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Decarbonising urban transportation

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The transportation sector is a major contributor to global greenhouse gas emissions, accounting for around one-quarter of current annual emissions. Surface transportation (passenger vehicles, buses, rail, and freight transportation) contributes 75% of total emissions, with the remaining 25% allocated equally between air and water transport. According to the recently released 5th Assessment Report of the IPCC (September 2013), the transportation sector is expected to grow significantly in future years, particularly in rapidly developing countries around the world, and will therefore be one of a few key drivers of increasing global warming. Unless there is a major political effort and consumer willingness to change current energy consumption patterns and travel modes over the next few decades, transport-related emissions are likely to double by 2050 relative to levels observed in 2010. Because of the contribution of transportation to climate change and its impact on urban air quality, a comparative assessment of potential carbon emission reductions and health benefits of reduced particulate matter emissions was undertaken considering several low carbon pathways for development of the urban road transport sector up to 2050. As a result, we conclude that aggressive changes will be needed to scale back future emissions by 20% (or more) compared to present day emissions. These changes will impact vehicle fuel economy (+50%), urban mobility patterns (lower private car demand and greater use of public transportation), choice of alternative fuels (less use of petroleum-based fuels and greater use of biofuels and electrons) and electricity generation mix (greater use of renewables, carbon capture technologies for limiting fossil fuel carbon emissions, and/or nuclear energy). Public acceptance is fundamental to bring about changes in consumer attitudes and behaviour. Given the long lead times required for research, development, demonstration and deployment of new technologies, the time to act is now if we are to limit the global mean surface temperature increase to within 2°C above preindustrial levels.

Keywords: transportation; biofuels; climate change; low carbon pathways; carbon price; electricity decarbonisation; health impacts; DALY.

JEL classification: C63, I18, O13, Q41, Q53, Q54

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1 Introduction

A reliable, efficient and cheap transportation system is essential to social development and economic growth. The rapidly increasing worldwide demand to move people and goods is outpacing the available transportation infrastructure, including road and public transportation networks. The projected deficit will be felt most acutely in developing countries, where personal travel is expected to grow several-fold between 2000 and 2050, driven primarily by rising incomes that lead to higher rates of vehicle ownership and greater demand for recreational travel. Freight transport will also increase owing to greater industrialization and globalization, which stimulate regional and international shipment of goods and materials (including food trading). The increasing transport demand is contributing to an increase in congestion, traffic injuries and fatalities and increasing dependence on petroleum.

Environmentally, transportation is affecting global climate change through emissions of greenhouse gases (GHG) and is the main driver of degradation of urban air quality, contributing to increasing concentrations of fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), carbon monoxide (CO), volatile organic compounds (VOC), and indirectly to formation of ozone (O_3). These pollutants have an adverse impact on human health (ExternE, 2000; van Essen et al., 2011). As a matter of fact, according to the Global Burden of Disease Study 2010, air pollution is responsible annually for 3.2 million deaths from exposure to $PM_{2.5}$ and 0.15 million deaths from exposure to O_3 (Lim et al., 2012); traffic-related injuries (including injuries to motorists, pedestrians and cyclists) contribute an additional 1.4 million fatalities per year (Lozano et al., 2012).

Transportation is a major contributor to GHG, accounting for nearly one-quarter ($\approx$ 7 $GtCO_2$) of annual emissions, 75% of which can be attributed to road transportation (Kahn Ribeiro et al., 2007). In Europe and the U.S., transportation contributes 25% to 30% of the regional GHG budget, of which 75% is from passenger cars (incl. vans), 20% from freight, and less than 5% from buses and rail. CO_2 accounts for the bulk of GHG emissions, with less than 3% for CH_4 and N_2O, and 5% to 10% for F-gases. For traditional petroleum-based fuels, CO_2 tailpipe emissions typically account for 80% of total lifecycle inventory.

Reduction of transportation emissions, which include vehicle emissions from use, construction, delivery, dismantling and recycling, as well as fuel lifecycle emissions from extraction, preparation and delivery, has proven to be a difficult task. Apart from the technological effort, the challenge to vehicle manufacturers has been to limit emissions while keeping prices competitive. The European target for CO_2 tailpipe emissions for new cars sold in 2020 is 95 gCO_2/vkm (vkm – vehicle kilometre), that is a 30% reduction from the current fleet average of 132 gCO_2/vkm. In Europe, and increasingly in other countries around the world, emission limits of $PM_{2.5}$, CO, VOC and NOx are established by Euro emission standards (currently, Directive 715/2007/EC). Real time emissions vary by vehicle age, engine performance, road conditions and driving habits (e.g., vehicle speed and acceleration, or road gradient). Emissions are regulated by on-board exhaust control technologies. Exhaust control technology is only part of the solution, though; consumer attitudes and choices also impact the success rate and outcome of public policy efforts that aim to limit traffic emissions.

World transportation energy use is expected to grow 1.75% annually between 2000 and 2050, with rates two to three times higher in rapidly developing countries (Fig. 1). For Western Europe, the growth in energy demand is expected to be much slower (around 20% to 25% of the global rate) because of projected low population growth, improvements in vehicle efficiency, and high fuel taxes. Transport-related carbon emissions are projected to double by 2050 relative to 2010 levels (Fig. 1), assuming governments will not implement any new climate policies in the future. Major reductions could be achieved by switching to public transportation or privately operated minibus jitneys in urban areas and switching to less polluting fuels and technologies, such as advanced biofuels and electric

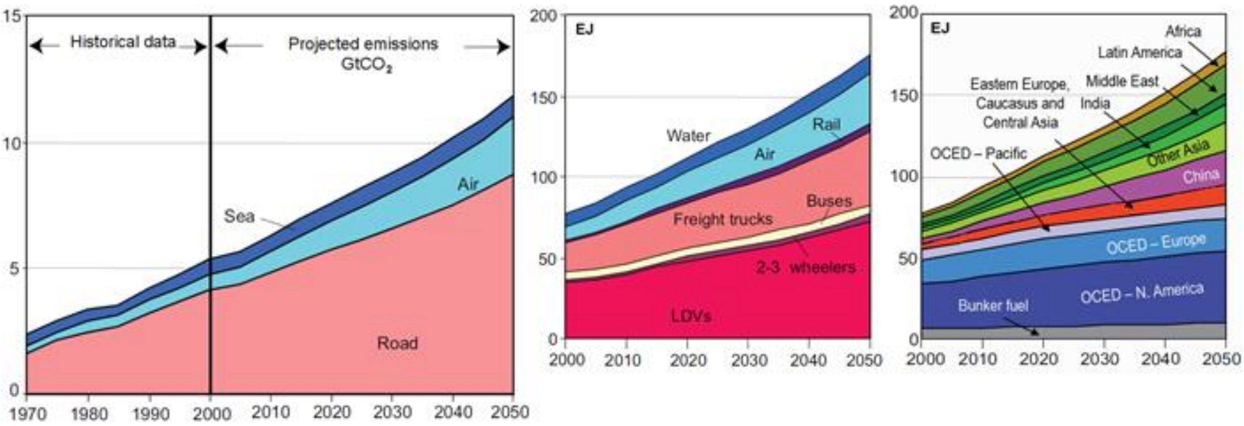

Figure 1: Historical and projected trends for transportation energy use and carbon emissions by mode and region (adapted from Kahn Ribeiro et al., 2007)

drivetrains. Improving energy efficiency[1] can also deliver carbon reductions. Material substitution and advanced design that lowers airflow drag coefficient could improve light-duty vehicle (LDV) fuel efficiency by 12% to 18%. Another 5% to 20% improvement could be achieved through a variety of vehicle operating efficiencies, such as carpooling, increased vehicle inspections, improved maintenance and better traffic route choice. Aggressive driving habits, sudden and rapid starts and stops, can lower vehicle fuel economy by as much as one-third at highway speeds (U.S. Department of Energy, www.fueleconomy.gov).

Carbon emissions decrease with decreasing fuel carbon content, and for this reason biofuels[2] have been proposed as alternative low carbon fuels to traditional petroleum-based fuels. Issues concerning land competition for food production, for animal grazing and for other uses, and additional carbon releases from land use change (LUC) have, however, raised legitimate concerns about the long-term sustainability of the present[3] generation of biofuels. Further concerns exist about effects on crop prices, impact on energy security (biofuel feedstocks are often imported from outside Europe) and net effect on lifecycle carbon emissions. LUC emissions include direct emissions from existing land use plus indirect releases (iLUC) related to unintended emissions from changes in land use for biofuel production. LUC values can be large, increasing CO_2 lifecycle emissions by 50% or even more, but literature estimates vary by an order of magnitude (Laborde, 2011; Wicke et al., 2012; Darlington et al., 2013; Dunn et al., 2013). The potential of biofuels to mitigate carbon emissions depends on feedstock choice and requires a detailed carbon budget analysis, including emissions offset from use of by-products formed during fuel preparation and LUC emissions. Furthermore, vehicles powered by biofuels (and compressed natural gas, CNG) have lower fuel economy. The additional fuel consumption and CO_2 emissions partly offset the benefit of using these low carbon content fuels (Pelkmans et al., 2001; USEPA, 2002).

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[1] Carbon emissions decrease with increasing fuel economy. Real world fuel consumption is higher than manufacturers' estimates; variances reach upwards of 35% with 25% reported as a typical underestimation (Mock et al., 2013).

[2] In 2011, liquid biofuels in the transportation sector accounted for 2.5% of global transportation demand, 3.4% of road transportation (REN21, 2013). Gaseous biofuels (biomethane derived from biogas) contributed only a tiny, but growing, fraction of transportation demand. Over the 5-year period from 2007 to 2012, biodiesel production has grown at an annual rate of 17%, compared to 11% for bioethanol. Although biodiesel production increased in 2012 to 22.5 billion litres, the growth rate against 2011 was less than 0.5%. Bioethanol production was four times higher than that of biodiesel. Renewable electricity is also used in the transportation sector to power trains and electric vehicles; in the future, renewables offer the potential to produce hydrogen renewably.

[3] Present or 1st generation biofuels typically include ethanol from maize, wheat, sugar beets and sugarcane, and biodiesel from palm, rapeseed, soybean, sunflowers, animal waste (tallow oil) and waste cooking oils.

Substantial cuts in carbon emissions could be achieved using plug-in hybrids (PHEV[4]), battery electric vehicles (BEV) and hydrogen-based fuel cell vehicles (FCV), provided that they rely on low carbon or decarbonised electricity sources. BEV will play an increasingly important role in achieving future carbon reduction targets in the transportation sector, not to mention improving urban air quality at the same time. The benefits of hybrids and electric cars is currently limited by low market share, 0.7% of current sales in Europe (2% in the U.S., the world's largest market for hybrids) and is expected to increase to 4% by 2020, with BEV leading the way with 80% of market sales. In Europe, electrically assisted hybrids (HEV) have not been selling as well as they have in the U.S. because the smaller gasoline and diesel vehicles sold in Europe are more fuel efficient than their U.S. counterparts. Average fuel efficiency of passenger cars in Europe is 12.8 km per litre vs. 9.6 km per litre in the U.S. New car sales have fuel economies 50% greater than current fleet estimates in both regions.

Renewables, nuclear power, and carbon capture and storage (CCS) technology all provide significant opportunities to decarbonize the power sector and improve local air quality by eliminating tailpipe emissions of critical pollutants. However, renewables suffer from supply intermittency;[5] backup generation is likely to come from use of fossil fuels, most probably from combustion of natural gas. High capital costs, potential risks of a severe accident, long-term waste fuel management, and proliferation fears have had a profound impact on social acceptance of nuclear technology. In the aftermath of the Fukushima Daiichi accident, public opinion in Japan, and in several countries in the West, has turned against further use of nuclear energy, whereas other countries have opted for a temporary time out to review national nuclear policies. For this reason, current estimates of 2030 projections of nuclear capacity expansion may be delayed by a decade (Rogner, 2013). Finally, CCS technology is still at the demonstration phase. Only a handful of countries in Europe have addressed CCS in national energy policies that anticipate commercial deployment in new power plant construction sometime in the mid-2020s (CCC, 2010).

2 Alternative carbon trajectories for urban transportation

In September 2013, the Intergovernmental Panel on Climate Change (IPCC) released its 1st instalment of the 5th Assessment Report[6] (AR5) titled "Working Group 1 (WG1): The Physical Science Basis." WG1-AR5 has identified transportation as a primary driver of anticipated near-term global temperature rise and as one of the four largest contributing sources to global warming over the next 100 years, along with power generation, industry and biomass burning (Stocker et al., in press). Furthermore, concern over population exposure to traffic-related pollutants has grown in response to increasing evidence from epidemiological studies which find that vehicle emissions are linked to both short- and long-term adverse health effects. Emissions from transport are particularly damaging to human health because releases occur at ground-level; moreover, roadside buildings create "street canyons" that prevent pollutant dispersion. Hence, kerbside concentrations can be several times higher than urban background concentrations (Krzyzanowski et al., 2005; EEA, 2012), which in turn can be several-fold higher than rural background concentrations. In-vehicle concentrations, leading to exposure of car occupants, are typically 50% higher than roadside concentrations (AIRPARIF, 2009). Because of the important contribution of transportation to climate change and urban air pollution, we

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[4] PHEVs are similar to hybrid electric vehicles (HEV) but the battery can also be charged using grid electricity. Plug-in hybrids represent an intermediate (evolutionary) drive technology between HEVs and BEVs.

[5] Denmark is at the forefront in the exploitation of renewable energy. The country plans to build two additional offshore wind farms, having a total electricity capacity of 1 GW, by 2020. This would allow the country to supply 35% of its total electricity supply from renewables, with wind power contributing up to 50%. In recent years, Danish offshore wind farms have achieved the highest capacity factors (fraction of time of year that wind turbines produce electricity) in the wind power industry, reaching well in excess of 40%.

[6] IPCC-WG1-AR5 (2007), www.ipcc.ch/report/ar5/wg1/

present here the results of a comparative analysis that considers the potential emission reductions and avoided $PM_{2.5}$ health burdens of low carbon measures for road transportation up to 2050.

We have considered the combined effects of modal shift, fuel switching, and changes in drive technology within the context of urban passenger transport. The results are indicative estimates of the potential outcomes of various strategies that take into account the gradual transformation of current mobility patterns and future infrastructure build-up. A different choice of inputs would certainly yield different answers, but our conclusions would not change. The analysis was carried out using the LEAP model, an integrated energy planning and climate change mitigation analysis tool developed by the Stockholm Environment Institute (Heaps, 2012). The electricity generation mix for our urban area and transportation sector baseline up to 2050 is specified below as [BASE] scenario. Other future pathways, in addition to [BASE], have been assessed to explore the impact of transportation mode, alternative fuels for transportation, vehicle efficiency, and drive technology. These alternatives are also based on the same electricity mix as [BASE]. Furthermore, we have considered three additional baseload electricity mixes: two fossil-intensive scenarios based on natural gas or coal, and the third dependent on nuclear generation. For each alternative fuel mix, we assume different carbon and air pollution abatement options. All of the options considered can reduce future emissions but do not address the carbon that has already accumulated in the atmosphere in the past, which according to WG1-AR5 report may further contribute to climate change and ocean acidification in the coming centuries.

A description of each baseload scenario and its alternatives is presented below.

(1) Base scenario [BASE]

The analysis is for an urban area in Spain with a population of 360 thousand inhabitants.[7] In the year 2010 (base year of the analysis), we assume, 2.8 billion passenger kilometres (pkm[8]) were travelled within city limits. Passenger cars contributed 59% of total pkm (8,800 vkm), whereas city buses and metro accounted for 12% and 29%, respectively. This is the current mix for Spanish cities. The existing car fleet is made up of gasoline (11 km to the litre, vkm/L) and diesel (14.5 vkm/L) vehicles in the ratio 63% to 37%, equal to the European fuel share breakdown as of 2008.[9] Buses run on diesel fuel with real-city fuel economy 1.6 vkm/L (Pelkmans et al., 2001). Electricity generation is based on natural gas (combined-cycle, 72% of energy mix), coal (condensing, 18%), and renewable resources RES (wind and hydro, 10%). Emission factors for cars (Euro IV and later) and buses are based on published literature or manufacturers' data (Pelkmans et al., 2001; EEA, 2013; JRC, 2013). Electricity demand for the metro system (including energy consumption for train and supporting infrastructure, as well as transmission and distribution (T&D) losses) is estimated at 525 kJ/pkm (Anderson et al., 2009; IEA/UIC, 2012). Lifecycle carbon and particulate emissions from electricity production are estimates based on the work carried out in the European Commission FP6 project CASES (Markandya et al., 2010).

By 2050, we anticipate the share of diesel cars to increase to 70%, consistent with the current share of new vehicle sales in Spain, 15% of city buses will run on CNG, there will be a 25% improvement in the average fleet fuel economy of cars and buses, and electricity consumption will decrease by 25% due to supply- and demand-side efficiency improvements. Travelled distance will increase with income growth (elasticity between 1 and 1.3), and use of private cars will decrease by 25% in terms of pkm travelled, with growth picked up by buses and metro (modal shift: private cars to public transport).

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[7] Equivalent to the population of the municipality of Bilbao in the Basque Country (northern coast of Spain).

[8] One pkm equals one vkm multiplied by vehicle occupancy load (2 persons for passenger cars and 25 persons per bus).

[9] European Automobile manufactures' Association, www.acea.be/news/news_detail/vehicles_in_use

Alternative scenarios for same electricity mix as [BASE]

- *Diesel to Compressed Natural Gas buses [CNG]*

After 2025, all city buses will use CNG fuel (gradual changeover starting in 2011). By 2050, cars contribute 25% fewer passenger-km than in 2010, with the difference and future transport growth picked up solely by buses (modal shift: private cars to city buses).

- *Biodiesel buses (Rapeseed, excluding LUC emissions) [BIO-R]*

Conventional diesel buses are gradually replaced by a combination of CNG and biodiesel buses (imported rapeseed feedstock with no accounting for land use change emissions) by 2025. Biodiesels come on line in 2015, and starting in 2030 buses operate exclusively on biodiesel. Other parameters are the same as in scenario [CNG]. Biofuel consumption and tailpipe emissions data, including CO, VOC, NOx and $PM_{2.5}$, are taken from the study USEPA (2002), whereas carbon lifecycle estimates are from JRC (2013). Sulphur emissions from biofuel and CNG consumption are negligible.

- *Biodiesel buses (Rapeseed, including LUC emissions) [BIO-R, LUC]*

Same as previous scenario except CO_2 from land use change is now included in the carbon lifecycle assessment for biomass production (well-to-tank WTT carbon analysis). Tailpipe carbon releases (tank-to-wheel TTW emissions) are biogenic emissions, offsetting exactly the carbon sequestered during plant growth. LUC emissions are assumed to range between 5 and 54 gCO_2/MJ of energy use[10] (Laborde, 2011; Darlington et al., 2013; Dunn et al., 2013). WTT emissions from production of rapeseed, by comparison, vary between 37 and 59 gCO_2/MJ (JRC, 2013), considerably higher than values for either tallow oil (26 gCO_2/MJ) or waste cooking oils (14 gCO_2/MJ). Biofuels from waste residues have no LUC emissions.

- *Biodiesel buses (Tallow oil) [BIO-TO]*

Same as scenario [BIO-R] but biofuel production is based on chemical transesterification[11] of animal fat (LUC = 0).

- *Biodiesel (Tallow oil) for car and bus use, plus electric propulsion [BIO-TO, HYB+BEV]*

This is the most "aggressive" scenario. In addition to its universal use in city buses, biodiesel also displaces consumption of conventional diesel use in passenger cars. By 2050, passenger cars will travel 50% fewer pkm than in 2010, and the share of pkm by fuel type and drive technology will be as follows: 3% gasoline hybrids, 12% battery (all) electric vehicles (BEV), 15% gasoline, and 35% each for conventional diesel fuel and biodiesel. Fuel economy of cars and buses, in the meantime, will improve more rapidly than supposed in the base scenario, the fleet average increasing by 50%.

(2) Natural gas electricity mix and alternative scenarios

- *Natural gas-based generation [ELEC-Gas]*

By 2050, car demand has decreased by 60%, contributing only 24% of annual passenger kilometres travelled, while the average fleet fuel economy increases by 25% (same as [BASE]). Biodiesel buses (running on tallow oil since 2030) and metro system now account for 29% and

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[10] LUC emissions from ethanol production range between 4 and 14 gCO_2/MJ.

[11] Transesterification is the chemical process in which one type of alcohol is replaced for another in an ester. Biodiesel fuel can be made from almost any fatty acid, including vegetable oils and animal fats (tallow oil). Because vegetable oil is too thick to flow through modern diesel engines without causing significant damage, transesterification is used to lower fuel viscosity (National Renewable Energy Laboratory, www.osti.gov/scitech/servlets/purl/938562).

47% of total pkm, respectively. Electricity generation is from 100% natural gas combined cycle (NGCC). The time-averaged system-wide conversion efficiency, including T&D losses, is 54%.

- *Natural gas + RES [ELEC-Gas+RES]*

Renewable technologies supply 35% of electricity demand, while the remainder is delivered by NGCC. All other input parameters are the same as already specified in [ELEC-Gas].

- *Natural gas + RES + hybrid cars [HYB-Gas]*

By 2050, 40% of cars on the road are gasoline full[12] hybrid electric vehicles (GHEV). In 2010, the fuel efficiency is 21.5 vkm/L or 4.6 L per 100 vkm. The rest of the passenger car stock is 70% diesel and 30% gasoline vehicles. All other parameters are the same as in [ELEC-Gas+RES]. Compared to the previous scenario, this is an example of a drive technology shift.

- *Natural gas + RES + electric cars [BEV-Gas]*

This scenario is the same as the previous one [HYB-Gas] except hybrids have been replaced by all electric vehicles (BEV) in the same 40% proportion of total passenger cars by 2050. In 2010, BEV fuel efficiency is 53.5 vkm/L (0.74 MJ/vkm). An important distinction between this scenario and [HYB-Gas] is that electricity emissions occur from tall stacks (50 m to 100 m above ground for the case of NGCC generation), while hybrid emissions occur at ground-level. Population exposure is an important consideration in the assessment of health impacts. Although, more people are exposed from tall stack emissions, air concentrations are lower due to larger air dilution rate.

(3) Coal-based electricity mix and alternative scenarios

- *Coal-based generation [ELEC-Coal]*

Same as [ELEC-Gas] except electricity is supplied by coal generation, with 38.5% net transformation efficiency.

- *Coal + carbon capture and storage (CCS) technology [ELEC-Coal+CCS]*

Same as [ELEC-Coal] scenario, but beginning in 2023 all existing coal-based electricity production is replaced by integrated gasification combined cycle generation (IGCC) equipped with CCS (this is an example of a generation technology shift). The phase-in period lasts to 2035, at which time all coal generation is IGCC with CCS. The net conversion efficiency, including T&D losses, is 44.5%.

- *Coal + CCS + electric cars [BEV-Coal]*

Same as [ELEC-Coal+CCS], but demand for battery electric cars reaches 40% share of car passenger-km by 2050.

(4) Nuclear-based electricity mix and alternative scenarios

- *Nuclear-based generation [ELEC-Nuclear]*

Same as scenario [ELEC-Gas] except electricity supply is from nuclear energy. CO_2 and $PM_{2.5}$ releases represent lifecycle emissions, which account for fuel chain emissions (fuel extraction, processing and final delivery) and plant construction, operation and decommissioning. Direct or power plant operation releases are very small, accounting for around 0.5% of CO_2 and 1% of $PM_{2.5}$ lifecycle emissions (Markandya et al., 2010).

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[12] A full GHEV can be started without the assistance of the gasoline engine.

- *Nuclear + electric cars [BEV-Nuclear]*

This scenario is the same as [BEV-Gas], but with nuclear-based electricity.

3 Results of Comparative Analysis

The results of our scenarios assessment are presented in Table 1 in terms of aggregate emissions and aggregate health impacts over the 40-year time period extending from 2011 to 2050, whereas cumulative time trends for CO_2 emissions are indicated in Fig. 2. For each of the three electricity baseload mixes, the total CO_2 avoided emissions and $PM_{2.5}$ avoided health burdens (health benefits) are normalized by their respective reference scenarios. In the case of carbon emissions, we also indicate the reduction in annual emissions for the year 2050 (end year of the analysis) compared to base year 2010. For particulate matter emissions, which affect local air quality, we calculate public health impacts, expressed in disability adjusted life years DALY,[13] following the ExternE[14] methodology of the European Commission as implemented in Spadaro (2011) for electricity generation and in Spadaro (2013) for transport emissions. Mortality impacts, which in ExternE are quantified in terms of loss of life years rather than number of deaths, account for about 85% of total DALYs with the remaining 15% allocated to health morbidity cases including hospital stays, respiratory diseases in adults and children (e.g., chronic bronchitis and asthma attacks) and days of restricted activity due to ill health (e.g., work days lost). For ground-level (tailpipe) emissions, the bulk of the health impacts are experienced by the population living closest to the road[15] (mostly within

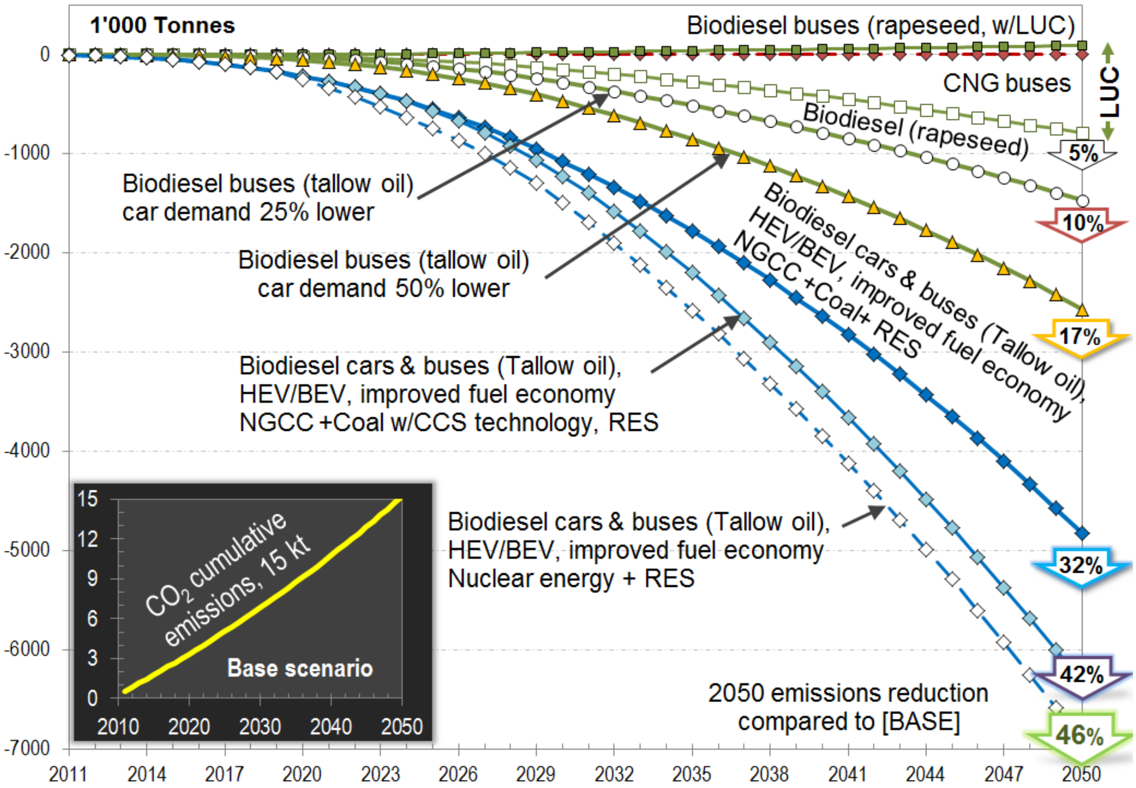

Figure 2: Saved cumulative emissions of CO_2 relative to [BASE]; baseload electricity mix: 72% gas, 18% coal and 10% renewables. Source: current study

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[13] DALY is an integrated health impact indicator accounting for years of life lived disabled due to pain and suffering and loss of life (Mathers et al., 2001).

[14] ExternE (External Costs of Energy), www.externe.info

[15] See discussion on local and regional effects of transportation on air quality in EEA (2012), or impact attribution by geographic-scale in van Essen et al. (2011).

10–20 km), while emissions from power generation (tall stack emissions) have a greater geographical reach, potentially affecting the European population up to a 1000 kilometres from the site where the emissions occur.

Table 1: CO_2 and $PM_{2.5}$ aggregate emissions and health burdens (2011-2050). Source: current study.

Scenarios	**CO_2 Emissions**			**$PM_{2.5}$ Emissions and health burdens**		
	kilo tonnes	Avoided[†] emissions	2050[‡] / Base year	tonnes	DALY	Health benefits[†], avoided DALY
(1) Baseload electricity mix: 72% Natural Gas (combined cycle, NGCC), 18% Pulverized coal (steam turbine) and 10% Renewables (RES); 25% lower car use by 2050						
Base scenario [BASE]	14,930	**Reference**	63% ↑	1,019	3,015	**Reference**
Bus ↪ Diesel to CNG [CNG]	14,928	≈ 0%	63% ↑	892	2,636	–13% ↓
Bus ↪ Diesel to Biodiesel [BIO-R] (Rapeseed, no LUC)	14,138	–5% ↓	48% ↑	960	2,871	–5% ↓
Bus ↪ Diesel to Biodiesel (Rapeseed, incl. LUC) [BIO-R, LUC]	15,020	1% ↑	64% ↑	960	2,871	–5% ↓
Bus ↪ Diesel to Biodiesel [BIO-TO] (Tallow oil)	13,460	–10% ↓	36% ↑ 13% ■	945	2,819	–7% ↓
Car and Bus ↪ Biodiesel (Tallow oil),gasoline HEV/BEV 50% higher fleet fuel economy, 50% lower car demand; plus CCS [BIO-TO, HYB+BEV]	10,108 8,601 ◆ 7,998 □	–32% ↓ –42% ◆ –46% □	–22% ↓ –49% ◆ –55% □	614	1,697	–44% ↓
(2) Alternative baseload based on NATURAL GAS (incl. carbon capture & storage, CCS, and 35% RES); 60% reduced car use, with significant BEV/HEV penetration by 2050, biodiesel buses (Tallow oil)						
Car ↪ Bus, Metro [ELEC-Gas] (NGCC electricity)	12,104	**Reference**	14% ↑	738	2,196	**Reference**
Car ↪ Bus, Metro [ELEC-Gas+RES] (NGCC & RES electricity)	10,869	–10% ↓	3% ↑	728	2,193	≈ 0% ↓
Car ↪ HEV, Bus, Metro [HYB-Gas] (NGCC & RES electricity)	10,353	–14% ↓	–5% ↓	590	1,715	–22% ↓
Car ↪ BEV, Bus, Metro [BEV-Gas] (NGCC & RES electricity); plus CCS	9,819 8,351 ◆	–19% ↓ –31% ◆	–12% ↓ –44% ◆	599	1,713	–22% ↓
(3) Alternative baseload based on COAL (condensing plus integrated gasification combined cycle, IGCC); 60% reduced car use, with BEV contributing up to 40% of pkm by 2050, biodiesel buses (Tallow oil)						
Car ↪ Bus, Metro [ELEC-Coal] (Coal electricity)	16,194	**Reference**	41% ↑	1,200	2,317	**Reference**
Car ↪ Bus, Metro [ELEC-Coal+CCS] (Coal w/CCS electricity)	11,678	–28% ↓	–37% ↓	998	2,264	–2% ↓
Car ↪ BEV, Bus, Metro (Coal w/CCS electricity) [BEV-Coal+CCS]	10,659	–34% ↓	–48% ↓	901	1,831	–21% ↓
(4) Alternative baseload based on NUCLEAR ; 60% reduced car use, with BEV contributing up to 40% of pkm by 2050, biodiesel buses (Tallow oil)						
Car ↪ Bus, Metro [ELEC-Nuclear]	8,562	**Reference**	–20% ↓	728	2,193	**Reference**
Car ↪ BEV, Bus, Metro [BEV-Nuclear]	7,219	–16% ↓	–42% ↓	599	1,838	–16% ↓

† Percent change relative to Reference for a given baseload electricity generation mix

‡ Percent change in absolute annual emissions: 2050 (end year) vs. 2010 (base year)

◆ Improvement from CCS installation (77% to 80% lower CO_2 lifecycle emissions from power generation)

■ Improvement assuming 50% lower car demand by 2050 (+4% if 60% lower demand)

□ Nuclear-based electricity (gradual replacement of NGCC & coal generation by 2030), plus 10% RES

In addition to PM releases, we also calculated emissions of CO, NOx (both pollutants are precursors of ozone formation) and SO_2. Health impacts from exposure to these pollutants are relatively small by comparison to $PM_{2.5}$ because either the emission rates are small (low concentrations), or the urban population exposure is negligible (NOx affects human health through the formation of secondary chemical species that form several tens of kilometres from the emission site). Current estimates of the health impacts of ozone are typically an order of magnitude smaller than PM (Lim et al., 2012).

Our results for the electricity mix in [BASE] (72% natural gas, 18% coal and 10% renewables) show that fuel switching, from diesel to CNG or to biodiesel in buses, in conjunction with a 25% modal shift, from passenger cars to public transport, will only decrease aggregate carbon emissions by a modest 10%. Absolute emissions, meanwhile, are expected to grow by 2050 between 36% and 64% above 2010 levels. Reducing passenger car demand by half will decrease CO_2 aggregate emissions by 17% (Fig. 2), but absolute emissions in 2050 will still be 13% higher than in 2010. Modest reductions are also projected for cumulative particulate emissions (between 6 and 13%), although annual estimates double by 2050. Health impacts, which include premature mortality[16] and health morbidity, are proportional to PM emissions. Tailpipe emissions account for 95% of health burdens. Thus, increasing vehicle fuel economy or using battery electric vehicles can significantly reduce the burden to human health. Fuel substitution from diesel to CNG in buses did not bring any significant carbon savings because of lower bus fuel economy, although the switch did improve local air quality compared to [BASE].

According to our analysis, LUC emissions from rapeseed production in scenario [BIO-R, LUC] led to comparable CO_2 aggregate emissions as observed for the base scenario [BASE]. We have used emission factors for tallow oil and rapeseed to present an indicative range that covers most other current generation biofuels, including soybean, palm oil and hydrotreated vegetable oils.

Significant carbon savings can be achieved as indicated in the scenario [BIO-TO, HYB+BEV], which assumed 50% reduction in car use, 50% improvement in fleet fuel economy, significant penetration of HEV/BEV drive technologies,[17] and switch to biodiesel use for both cars and buses. Emission reductions by 2050 compared to 2010 levels range between 22%[18] and 49% if fossil fuel generation is equipped with CCS abatement technology. Relative to [BASE] cumulative carbon emissions decrease by 32%. Even greater reductions are potentially achievable (42%) if CCS technology is employed (Fig. 2). Particulate cumulative emissions are nearly halved, compared to [BASE].

It is clear from Table 1 that decarbonisation of electricity supply leads to significant CO_2 reductions, with nuclear-based electricity scenarios having the lowest aggregate emissions. Switching from fossil fuels to nuclear generation over the period from 2020 to 2030 in [BIO-TO, HYB+BEV] reduces carbon aggregate emissions by 46% relative to [BASE], and absolute emissions in 2050 are 55% lower than in 2010 (Fig. 2).

4 Transportation sector marginal abatement costs of carbon

Carbon avoidance costs are highly sensitive to assumptions about the performance characteristics of the reference vehicle to which alternatives are compared, purchase price of the substitutes, the cost of

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[16] 3,000 DALYs are equivalent to 240 premature deaths, or 2,560 life years lost across the urban population. Such an impact is equivalent to a lifetime loss of 1 week for each man, woman, and child in the population.

[17] Gasoline hybrids, for instance, have much lower tailpipe emissions of particulates and tropospheric ozone precursors like CO, NOx and volatile organic compounds (VOC) than regular gasoline cars.

[18] Particulate cumulative emissions increase by 6%. In the [BASE] scenario, on the other hand, the cumulative emissions increase by a factor two.

fuel, vehicle lifetime, kilometres driven, time horizon for the comparison, social discount rate, and for the case of biofuels, estimates of emissions from land use change. Depending on the assessment methodology and input data (especially assumptions about future oil price), estimate comparisons from different studies can vary by a factor of 2 or more. In Chapter 4 of the report by Smokers et al. (2009), the authors provide an excellent review of carbon abatement costs and future mitigation potentials for the transportation sector segregated by country and world region.

In Fig. 3 we present the marginal costs of carbon saved (top) and potential carbon reductions (bottom) for the transportation sector (IEA, 2009; IEA, 2010). The various drive technologies and fuel

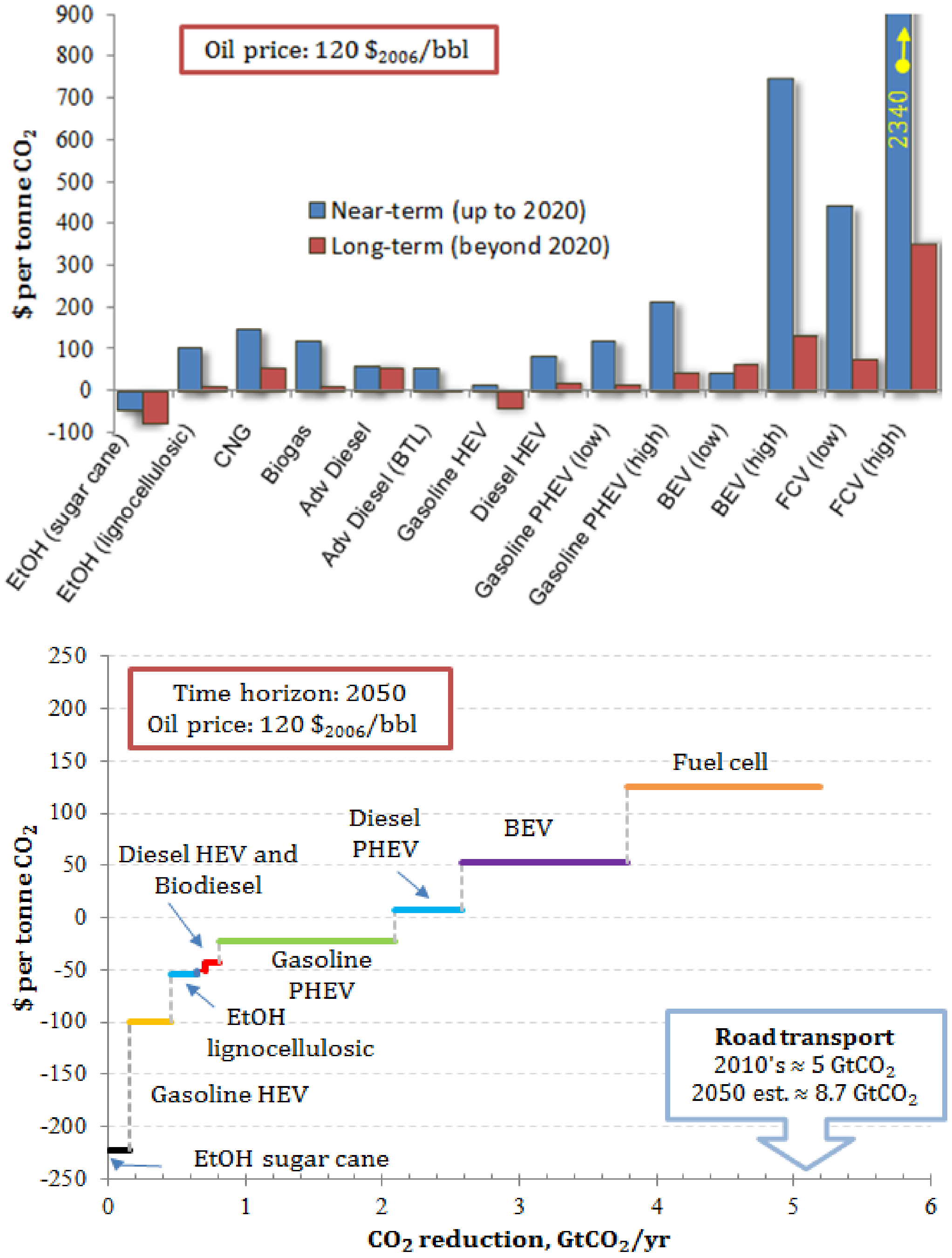

Figure 3: Marginal costs of carbon (top) and carbon mitigation potential (bottom) for different light-duty vehicles and fuel options relative to a conventional gasoline car. The global abatement potential in 2050 is around 5 GtCO2 (ca. 55% of emissions) at an average carbon cost of $26 (2006 prices). BTL = biomass to liquid (biodiesel). Source of data: IEA 2010 (top) and IEA 2009 (bottom)

alternatives are compared against the lifetime ownership cost for a conventional gasoline car driven 200,000 km over its 15-year useful lifetime. Oil price in real terms is assumed constant over time at \$120 per barrel (bbl), and the social discount rate is 3%. For biodiesel fuels from rapeseed (no LUC) the carbon price ranges between \$100 and \$400 per tonne of avoided $CO_{2,eq}$ (JRC, 2008). For biodiesel produced from fatty acids, the carbon price in 2030 ranges from −20 \$/tCO_2 to 100 \$/tCO_2 (Smokers et al., 2009). These costs and those from Fig. 3 provide key hints into the cost viability of different options for mitigating greenhouse gas emissions in the transportation sector and also permit comparison with opportunity costs from other sectors in the economy since a cost effectiveness assessment is paramount to good policymaking in the framework of sustainable development.

5 Conclusion

To achieve significant carbon emission reductions in the transportation sector by 2050 it will be necessary to reduce the demand for passenger cars, improve vehicle efficiencies, increase share of electric vehicles, and decarbonize electricity supply through greater use of renewables, carbon sequestration from flue gases emitted from fossil fuel-fired power plants, and/or use of nuclear energy. Biofuels will also have an important role. The next generation of biofuels (based on cellulosic feedstocks and non-food crops such as algae cultivation) are expected to have much lower carbon lifecycle emissions than current generation biofuels, significantly higher yield rates per land use, and will compete less for croplands (Dunn et al., 2013; Xiaowei et al., 2013).

At the city-level many "green" measures are possible to reduce final energy consumption and GHG emissions, including local generation of green electricity (de-centralized production) and sustainable transportation based on renewable energy, among other things. Examples of “green” cities are mentioned below.

- The city of Freiburg in Germany is one of many examples of green cities in Europe that focus on local planning and social cooperation by creating a situation in which citizens are committed stakeholders that live by principles of environmental protection. Freiburg provides incentives that promote active transport, such as cycling, and the use of solar panel installations. In fact, in some districts as many as 50% of the roofs are covered by solar panels. Freiburg is a net exporter of electricity, which provides significant annual revenues to the city’s treasury.
- Malmö in Sweden is another example of a leading eco-city. Several areas of the city run on 100% renewable energy generated by photovoltaics, wind and hydropower, as well as biofuels that use organic wastes as feedstock. Augustenborg is known for its emissions-free electric street trains.
- Copenhagen is another city that comes to mind as an eco-friendly urban area. In 2001, Copenhagen opened the world's largest offshore windmill park at the time, capable of providing the power needs of 32,000 homes in the city, or around 3% of the city's energy needs.
- Masdar city in the United Arab Emirates has been called the most sustainable community in the world (www.masdarcity.ae/en/). The city is being built outside of Abu Dhabi, and will depend entirely on solar energy and other renewable sources. When completed (2020–25) it will host the headquarters of the International Renewable Energy Agency. Masdar is a prototype of future zero-carbon cities.
- Vancouver (Canada) plans to reduce fossil fuel consumption through investments in wind, solar, wave and tidal energy systems. Already 90% of Vancouver's electricity supply comes from hydropower.

GHG concentrations are going up at a rate that makes meeting the 450 ppm stabilisation target increasingly difficult. This target is the one that is likely to keep global mean surface temperature increase within 2ºC from pre-industrial levels, a figure the global community agreed upon in 2009. Because of the long lead times for mitigation measures and the long atmospheric residence time of

CO_2 (centuries), urgent action is needed to make progress toward the target and one of the most difficult sectors is transportation. Aggressive changes in modes of transportation and fuels for transportation will be needed to make major cuts in carbon emissions. We believe these are both possible and justifiable, on health grounds as well as climate change grounds. Societies need to take the big steps necessary to make this transition and the time to start is now.

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