement cost represents the value of an electric rail focused policy for carbon emissions mitigation. Two important ancillary benefits of an electric rail policy that we have highlighted are enhanced energy security through reduced dependence on oil for transport service, and reduction in road congestion.

Greater reliance on public transportation and electric rail is important from the point of view of sustainable urban transportation systems. Our aim is to explore scenarios focused on the public rail system and clarify the energy and emissions implications of alternative transportation policies. A portfolio of solutions for the climate change problem and other alternative strategies can go hand-in-hand even with a public transportation focused strategy. This study has shown that electric rail based public transportation system is one important strategy for managing the diverse challenges of future transportation systems across the world.

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