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On the electrification of road transportation – A review of the environmental, economic, and social performance of electric two-wheelers

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A B S T R A C T

Electrification is widely considered as a viable strategy for reducing the oil dependency and environmental impacts of road transportation. In pursuit of this strategy, most attention has been paid to electric cars. However, substantial, yet untapped, potentials could be realized in urban areas through the large-scale introduction of electric two-wheelers. Here, we review the environmental, economic, and social performance of electric two-wheelers, demonstrating that these are generally more energy efficient and less polluting than conventionally-powered motor vehicles. Electric two-wheelers tend to decrease exposure to pollution as their environmental impacts largely result from vehicle production and electricity generation outside of urban areas. Our analysis suggests that the price of e-bikes has been decreasing at a learning rate of 8%. Despite price differentials of 5000 ± 1800 EUR_{2012} kW h^{-1} in Europe, e-bikes are penetrating the market because they appear to offer an apparent additional use value relative to bicycles. Mid-size and large electric two-wheelers do not offer such an additional use value compared to their conventional counterparts and constitute niche products at price differentials of 700 ± 360 EUR_{2012} kW^{-1} and 160 ± 90 EUR_{2012} kW^{-1}, respectively. The large-scale adoption of electric two-wheelers can reduce traffic noise and road congestion but may necessitate adaptations of urban infrastructure and safety regulations. A case-specific assessment as part of an integrated urban mobility planning that accounts, e.g., for the local electricity mix, infrastructure characteristics, and mode-shift behavior, should be conducted before drawing conclusions about the sustainability impacts of electric two-wheelers.

Introduction

Scientists, policy makers, and industry experts support the gradual electrification of road transportation as a strategy to reduce transport-related oil dependency, carbon dioxide (CO_2) emissions, and urban air pollution (e.g., IEA, 2009; EGCI, 2010; EU, 2012; Weeda et al., 2012). In pursuit of these objectives, mass-produced battery-electric cars were introduced to the

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market around the year 2010. The number of manufacturers and the diversity of models offered has been growing since. However, battery-electric cars are still relatively expensive and suffer from short drive ranges and the absence of a widespread recharging infrastructure. It appears questionable whether battery-electric cars can penetrate the market at a large scale without policy support or substantially increasing oil prices (Weiss et al., 2012). More, immediate potentials for the electrification of road transport, notably in urban areas, may be offered by electric two-wheelers such as e-bikes, e-scooters, and e-motorcycles.

Electric two-wheelers are lightweight and require battery capacities from 0.4 kW h for e-bikes to 10 kW h for large e-motorcycles (Weinert et al., 2007b; ZM, 2013), incurring lower costs than the capacities of 18–85 kW h installed in battery-electric cars. Fully-charged drive ranges of 20–160 km (Weinert et al., 2007b; Eicher, 2010; ZM, 2013) appear to be sufficient for urban operations, where trips typically remain within a distance of 10 km (e.g., Weinert et al., 2007c; Hendriksen et al., 2008; ITRANS, 2009; Delcampe, 2010; Paffumi et al., 2013). Bag-sized portable battery systems for, e.g., e-bikes could be recharged via standard wall outlets (Cherry, 2007), rendering a dedicated recharging infrastructure superfluous.

Whether electric two-wheelers can make a noteworthy contribution to the electrification of road transportation depends on their techno-economic, environmental, and social performance relative to competing modes of transportation. It is reasonable to assume that electric two-wheelers can decrease (i) urban air pollution when substituting conventionally-powered two-wheelers and (ii) demand for infrastructure when substituting passenger cars. However, anticipated benefits could turn into shortcomings if electric two-wheelers substitute public transportation and bicycle use.

The available literature provides a comprehensive assessment of e-bikes in China (e.g., Weinert et al., 2007a, 2007b, 2007c, 2008; Cherry, 2007, 2010; Cherry et al., 2009). However, a multidisciplinary analysis that reviews and expands the established knowledge on electric two-wheelers is still missing. Here, we address this gap and provide an overview of the environmental, economic, and social performance of electric two-wheelers. Our analysis focuses predominantly on e-bikes for two reasons. First, the bulk of the literature on electric two-wheelers addresses this vehicle category. Second, e-bikes outsell globally any other category of electric two-wheelers and currently seize a rapidly growing market in Europe. The results of our research can provide rationale for (i) designing energy and transportation policies and (ii) advancing vehicle technology and urban transportation infrastructure with the objective of making road transportation more sustainable.

Methods

We define electric two-wheelers as two-wheel vehicles designed for transporting passengers by means of an electric motor alone or in combination with human force (Fig. 1; Table 1). In line with EC (2013), we differentiate:

- e-bikes: pedal assisted two-wheelers (also referred to as pedelecs) with a maximum speed of $\leqslant$25 km h^{-1} and an electric motor a maximum continuous rated power of $\leqslant$0.25 kW; e-bikes include electric two-wheelers that are exempted from type approval and also larger pedal-assisted electric-powered cycles of category L1e-A that are subject to type approval;
- e-mopeds and small e-scooters referred to here as mid-size electric two-wheelers: two-wheelers of category L1e-B without pedal assistance and a maximum speed of $\leqslant$45 km h^{-1}, equipped with an electric motor of a maximum continuous rated power of >0.25–4 kW;
- e-motorcycles and large e-scooters referred to here as large electric two-wheelers: two-wheelers of category L3e equipped with a maximum speed of >45 km h^{-1} and an electric motor of a maximum continuous rated power of >4 kW.

Fig. 1. Illustration of an e-bike, mid-size and large electric two-wheeler (from left to right); courtesy of Koga B.V., efw – suhl GmbH, Brammo Inc.

Table 1
Generic technical features of e-bikes, mid-size and large electric two-wheelers (Data sources: Brammo, 2013; Conrad, 2013; Fu, 2013; ZM, 2013).

Powertrain component	E-bike	Mid-size and large electric two-wheelers
Traction source	Electric motor assisting human pedalling	Electric motor
Motor	Mainly direct-current motors; controller	(brushless) direct-current motors; (brushless) alternating current motors (synchronous machines); controller
Transmission	Mainly direct or in combination with reduction gearing at the wheel-hub; through a separate gear at the bicycle chain; through a helical gear box at the bottom bracket	Direct-drive configuration or in combination with a multi-speed gear box
Energy storage	Rechargeable lead-acid, nickel-metal hydride, lithium-ion batteries	Predominantly rechargeable lithium-ion batteries (in Europe and the USA); to a minor extent lead-acid, nickel-metal hydride, lead/sodium-silicate batteries
Battery capacity (kW h)	0.3–0.6	0.5–15
Indicative charging time (80% battery capacity)	Typically between 8 h through wall outlets and 3 h to less than 1 h through fast charging as a growing niche application	
Battery swapping	Mostly standard	Possible for several models but not standard
Recent trends	Market diversification, retrofitting (bicycles), reduction of battery weight, energy recuperation, hybridization of power trains (large motorcycles)	

We do not explicitly address electric three- and four-wheelers (categories L2e, L5e–L7e; EC, 2013) because of their minor importance in Europe (ACEM, 2013b). We consider in our review (i) peer-reviewed articles that are available through the academic search engines *web of science* and *scopus* and (ii) scientific reports and presentations, workshop documents, and working papers that are publicly available online. We conduct our online search by using the key words: "electric two-wheelers", "pedelecs", "e-bikes", "e-scooters", and "e-motorcycles" in combination with the terms "cost-benefit", "economic performance", "financial performance", "environmental impacts", "life cycle assessment", and "safety". We identify around 60 relevant documents that were published before April 2013 in English, German, and Dutch. As mentioned, our assessment focuses on e-bikes but also seeks to benchmark the environmental, economic, and social performance of mid-size and large electric two-wheelers against conventional modes of passenger transport. Given the limited information on mode-shift behavior (see Table A3 in Appendix), we abstain from presenting pairwise comparisons (e.g., e-bike versus bicycle) but instead display absolute results for various electric and conventional modes of passenger transport.

We complement our literature review with own analysis on the economic performance of electric two-wheelers. To this end, we establish estimates for the mean price, as well as mean price differential between electric-two wheelers and conventional two-wheelers, based on the data samples shown in Tables S3–S7 (see Supplemental Material). To quantify the cost decline in the manufacturing of e-bikes, we conduct an experience curve analysis (Henderson, 1974). We separately model the absolute price [EUR_{2012}] and the specific price [EUR_{2012} kW h^{-1}] of e-bikes as well as the price differential [EUR_{2012}] between e-bikes and bicycles [$P(x_t)$] as a power-law function of the cumulative global e-bike production [number of vehicles] as:

$$P(x_t) = P(x_0) \times \left(\frac{x_t}{x_0}\right)^b \tag{1}$$

where $P(x_0)$ represents each of the three price parameters expressed in Euro less value-added tax, deflated to the base year 2012; x_0 and x_t represent the cumulative global e-bike production at starting point 0 and at the end point t of our analysis; b represents the experience index. By plotting experience curves on a double-logarithmic scale, we obtain a linear curve with b as slope parameter. We calculate for each experience curve the learning rate LR (%) that represents the percentage change of the respective price parameter with each doubling of cumulative production:

$$LR = (1 - 2^b) \times 100\% \tag{2}$$

We estimate the error of the learning rate based on the standard deviation of the slope parameter b. We convert currencies by applying mean market exchange rates for the year 2012 (X-Rates, 2013). Nominal prices are deflated by using gross domestic product deflators obtained from the World Bank (WB, 2013). We establish separate experience curves for: (i) e-bikes sold in China and (ii) e-bikes sold in Germany and the Netherlands (see Table S2 in the Supplemental Material). The focus on Germany and the Netherlands is justified because these two countries together constitute 65% of the European e-bike market (Colibi and Coliped, 2014). Throughout the article, error intervals represent the standard deviation of data samples.

Results

The global electric two-wheeler market

To put the emergence of electric two-wheelers into context, we first focus on the market for conventional two-wheelers. By 2012, one billion bicycles (WOM, 2013) and 320 million conventionally-powered two-wheelers were in use worldwide (IEA, 2010); the yearly global production has reached 100 million bicycles and 60 million conventionally-powered two-wheelers, respectively (Fig. 2). Asia accounts for 95% of the global powered two-wheeler production and also harbors the largest fleet of two-wheel vehicles (IEA, 2010). Small two- and three-wheelers with engine displacements of ⩽125 ccm represent more than 50% of motorized road vehicles in India, China, Thailand, and Vietnam (estimate based on Meszler, 2007; Kamakaté and Gordon, 2009). Fuelled by economic growth and rising household income, sales of conventionally-powered two-wheelers have been growing in many Asian countries by more than 10% annually in recent decades (Kamakaté and Gordon, 2009).

In the European Union (EU), 200–250 million bicycles (estimate based on Colibi and Coliped, 2014; Dekker, 2013) and 33 million conventionally-powered two-wheelers were in use by 2011; the yearly sales reached 20 million bicycles (11 million of which were produced domestically; van Schaik, 2013) and 1.5 million conventionally-powered two-wheelers (ACEM, 2013a). Only 1% and 2% of all passenger kilometers are travelled on bicycles and powered two-wheelers (EC, 1999, 2012; EU, 2012), compared to 73% and 15% travelled in cars and by public transport, respectively (EU, 2012).

Electric two-wheelers first emerged in China, where yearly production of e-bikes (comprising small bicycle-style e-bikes, as well as larger pedal-equipped e-scooters), reached 10,000–20,000 units in the early 1980s. Low battery performance and high prices initially limited the market penetration at a large scale (Weinert et al., 2007a). Mid-size e-scooters received subsidies in Taiwan (Weinert et al., 2007a, 2007c) but only reached a 1.3% share in the Taiwanese scooter market by the end of the 1990s (Tso and Chang, 2003; Cherry, 2007).

In China, sales of e-bikes began to grow exponentially in the late 1990s, reaching annual growth rates of 86% (Ji et al., 2012). By 2005, the Chinese e-bike fleet counted 120 million and outnumbered by far the fleet of 80 million conventionally-powered scooters (Weinert et al., 2007c). With e-bike sales reaching 28 million units in 2012 (estimate based on Bento, 2012), China comprises 90% of both, the 31 million e-bikes yearly sold and the 150 million e-bikes used worldwide (Jamerson and Benjamin, 2013). Factors driving the market penetration of e-bikes in China include (Weinert, 2007; Weinert et al., 2007a, 2007c, 2008; Cherry, 2010):

- Legislative support: gasoline-powered two-wheelers were banned in 148 Chinese cities in 2006 following air quality concerns; policy intervention made bicycle-style and scooter-style e-bikes compete mostly against public transportation or bicycles; the introduction of performance standards that classify e-bikes as bicycles if these weigh less than 40 kg and have a maximum speed of 20 km h^{-1} allowed consumers to use e-bikes without a driver's licence and vehicle registration on a designated bicycle infrastructure; performance standards and vehicle legislation were loosely enforced on larger electric two-wheelers.

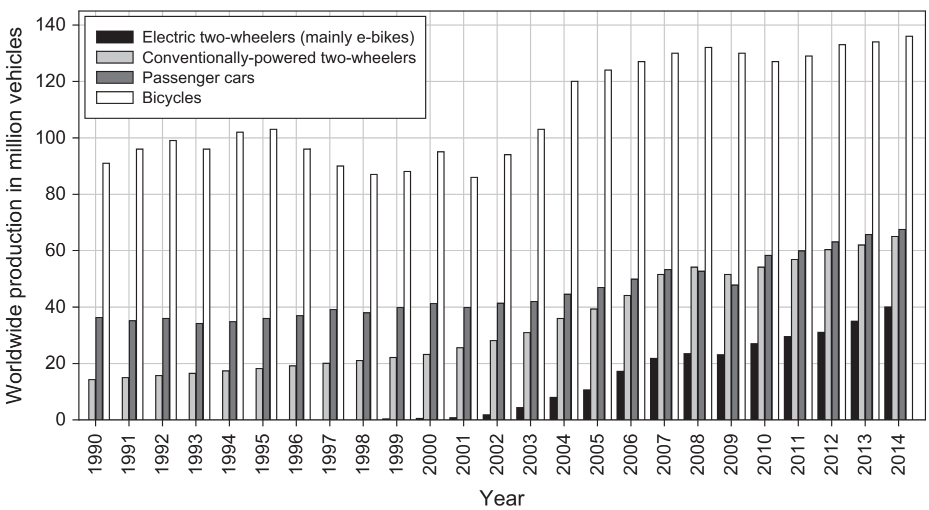

Fig. 2. Estimated worldwide production of road vehicles for individual passenger transportation (Data sources: Weinert et al., 2007a; CB, 2010; Bento, 2012; ACEM, 2013a; Bastiaensen, 2013; INSG, 2014; OICA, 2015).

- Technological improvement: Between 1990 and 2006, the introduction of valve-regulated lead-acid batteries increased the energy density by 30% and the battery life time by 160%, resulting in larger drive ranges and lower maintenance costs; the introduction of brushless motors and neodymium magnets increased the lifetime, power output, and efficiency of electric motors.
- Price reduction: E-bike prices declined by one third between 1999 and 2006 (Bento, 2012) driven by technological learning, innovation, economies of scale, and enhancing market competition.
- Favorable transportation infrastructure: Public transportation appeared often inconvenient, while individual transportation suffered from road congestions. At the same time, a dedicated bicycle infrastructure was available in many cities.
- Favorable socio-economic and cultural conditions: Decreasing electricity prices and increasing gasoline prices have been accompanied by rising household income and an increasing need for mobility. Anecdotal evidence suggests that the outbreak of the Severe Acute Respiratory Syndrome (SARS) in 2002 accelerated the mode shift from public transportation to e-bikes, supported by a wide-spread cycling culture.

The success of e-bikes in China is still unmatched in other Asian countries, largely due to the absence of the factors mentioned above. E-bikes suffer from inferior speed, driving range, comfort, and high prices compared to conventionally-powered two-wheelers. Decreasing battery performance under tropical weather conditions presented a problem in South-East Asia, alongside negative public perception from unreliable electric two-wheelers sold in the 1990s (Chiu and Tzeng, 1999; Weinert et al., 2008; ADB, 2009).

Yearly e-bike sales in the EU have been growing to 904,000 vehicles in 2013, which accounts for 5% of the European bicycle market and for 2% of the global e-bike market. The largest European e-bike markets constitute Germany and the Netherlands, with sales of 410,000 and 192,000 e-bikes, respectively (Oortwijn, 2013; Colibi and Coliped, 2014). E-bikes sold in Europe and China differ distinctively in their battery technology: In China, the vast majority of e-bikes are equipped with lead-acid batteries, offering an energy density of around 30 W h kg^{-1} (Weinert et al., 2007b; Wei, 2013). By contrast, e-bikes sold in Europe are typically equipped with metal-hydride or lithium-ion batteries that are more expensive but offer an energy density of up to 140 W h kg^{-1} (Weinert et al., 2007b) in combination with comparatively long life times.

Forecasts suggest that global e-bike sales may reach 40 million in 2015 (Jamerson and Benjamin, 2013). However, the prospects for larger electric two-wheelers are less optimistic. As of 2011, e-scooters and e-motorcycles have reached sales of 15,000 in the EU, account for less than 1% of the European motorcycle market (Euractive, 2012). Neither in Asia nor in America have mid-size and large electric two-wheelers reached a substantial market share. Navigant (2015) estimates that the global annual sales of mid-size and large electric two-wheelers combined may reach 4.3 million in 2015 but may only increase by about 10% within the next decade at current fuel prices.

Based on the data presented above, we estimate that the battery capacity of the global electric two-wheeler fleet (125 ± 42 GW h)[1] exceeds that of the global fleet of battery-electric cars (4 ± 2 GW h) by a factor of 30. Although battery sizes and technologies are not directly comparable, the comparison illustrates the dimension of the market and the potential for technological spill-over among electric vehicles.

Environmental performance

General considerations

Electric two-wheelers generate no tail-pipe emissions, but (i) are equipped with a battery those production is energy intensive and (ii) run on electricity that causes environmental impacts during its generation (Cherry, 2007, 2010; Cherry et al., 2009). Compared to conventionally-powered two-wheelers, the environmental impacts of electric two-wheelers are shifted from vehicle use to vehicle production, end-of-life treatment, and electricity generation. Electric two-wheelers, just as battery-electric cars, shift the environmental impacts of motorized transport away from numerous and difficult-to-control vehicles to less numerous and more concentrated point sources, predominantly located outside of urban areas (Cherry, 2007). Such relocation decreases human exposure to pollution, and can be expected, *ceteris paribus*, to decrease the detrimental health impacts of road transportation (Cherry, 2007; Ji et al., 2012). However, caution is necessary because mode-shift behavior matters: Electric two-wheelers could increase energy use and come at an environmental burden when replacing bicycles or public transportation instead of conventionally-powered two-wheelers or cars.

Energy use and greenhouse gas emissions

Energy use and GHG emissions of electric two-wheelers critically depend on the system boundary of the analysis, i.e., whether tank-to-wheel, well-to-wheel, or the entire life cycle of the vehicle is considered (Fig. 3). The tank-to-wheel electricity consumption of electric two-wheelers ranges from 1.5 ± 0.5 kW h 100 km^{-1} for e-bikes (Weinert et al., 2007b, 2008) to 7.0 ± 3.0 kW h 100 km^{-1} for e-motorcycles (Brammo, 2013; ZM, 2013), making e-bikes and mid-size electric two-wheelers

[1] We assume here a battery capacity of 0.7 ± 0.2 kW h per electric two-wheeler (average of bicycle-style and scooter-style e-bikes sold in China; Weinert et al., 2007c; EVI, 2013) and 25 ± 12 kW h per battery-electric car. Note that e-bikes are mainly equipped with cheap lead-acid batteries while battery-electric cars typically run on advanced lithium-ion batteries.

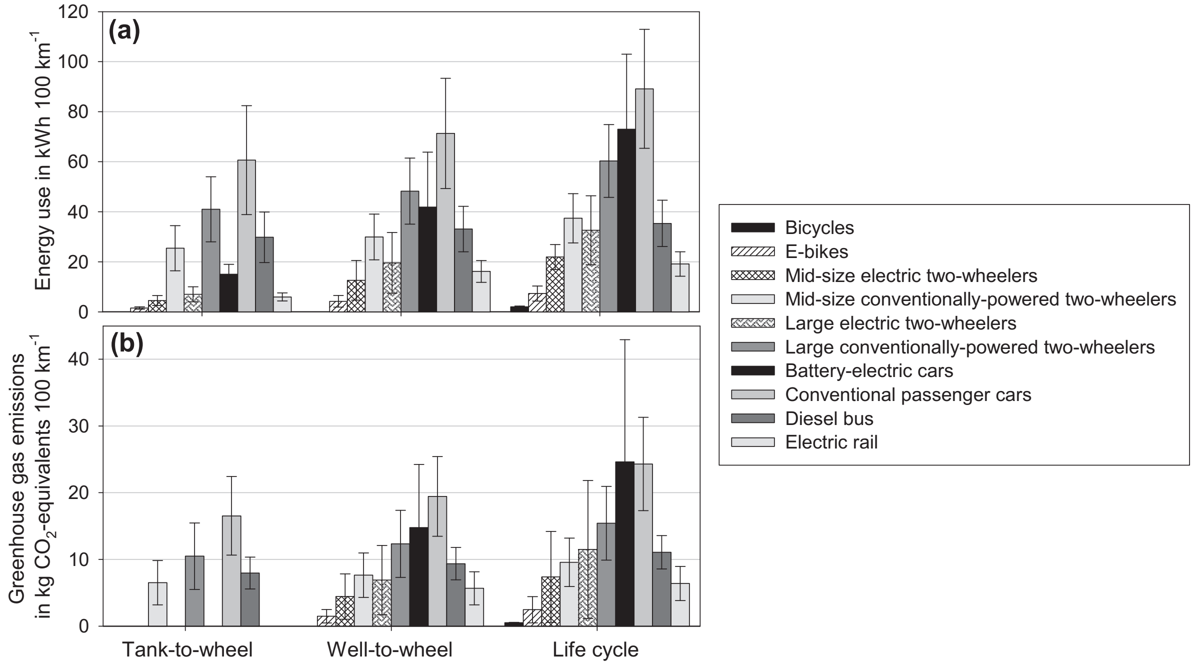

Fig. 3. Indicative distance-specific tank-to-wheel, well-to-wheel, and life-cycle energy use (a) and greenhouse gas emissions (b) of selected vehicles for passenger transportation (Principal data sources and assumptions: see Tables A1 and A2 in Appendix; error bars represent the standard deviation of our estimates).

the most energy efficient powered vehicles for individual road transportation. By comparison, the tank-to-wheel energy use of conventionally-powered two-wheelers ranges from 25 ± 9 kW h 100 km^{-1} (3 ± 1 l 100 km^{-1}) for scooters to 41 ± 13 kW h 100 km^{-1} (4 ± 2 l 100 km^{-1}) for motorcycles (Fig. 3a). If electric two-wheelers replace conventionally-powered two-wheelers, tank-to-wheel energy savings of 50–90% can be achieved as electric motors are more efficient than internal combustion engines.

The efficiency benefits of electric two-wheelers decrease, however, when the well-to-wheel energy chain of resource extraction, conversion, and energy transport is considered. While losses from the extraction of energy resources, electricity transmission, and vehicle recharging are typically small but not negligible, conversion losses in the power sector may amount to 60 ± 10% if electricity is produced from fossil fuels. Moreover, conversion losses can vary greatly among regions depending on the electricity mix and the efficiency of power plants. Chiu and Tzeng (1999) find that electric two-wheelers in Taiwan, with largely fossil-based electricity generation, reach a well-to-wheel efficiency of about 15%, which is similar to the efficiency of conventionally-powered motorcycles. Weinert et al. (2008) report for China a well-to-wheel energy use of small electric two-wheelers (7 ± 1 kW h 100 km^{-1}) that is substantially lower than that of conventionally-powered two-wheelers (29 kW h 100 km^{-1}). The regional variability in both electricity mix and power plant efficiency demands a case-by-case assessment of the well-to-wheel energy use of electric two-wheelers. The majority of the well-to-wheel energy use of electric two-wheeler can be attributed to the well-to-tank stage, contrasting the situation for conventionally-powered vehicles that tend to consume three-fourths of their well-to-wheel energy use in the tank-to-wheel stage.

The life cycle energy use of vehicles is subject to the well-to-wheel considerations and additionally determined by: (i) the energy use during vehicle production and (ii) the actual vehicle use pattern (e.g., yearly mileage and vehicle lifetime). The production of an e-bike and its lead-acid battery in China consumes 7.1 kW h and 2–8 kW h, respectively. This amount of energy is equivalent to the electricity use for driving 9000–15,000 km, a distance that is typically covered by an e-bike in China within 3–5 years (Cherry, 2007). For electric vehicles, the production phase can account for more than half of the life-cycle energy use; for conventionally-powered vehicles, the use phase tends to account for three-fourths of the life-cycle energy use (see, e.g., Meszler, 2007; Cherry et al., 2009).

At the average global electricity mix, the greenhouse gas emissions of electric two-wheelers (largely comprised of CO_2) tend to follow the dynamics of energy use (Fig. 3b). This observation also holds for India and China where the electricity is carbon intensive (ADB, 2009; del Duce, 2011; Doucette and McCulloch, 2011). Depending on the carbon intensity of the electricity mix, the well-to-wheel and life-cycle GHG emissions can vary substantially. The carbon intensities of electricity generation (considering gross electricity production and excluding transmission and transformation losses) in Europe range from 0 g CO_2 kW h^{-1} in Iceland where electricity is mainly produced from hydro power to 1059 g CO_2 kW h^{-1} in Estonia

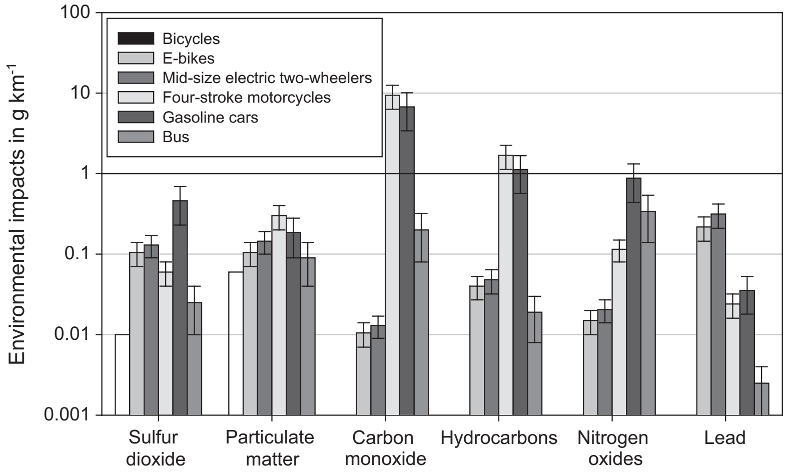

Fig. 4. Indicative emissions of electric two-wheelers during production and use in China compared to other modes of road transportation; error bars represent the range of likely values; the magnitude of emissions is displayed on a logarithmic scale (Data sources: Cherry et al., 2009; Meszler, 2007)[2].

where electricity is mainly produced from coal (IEA, 2012). Gross electric energy production in the EU-27 (442 g CO_2 kW h^{-1}; IEA, 2012)[3] is 40% less carbon intensive than the gross electric energy production in China (790 CO_2 kW h^{-1}; IEA, 2012). These value ranges suggest that the de-carbonization of electricity generation can greatly reduce the life-cycle GHG emissions of electric two-wheelers.

Additional environmental impacts

Conventionally-powered two-wheelers contribute substantially to the transport-related emissions of hydrocarbons and carbon monoxide in Asia (Meszler, 2007) and Europe (EC, 2010) and show higher life-cycle emissions of particulates, carbon monoxide, hydrocarbons, and nitrogen oxides than electric two-wheelers (Fig. 4). The pollutant emissions related to electric two-wheelers can be decreased by a large margin, (i) if coal as primary source for electricity production (as assumed in Fig. 4) is replaced by natural gas or renewables and (ii) if the exhaust treatment of power plants becomes more effective (e.g., Cherry, 2007; Cherry et al., 2009; Ji et al., 2012).

Moreover, large parts of the emissions associated with electric two-wheelers do not occur in cities but at locations outside of densely populated areas. This, in turn, leads to substantially decreased exposure rates and intake fractions compared to those resulting from conventionally-powered two-wheelers and cars (Ji et al., 2012). Assuming a low-carbon electricity mix of Switzerland, del Duce (2011) find that e-bikes and mid-size e-scooters show along their life cycle lower human toxicity and photochemical oxidation potentials, as well as lower overall eco-indicator scores, but tend to increase eutrophication and competition for land relative to conventional scooters and passenger cars.

Arguably, the most critical environmental impact of electric two-wheelers results from lead pollution during the production, recycling and disposal of lead-acid batteries. Lead pollution is unproblematic in Europe where electric two-wheelers tend to be equipped with nickel–metal-hydride and lithium-ion batteries. However, until a decade ago, lead losses in China along the life cycle of batteries (i.e., through mining, virgin lead production, battery manufacturing, recycling, and disposal) may have reached 45 ± 15% (Mao et al., 2006; Cherry, 2007. Following health-related and environmental concerns, the Chinese government forced around 80–90% of the country's lead-acid battery plants to shut down in 2011 (Bento, 2012; Fu, 2013). This intervention may provide an incentive for an increased market penetration of e-bikes equipped with lithium-ion batteries (Bento, 2012).

Environmental impacts and mode-shift behavior

Whether electric two-wheelers can decrease the energy demand and the environmental impacts of road transportation depends on the actual mode-shift behavior of consumers. The empirical insight into mode-shift behavior remains partial and largely case specific. Still, literature suggests that consumers substitute e-bikes to a considerable extent for bicycles and public transportation and tend to undertake trips they would not have done in the absence of e-bikes (Table A3 in Appendix). Such mode-shift behavior appears to increase consumer well-being but diminishes

[2] We present here the environmental impacts of four-stroke motorcycles because these account for the vast majority of powered two-wheelers in China. Four-stroke motorcycles emit substantially less carbon monoxide and unburned hydrocarbons than two-stroke motorcycles (Cherry et al., 2009; Meszler, 2007). The environmental benefits of electric two-wheelers increase when replacing older two-stroke motorcycles.

[3] The net carbon intensity at low voltage (including transmission and transformation losses) of the electricity mix in the EU-27 as of 2013 is 540 g CO_2 kW h^{-1}.

environmental benefits that would emerge if e-bikes and larger electric two-wheelers substituted conventionally-powered two-wheelers or passenger cars only. To illustrate the case: Assuming the mode shift behavior observed by Dekker (2013) in two cities of the Netherlands[4], e-bikes can save 286 ± 83 GW h (44 ± 61 kt CO_2-eq.) compared to the current transportation pattern. These savings are, however, 50 ± 50% lower than the potential energy saving of 533 ± 208 GW h and 60 ± 120% lower than the potential CO_2 emission savings of 102 ± 91 kt CO_2-eq. that could be achieved if e-bikes solely replaced conventionally-powered two-wheelers. Thus, mode shift in not negligible and should be accounted for when evaluating the environmental impacts of electric two-wheelers. This, in turn, necessitates case-specific analyses. Finally, electric two-wheelers can only decrease the energy use and environmental impacts of road transportation if they penetrate the market at a large scale. Whether this is likely to happen depends, among others, on their economic performance, which we address next.

Economic performance

E-bikes prices span a wide range from 100 EUR_{2012} for e-bikes equipped with lead-acid batteries in China (Weinert, 2007; Weinert et al., 2008) to 5600 EUR_{2012} for e-bikes equipped with lithium-ion batteries in Europe. Mid-size electric two-wheelers are sold in Germany on average for 2400 ± 1300 EUR_{2012} (estimates based on Eicher (2010), Conrad (2013), Idealo (2013)),[5] whereas large e-motorcycles can cost up to 14,000 EUR_{2012} (ZM, 2013).

The variety of electric two-wheelers makes it difficult to establish price differentials relative to conventional two-wheelers. Data samples from miscellaneous retailers, manufacturers, and consumer organizations in Germany and the Netherlands suggest that e-bikes, as well as mid-size and large electric two-wheelers, are in the range of 5000 ± 1800 EUR_{2012} kW^{-1}, 700 ± 360 EUR_{2012} kW^{-1}, and 160 ± 90 EUR_{2012} kW^{-1}, respectively more expensive than their conventional counterparts (Tables S3–S7 in the Supplementary Material). These preliminary findings suggest higher relative price differentials for e-bikes and mid-size electric two-wheelers than for battery-electric cars (320 ± 210 EUR_{2012} kW^{-1}; Weiss et al., 2012). The absolute price differentials of e-bikes (1300 ± 700 EUR_{2012}), mid-size electric two-wheelers (1200 ± 1400 EUR_{2012}), and large electric two-wheelers (4000 ± 2100 EUR_{2012}) are, however, lower than those of battery-electric cars because the former are equipped with smaller batteries. The relatively low absolute price differential may explain the rapid market penetration of e-bikes that offer an obvious additional use value compared to bicycles, i.e., power assistance. The additional use value of e-scooters and e-motorcycles, e.g., the availability of low-end torque for strong acceleration may be less apparent to consumers and may not yet justify the present price differentials.

We find that the absolute real price of e-bikes has been declining in China at a learning rate of 8 ± 5% (Fig. 5a), which is equivalent to a 30% decline in the inflation-adjusted price between 1999 and 2005 (Weinert et al., 2008). The observed price dynamics result from decreasing production costs achieved through enhanced competition, economies of scale, and the sourcing of components from a decentralized network of competing suppliers. An open and modular industry structure allowed in China for rapid innovation, standardization of components, flexibility in design and manufacturing, and established low entry barriers for new competitors (Weinert et al., 2008).

By contrast, absolute e-bike prices in Germany and the Netherlands show no verifiable trend between 1999 and 2012 (Fig. 5b). This observation may be attributed in part to inhomogeneities of e-bike technology, i.e., the shift from lead-acid batteries to more expensive lithium-ion and metal-hydride batteries, the increase in battery capacity, the recent introduction of LED lighting, disk brakes, and aluminum frames (Dekker, 2013). Anecdotal evidence suggest that only a few manufacturers shared a low-volume but growing market around the year 2000 while increasing market competition only occurred after 2006. Demand-induced changes in profit margins may thus explain part of the observed price trend, including the price decrease in recent years (see Fig. 5b).

Controlling for the increase in battery capacity suggests that the specific e-bike price in Germany and the Netherlands has been declining at a learning rate of 8 ± 1% (Fig. 6a). Although uncertain, the price differential between e-bikes and bicycles appears to have remained constant over the past decade, as suggested by a learning rate of −0.5 ± 1.6% (Fig. 6b). The learning rates for the price of e-bikes in China and the specific price of e-bikes in Germany and the Netherlands are similar to those of hybrid-electric cars (7 ± 2%; Weiss et al., 2012) and lithium-ion batteries (6–9%; Nykvist and Nilsson, 2015) but lower than the average learning rate of energy-demand technologies (18 ± 9%; Weiss et al., 2010).

The price dynamics identified for e-bikes may apply, in first-order approximation, also to mid-size and large electric two-wheelers as powertrain components are comparable. However, battery technology, arguably the single largest contributor to manufacturing costs, could differ between and within the individual categories of electric two-wheelers. Battery production

[4] We assume here a fleet of 500,000 e-bikes, a yearly travel distance of 3800 km per e-bike, and mean life-cycle energy use and carbon emissions as depicted in Fig. 3.

[5] Prices are based on the mean and the standard deviation of data presented in Tables S4 and S5 in the Supplementary Information. Communication with ACEM (2014) suggests that our data sample may underestimate the actual price of mid-size electric two-wheelers in the EU by around 500 EUR.

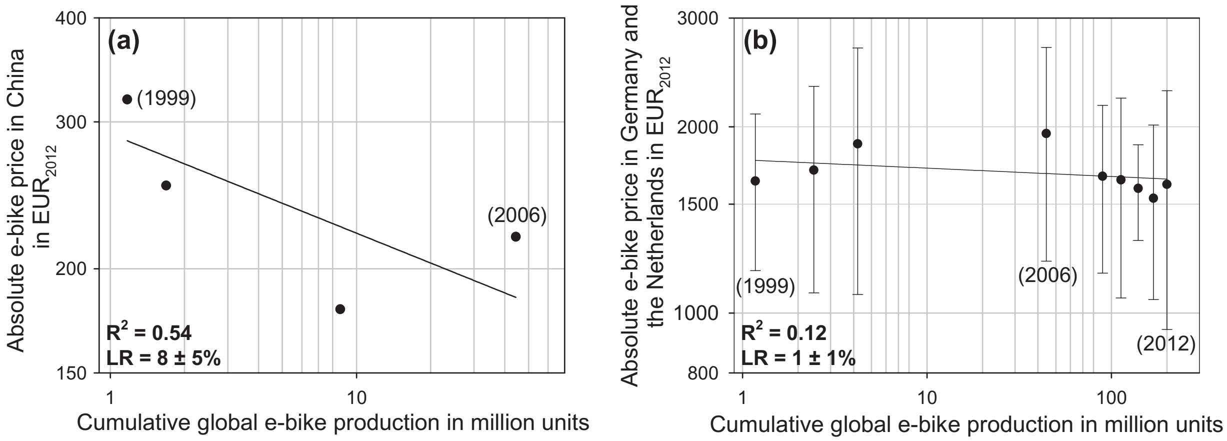

Fig. 5. Experience curves for e-bikes in China (a) and Germany and the Netherlands (b); numbers in parentheses indicate the year of observation; error bars indicate the standard deviation of price data (Data sources: see Table S2 in the Supplementary Material).

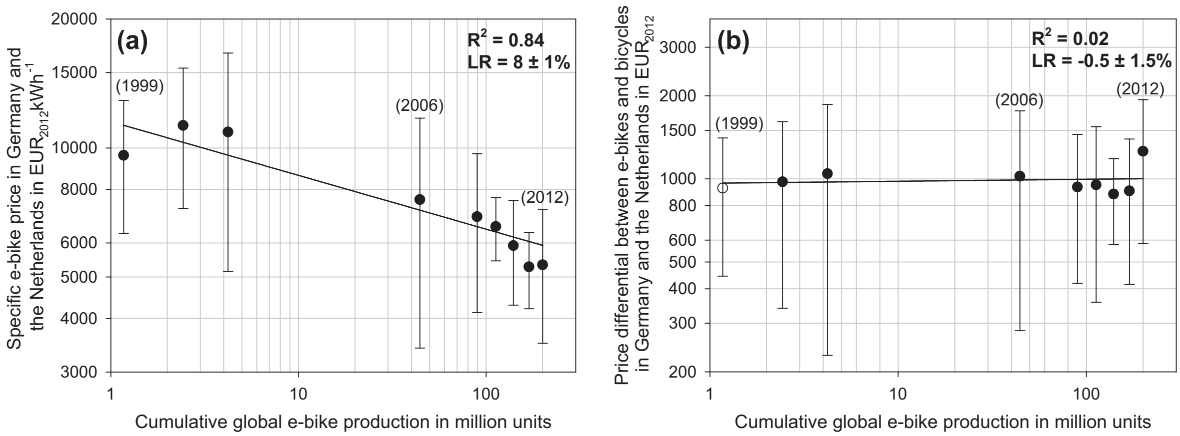

Fig. 6. Experience curves for the specific price of e-bikes (a) and for the price differential between e-bikes and bicycles (b) in Germany and the Netherlands; numbers in parentheses indicate the year of observation; error bars indicate the standard deviation of price data (Data sources: see Table S2 in the Supplementary Material).

costs range from 25–40 EUR_{2012} kW h^{-1} for lead-acid batteries (Budde-Meiwes et al., 2013) to 230–310 EUR_{2012} kW h^{-1} for lithium-ion batteries (Nykvist and Nilsson, 2015). Material substitution, pack integration of cells, and economies of scale could yield future cost savings in battery manufacturing (Weinert, 2007; Nykvist and Nilsson, 2015). We expect that research and development, technological learning, and economies of scale will drive down the future production costs to a larger extent for relatively novel lithium-ion batteries than for conventional lead-acid batteries.

The total user costs, i.e., the sum of costs for purchase, maintenance, and use of e-bikes and larger electric two-wheelers are higher than those for bicycles and public transportation but comparable to conventionally-powered two-wheelers (Fig. 7). E-bikes are less costly than any other model of individual motorized transport. We consider the results in Fig. 7 as indicative of the total user costs that are sensitive to assumptions regarding, e.g., the price of fuel and electricity, yearly mileage, and vehicle life time.

Social performance

General considerations

The social performance of electric two-wheelers may vary among regions depending on the specific socio-economic, topographic and climatic conditions, the actual mode-shift behavior, and the level at which electric two-wheelers penetrate the market. *Ceteris paribus*, impacts on urban mobility and infrastructure may be similar to those of comparable

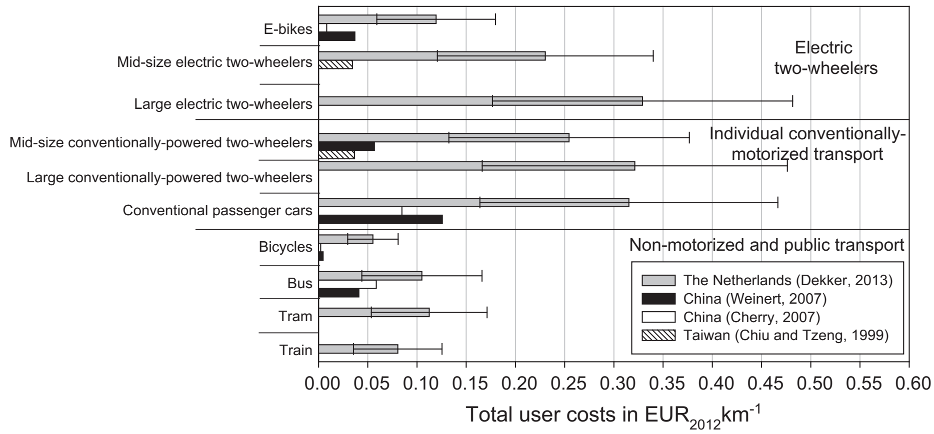

Fig. 7. Total user costs of electric two-wheelers and other vehicles for passenger transport; results are indicative only and sensitive to assumptions made in the referenced studies. (We include in the results of Dekker (2013) yearly maintenance costs related to the replacement of batteries in e-bikes (50 EUR), mid-size electric two-wheelers (100 EUR), and large electric two-wheelers (150 EUR).)

conventionally-powered two-wheelers with one exception, i.e., noise. Electric two-wheelers can help decrease noise pollution in cities, which, however, also evokes safety concerns.

Urban mobility and infrastructure

Both electric and conventional two-wheelers provide door-to-door mobility, require less area per vehicle for driving and parking than cars (Cherry, 2007), and often present the fastest mode of urban transportation (e.g., Cherry, 2007; Kopp, 2011). In fact, travel speed appears to be a main factor explaining why consumers prefer electric and conventionally-powered two-wheelers over alternative transportation modes (Cherry and Cervero, 2007; Montgomery, 2010; Kopp, 2011). With respect to electric two-wheelers, case studies indicate that e-bikes are faster than bicycles and buses in Kunming (China) but 11% slower than conventionally-powered scooters in Shanghai (China; Cherry, 2007). E-bike trips in the Netherlands are 1.5 times longer (9.8 km) than bicycle trips, suggesting mobility benefits for citizens. The use of two-wheelers in general faces practical constraints. Literature suggests that workers in business attire, as well as citizens in need of transporting goods, commuting in the dark, or faced with bad weather are less likely to commute by bicycle (Heinen et al., 2011). The number of bicycle trips appears to increase over car trips with rising temperature and sunshine duration. Although these findings address bicycle use, similar effects are likely to apply to electric and conventionally-powered two-wheelers.

In view of the current electricity supply infrastructure, most cities lack widely-available public recharging facilities. This deficiency may be most relevant for mid-size and large electric two-wheelers equipped with non-portable batteries. From the perspective of grid capacity, a potential large-scale market penetration of electric two-wheelers yet appears unproblematic. De Gennaro et al. (2014) show in a case study that a 28% share of battery-electric cars in the vehicle fleet of two Italian cities would, at most, add 5% to the present electricity demand.

Impacts on public health and road safety

We have mentioned that electric two-wheelers can reduce exposure to air pollution when replacing conventionally-powered vehicles and thereby improve public health. Moreover, electric two-wheelers can help reducing urban noise pollution. E-bike users may benefit from positive cardio-vascular effects (see, e.g., de Hartog et al., 2010). E-bikes are also considered beneficial in allowing elderly or physically impaired people to remain mobile (Hendriksen et al., 2008; MacArthur et al., 2014). However, the operation of electric two-wheelers, just as that of conventionally-powered two-wheelers, also raises safety concerns resulting from high vehicle speed and mass and the absence of engine noise. The latter led several cities in China start banning e-bikes around the year 2006 (Cherry, 2007; Weinert et al., 2007c).

The safety impacts of two-wheelers are addressed first and foremost as part of the national vehicle and traffic legislation that specifies, e.g., requirements for type approval, licensing, and maintenance of vehicles (see, e.g., Rose, 2012; EC, 2013). Users of two-wheelers are vulnerable in case of an accident (Weinert et al., 2007a; Haworth, 2012). Death rates per distance travelled are globally 30 times higher (Johnston et al., 2008; Haworth, 2012) and in the EU 18 times higher for powered two-wheeler users than for car drivers (EC, 2010). The growing use of powered two-wheelers in the city of Paris has increased both road accidents and fatalities. However, 'Safety in number' effects are documented, suggesting that an increase in the number of bicycles and other two-wheelers leads to a less-than-proportional increase in accidents mainly due to a rising awareness of road users (Jacobsen, 2003; Buehler and Pucher, 2012; ITF, 2012). Various technical measures are at hand to increase the user safety for both electric and conventional two-wheelers:

- weight reduction, e.g., by substituting lithium-ion batteries for lead-acid batteries (Rose, 2012);
- mandatory minimum noise requirements can increase audibility, thus visibility, of electric two-wheelers (Haworth, 2012);
- establishment of a dedicated infrastructure could reduce differences in the travel speed of vehicles sharing a common driveway;
- enforcement of speed limits, technical vehicle regulation, and improving the training of drivers to ensure the proper functioning and handling of two-wheelers.

Measurable, as well as perceived, safety improvements are found to cause a disproportionate increase in the use of bicycles (Noland, 1995; Buehler and Pucher, 2012. Similar effects can be expected for electric and conventionally-powered two-wheelers. Safety regulation is, however, also subject to unintended secondary effects that may reduce the use of two-wheelers or encourage risky driving behavior (BHRF, 2013).

Discussion

This articles reviews and evaluates the environmental, economic, and social performance of electric two-wheelers (Table 2). Our results provide a snap-shot indication of the likely performance of electric two-wheelers but may not necessarily capture all aspects relevant for a conclusive evaluation. Concrete case studies of electric two-wheelers in individual regions or cities that account for the specific electricity mix, urban infrastructure, geographic conditions, and mode-shift behavior are recommended.

Our research is subject to uncertainty. First, we draw extensively from Weinert (2007) and Cherry (2007), who studied electric two-wheelers in China. The data published in these studies date 8 years back and may not reflect accurately the situation in 2015. Although we consider our results to be robust, updating part of the presented data is recommended. Second, we assume average carbon intensities of the electricity mix when estimating the carbon emissions of electric two-wheelers. This assumption is made based on data availability, but it simplifies reality. The electricity demand of new electric two-wheelers would likely be satisfied by marginal electricity that is potentially produced by outdated and inefficient power plants that would otherwise be taken off the grid. If so, we may underestimate the primary energy use and carbon emissions associated with electric two-wheelers. Third, the presented experience curves are subject to a range of uncertainties, including heterogeneity of the analyzed technology and the use of prices as proxy for production costs (see Weiss et al., 2010).

The local electricity mix and the installed battery type present the two single most critical variables in determining the life-cycle impact of electric two-wheelers. Increasing the share of carbon-free renewables in the electricity mix and substituting lithium-ion batteries for lead-acid batteries can considerably decrease environmental impacts. Although electric two-wheelers consume less energy, emit less CO_2, and decrease exposure to pollution relative to conventionally-powered vehicles, mode-shift behavior can compensate part of the technically feasible saving and should thus be carefully analyzed.

Electric two-wheelers will only impact the environment, urban mobility, and air quality if they penetrate the market on a large scale. Currently, electric two-wheelers are more expensive than their conventional counterparts. In spite of persisting price differentials, e-bikes have been penetrating the market because they offer an apparent additional use value (i.e., power

Table 2
Semi-quantitative summary of results; symbols signify the performance as follows: + superior; +/o case-dependent but generally superior; o equal; o/− case-dependent but generally inferior, − inferior; +/− case-dependent and ambivalent.

Category	Criterion	Electric two-wheelers relative to conventionally-powered two- and four-wheel motor vehicles
Environmental performance	Energy use and CO_2 emissions (tank-to-wheel)	+
	Energy use and CO_2 emissions (well-to-wheel)	+/o
	Energy use and CO_2 emissions (life cycle)	+/o
	Air pollution	+
	Noise pollution	+
	Lead toxicity	o/−
Economic performance	Price	−
	Total user costs	+/−
Social performance	Human exposure to pollution	+
	Audibility and visibility	−
	Urban mobility	+/−
	Road accidents and fatalities	+/−
	Demand for road infrastructure	+/−
	Vulnerability in case of accident	+/−

assistance) as compared to bicycles. Larger electric two-wheelers do not offer such an apparent additional use value and may only penetrate the market if conditions change (e.g., fuel price, taxation, and infrastructure). Our research demonstrates that technological learning has been reducing the price differential between e-bikes and bicycles in the past decade. Similar dynamics are likely to also reduce the price differentials of larger electric two-wheelers and battery-electric cars. Technological learning in the manufacturing of electric two-wheelers can also generate spill-over to the benefit of novel ultra-light three- and four-wheel vehicles. In view of widespread urban traffic congestions, the mobility benefits offered by electric two-wheelers may provide scope for policy intervention, e.g., through the introduction of access taxes for conventional cars and two-wheelers or the establishment of environmental driving zones. These measures could be complemented by:

- the establishment of a dedicated infrastructure (Lamy, 2001);
- taxation that lowers the relative costs of electric two-wheelers;
- the provision of parking and recharging infrastructure (Chiu and Tzeng, 1999) and effective anti-theft protection (Lamy, 2001).

Conclusions

Our findings suggest that electric two-wheelers can make urban transportation more sustainable. However, immediate market potential exists only for e-bikes; persisting price differentials and the absence of an obvious additional use value appear to present a barrier for the market penetration of mid-size and large electric two-wheelers. We derive the following conclusions:

- If Europe is to decrease transport-related carbon dioxide emissions, urban noise and air pollution, and inner city traffic, policy makers should consider supporting electric two-wheelers.
- Given the regional variability in, e.g., the electricity mix, mode-shift behavior, infrastructure characteristics, and geographic and climatic conditions, the environmental, economic, and social performance of electric two-wheelers should be assessed on a case-specific basis by taking an integrated approach to urban mobility.
- The boom of bicycle-style and scooter-style e-bikes in China suggest that a mandatory phase out of conventionally-powered two-wheelers from urban environments is an effective measure to increase the market penetration of electric two-wheelers (Yang, 2010).
- Technological learning has been decreasing the price differential of e-bikes and will likely continue to decrease absolute prices and price differentials of all categories of electric two-wheelers. Battery costs will have to decline substantially before mid-size and large electric two-wheelers will penetrate the market at large scale.
- A shift from cars and conventionally-powered two-wheelers to electric two-wheelers will necessitate adaptations of the existing transport and electricity infrastructure and the management of newly emerging safety issues, e.g., through the introduction of dedicated drive lanes and minimum noise requirements.
- The battery capacity of the global electric two-wheelers fleet (125 ± 42 GW h) exceeds that of battery-electric cars (4 ± 2 GW h) by a factor of 30 and constitutes a huge reservoir for technological learning, economies of scale, spill-over effects from which economy-wide battery applications in general and the electrification of transport in particular could benefit.

Disclaimer

The views expressed here are those of the authors and may not be regarded as an official position of the European Commission.

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Appendix A.

See Tables A1, A2 and A3.

Table A1
Assumptions and data sources used to establish the energy use displayed in Fig. 3a; numbers are indicative for the energy use of vehicles; we do not account for differences in the passenger occupation of vehicles for private transportation; the average passenger occupation of bus and electric rail follows the assumptions made in the reverenced studies; the uncertainty margins are indicative of the standard deviation of energy use.

	Bicycles	E-bikes	Mid-size electric two-wheelers	Mid-size conventionally-powered two-wheelers	Large electric two-wheelers	Large conventionally-powered two-wheelers	Battery-electric cars	Conventional passenger cars	Bus	Electric rail (tram and train)
Tank-to-wheel energy use in kW h 100 km^{-1}	0	1.5 ± 0.5	4.5 ± 2	25 ± 9	7.0 ± 3.0	41 ± 13	15 ± 4	61 ± 22	30 ± 10	6.0 ± 1.6
Principal data source[a]	0	Cherry (2007), Weinert et al. (2007c) and Timmermans et al. (2009)	Cherry (2007)	Ntziachristos and Samaras (2012) and Eicher (2010); own estimates based on manufacturers' information	Brammo (2013) and ZM (2013)	Ntziachristos and Samaras (2012); own estimates based on manufacturers' information	Own estimates based on manufacturers' information	EEA (2012)	Mean of data for school bus and diesel bus (Chester and Horvath, 2009)	Based on mean values for light rail data (Chester and Horvath, 2009)
Comment	–	–	–	We assume a gasoline density of 0.75 g cm^{-3} and a heating value of 44 MJ kg^{-1} (IPCC, 2006)	–	We assume a gasoline density of 0.75 g cm^{-3} and a heating value of 44 MJ kg^{-1} (IPCC, 2006)	–	[b]	–	[c]
Well-to-wheel energy use in kW h 100 km^{-1}	0	4.2 ± 2.3	13 ± 8	30 ± 9	20 ± 12	48 ± 13	42 ± 22	71 ± 22	33 ± 9	16 ± 4
Principal data source[a]	–	(see tank-to-wheel energy use)	(see tank-to-wheel energy use)	(see tank-to-wheel energy use)	(see tank-to-wheel energy use)	(see tank-to-wheel energy use)	(see tank-to-wheel energy use)	(see tank-to-wheel energy use)	(see tank-to-wheel energy use)	(see tank-to-wheel energy use)
Comment	–	[c]	[c]	[d]	[c]	[d]	[c]	[d]	We assume a well-to-tank efficiency of 90 ± 10%.	–

Table A1 (*continued*)

	Bicycles	E-bikes	Mid-size electric two-wheelers	Mid-size conventionally-powered two-wheelers	Large electric two-wheelers	Large conventionally-powered two-wheelers	Battery-electric cars	Conventional passenger cars	Bus	Electric rail (tram and train)
Life-cycle energy use in kW h 100 km^{-1}	2.0 ± 0.3	7.3 ± 3.0	22 ± 5	37 ± 10	33 ± 14	56 ± 15	73 ± 30	89 ± 24	35 ± 9	19 ± 5
Principal data source[a]	Cherry (2007) and del Duce (2011); own estimates	Cherry (2007)	Cherry (2007) and del Duce (2011); own estimates	(see tank-to-wheel energy use)	(see tank-to-wheel energy use)	(see tank-to-wheel energy use)	Marques and Freire (2011) and Aguirre et al. (2012) and Hawkins et al. (2012)	(see tank-to-wheel energy use)	(see tank-to-wheel energy use)	(see tank-to-wheel energy use)
Comment	We exclude energy use for paddling based on the discussion presented by Cherry (2007) and Cherry et al. (2009)	Uncertainty margin based on own estimates and Cherry (2007)	–	[e]	We assume that 60 ± 20% of the life-cycle energy use is related to vehicle use	[e]	–	[e]	–	–

[a] Indicating the principal data source that is often complemented by own estimates based on miscellaneous sources and expert judgement.
[b] We assume: (i) on-road fuel use to be 25 ± 10% higher than during type approval (Mock et al., 2013) and (ii) the variability of energy use among vehicles to be 35% based on expert judgement.
[c] We assume an efficiency of: 90 ± 5% for resource extraction, 98 ± 1% for shipping, 45 ± 20% for electricity conversion, 93 ± 3% for transmission, and 97 ± 2% for battery charging based on Markowitz (2013) and expert judgement.
[d] We assume a well-to-tank efficiency of 85 ± 5%.
[e] We assume that 80 ± 10% of the life-cycle energy use is related to vehicle use.

Table A2
Assumptions and data sources used to establish the GHG emissions displayed in Fig. 3b; values are indicative for the GHG emissions of vehicles; we do not account for differences in the passenger occupation of vehicles for private transportation; the average passenger occupation of bus and electric rail follows the assumptions made in the referenced studies; assumptions vary among studies; the uncertainty margins are indicative of the standard deviation of GHG emissions.

	Bicycles	E-bikes	Mid-size electric two-wheelers	Mid-size conventionally-powered two-wheelers	Large electric two-wheelers	Large conventionally-powered two-wheelers	Battery-electric cars	Conventional passenger cars	Bus	Electric rail (tram and train)
Tank-to-wheel GHG emissions in kg CO_2-eq. 100 km^{-1}	0	0	0	6.5 ± 3.3	0	10 ± 5	0	17 ± 6	8 ± 2	0
Principal data source[a]	–	–	–	(See tank-to-wheel energy use)	–	(See tank-to-wheel energy use)	–	(See tank-to-wheel energy use)	(See tank-to-wheel energy use)	–
Comment	–	We allocate the emissions from electricity generation to the well-to-wheel system.	We allocate the emissions from electricity generation to the well-to-wheel system.	We assume a gasoline emission factor of 255.6 g CO_2 kW h^{-1}	We allocate the emissions from electricity generation to the well-to-wheel system.	We assume a gasoline emission factor of 255.6 g CO_2 kW h^{-1}	We allocate the emissions from electricity generation to the well-to-wheel system.	[b]	–	–
Well-to-wheel GHG emissions in kg CO_2-eq. 100 km^{-1}	0	1.5 ± 1.0	4.4 ± 3.4	7.6 ± 3.3	6.9 ± 5.2	12 ± 5	15 ± 9	19 ± 6	9 ± 2	6 ± 2
Principal data source[a]	–	Cherry (2007), Timmermans et al. (2009), IEA (2012) and Markowitz (2013)	Cherry (2007), Brammo (2013), ZM (2013), IEA (2012) and Markowitz (2013)	(See tank-to-wheel energy use)	Brammo (2013), ZM (2013), IEA (2012) and Markowitz (2013)	(See tank-to-wheel energy use)	(See tank-to-wheel energy use)	(See tank-to-wheel energy use)	(See tank-to-wheel energy use)	(See tank-to-wheel energy use)
Comment	–	[c]	[c]	We assume a well-to-tank efficiency of 85 ± 5% and a gasoline emission factor of 255.6 g CO_2 kW h^{-1}	[c]	We assume a well-to-tank efficiency of 85 ± 5% and a gasoline emission factor of 255.6 g CO_2 kW h^{-1}	[c]	We assume a well-to-tank efficiency of 85 ± 5%.	We assume a well-to-tank efficiency of 85 ± 5%.	–

Table A2 (*continued*)

	Bicycles	E-bikes	Mid-size electric two-wheelers	Mid-size conventionally-powered two-wheelers	Large electric two-wheelers	Large conventionally-powered two-wheelers	Battery-electric cars	Conventional passenger cars	Bus	Electric rail (tram and train)
Life-cycle GHG emissions in kg CO_2-eq. 100 km^{-1}	0.5 ± 0.1	2.5 ± 2.0	7.4 ± 6.8	9.6 ± 3.6	11 ± 10	15 ± 6	25 ± 18	24 ± 7	11 ± 2	6 ± 3
Principal data source[a]	Cherry (2007) and del Duce (2011); own estimates	Cherry (2007) and del Duce (2011); own estimates	Cherry (2007) and del Duce (2011); own estimates	del Duce (2011); own estimates	(See well-to-wheel GHG emissions)	(See tank-to-wheel energy use)	del Duce (2011), Aguirre et al. (2012), Hawkins et al. (2012) and Marques and Freire (2011); own expert judgement	(See tank-to-wheel energy use)	(See tank-to-wheel energy use)	(See tank-to-wheel energy use)
Comment	We exclude emissions from energy requirements for paddling based on the discussion presented by Cherry (2007) and Cherry et al. (2009)	We assume that 60 ± 20% of the life-cycle GHG emissions is related to vehicle use	We assume that 60 ± 20% of the life-cycle GHG emissions is related to vehicle use	We assume that 80 ± 15% of the life-cycle GHG emissions is related to vehicle use	We assume that 60 ± 20% of the life-cycle GHG emissions is related to vehicle use	We assume that 80 ± 15% of the of the life-cycle GHG emissions is related to vehicle use based on Chester and Horvath (2009)	We assume that 60 ± 20% of the life-cycle GHG emissions is related to vehicle use	We assume that 80 ± 15% of the life-cycle GHG emissions is related to vehicle use	–	–

[a] Indicating the principal data source that is often complemented by own estimates based on miscellaneous sources and own expert judgement.
[b] We assume on-road fuel use to be 25 ± 10% higher than during type approval (Mock et al., 2013) and the variability of energy use among vehicles to be 35% based on expert judgement.
[c] We assume here a transmission efficiency of 93 ± 3%, a charging efficiency of 97 ± 2%, a carbon intensity of electricity of 0.53 ± 0.33 g CO_2 kW h^{-1} (IEA, 2012). Prior to electricity generation, we assume an efficiency of extraction of 90 ± 5% and an efficiency of shipping of 98 ± 1%; for the losses prior to electricity generation, we assume an average emissions factor of 85 g CO_2 M J^{-1}.

Table A3
Overview of consumer perceptions and mode-shift choices with respect to electric two-wheelers.

Source	Scope and geographic location of the survey	Result
Chiu and Tzeng (1999)	Randomly selected persons at gas stations and 256 randomly selected households in Taipei City (Taiwan)	Important purchasing criteria for powered two-wheelers in general: price, operating cost, reliability, maximum speed, and drive range
Lamy (2001)	369 persons who tested e-bikes in Montreal, Quebec City, St. Jerome, and Toronto (Canada)	64% of all respondents, 71% of bicycle users, and 65% of car users would be interested in commuting by e-bike; motivation for using e-bikes: 79% exercise, 51% reducing pollution, 41% low costs
Weinert et al. (2007c)	751 bicycle users and 460 e-bike users in Shijiazhuang (China)	E-bike users travel 32% farther than bicycle users (5.8 km per trip versus 4.4 km per trip) and 10% longer (27.2 min per trip versus 24.7 min per trip); both user groups make 2–4 trips per day mainly for commuting; users chose e-bikes because these are faster than bicycles (80%) and avoid waiting for the bus (50%); 60% of e-bike users prefer bus over e-bike in bad weather conditions
Cherry (2007)	696 and 502 users of bicycles and e-bikes in Shanghai and Kunming (China), respectively	E-bike users travel 9–22% farther than bicycle users; users of conventional scooters travel 41% farther than e-bike users; e-bikes replace: bus (55–58%), bicycles (12–21%); for 80% of respondents, increased travel speed is the primary reason for choosing e-bikes over bicycles and public bus transport
Hendriksen et al. (2008)	1634 e-bike users and other persons; 1448 valid responses from all over the Netherlands	E-bikes replace: bicycles (34%), cars (18%), and public transport (2%); 38% of e-bike trips would not have been made in the absence of e-bikes
Montgomery (2010)	1171 persons interviewed on large cycle parking locations in Jinan (China)	E-bikes replace: bus (49%), previously owned bicycles or e-bikes (36%), walking (7%), cars (7%) and allow in 1% of cases for trips that would otherwise not have been made
Dekker (2013)	22 persons who bought an e-bike in Utrecht and Amsterdam (The Netherlands)	Respondents plan to use their e-bike for 85 km per week if living near city centers and 60 km per week if living in rural areas; the distance driven on e-bikes substitutes to: 36% cars and conventionally powered two-wheelers, 33% bicycles, 13% old e-bikes, 6% public transport, 3% non-specified means of transport, and lead in 9% to trips that would not have been made in the absence of e-bikes
Johnson and Rose (2013)	On-line survey among by 529 e-bike owners in Australia	60% of respondents acquired an e-bike to replace car trips; 50% of respondents acquired an e-bike to ride with less effort; half the respondents did not consider an alternative mode of transport prior to purchasing an e-bike; the other half of respondents considered, in descending order, bicycles, public transport, and motor-scooters as alternatives
MacArthur et al. (2014)	Online survey among by 553 e-bike owners or users across North America	30% of respondents had a physical condition that made riding a bicycle difficult; 94% of respondents rode a bicycle before owning an e-bike, but only 55% rode a bicycle weekly or daily prior to purchasing an e-bike; 65% of respondents acquired an e-bike to replace car trips; 52% of respondents acquired an e-bike to increase fitness; 25% of respondents indicated that they ride e-bikes to places that are farther away than those previously reached by bicycle

Appendix B. Supplementary material

Supplementary material associated with this article can be found online at http://dx.doi.org/10.1016/j.trd.2015.09.007.

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