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On the sustainability of electric vehicles: What about their impacts on land use?

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ABSTRACT

Electric vehicles (EVs) are widely regarded as the key to finally making private mobility clean, yet virtually no research is being conducted on their potential contribution to the expansion of impervious surfaces. This study aims to start a discussion on the topic by exploring three relevant issues: the impact of EVs' operating costs on urban size, the space requirements of charging facilities, the land demand of energy production through renewables. Given cheaper operating costs compared to conventional vehicles, EVs might lead a 100 km^2 European city to increase by about 0.2−1 km^2 (depending on adoption rate and the fuel price to electricity price ratio) and an equally-large North-American city to increase by about 1−4 km^2. Energy production would also have significant impacts, with Europe and the US potentially having to devote up to 5,000–6,000 km^2 of land to photovoltaic panels or 56,000–70,000 km^2 to wind turbines. The creation of charging spaces would have only minor effects in terms of overall land requirements, though attention should be paid as to whether easier charging in detached and semi-detached homes might increase the appeal of this land-intensive dwelling types. Research is needed to improve our understanding of these dynamics.

1. Introduction

The giant strides made by the electric car industry over the last ten years let us envision a future in which private mobility will be no longer dominated by traditional internal combustion engine vehicles (ICEVs). International agencies and financial companies speculate that, given the current rate of technological improvement (increasing autonomy, decreasing time of recharge, declining battery prices) and the adoption of ad hoc policies, the market share of light-duty battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) combined might get close to 40 % (EV30@30 scenario) in Europe, the US and China by 2030 (IEA, 2018) and reach 55 % globally by 2040 (BNEF, 2018). While such trend is often viewed as inherently positive, however, there is a considerable debate about the actual sustainability of electric vehicles (EVs) (Larcher & Tarascon, 2015; Needell, McNerney, Chang, & Trancik, 2016; Tessum, Hill, & Marshall, 2014; Yang, Xie, Deng, & Yuan, 2018).

The most obvious concern regards energy production: as long as EVs will run on energy generated from burning conventional fossil resources, their diffusion will mean pollution is transferred (to an extent depending on the type of fuel and the efficiency of the energy production process) from tailpipes to smokestacks (Larcher & Tarascon, 2015; Onat, Kucukvar, & Tatari, 2015; van Vliet, Brouwer, Kuramochi, van den Broek, & Faaij, 2011). The life-cycle of batteries is also deemed problematic as their production requires the extraction and treatment of various metals (e.g. lithium, aluminum, copper) that may have considerable environmental impacts and energetic costs (Notter et al., 2010), whereas their recycling and disposal imply significant logistical and environmental problems (Richa, Babbitt, Gaustad, & Wang, 2014). Yet, there is confidence that technological progress combined with sound policies will help us progressively tackle these issues (Yang et al., 2018), for example making sure all of EVs' energy demand in the future is satisfied through renewables (particularly solar and wind) (van Vliet et al., 2011).

There is another class of problems, however, that, despite their significance, are barely mentioned in the debate, namely the impacts of EVs on land use (Ahmadian et al., 2018; Sevtsuk & Davis, 2019). EVs, just like their traditional counterparts, occupy space, require infrastructures that occupy space and, by allowing point-to-point mobility, favor lower density settlements, therefore enabling a massive expansion of impervious surfaces and a kind of settlement pattern that is often referred to as

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sprawl (Burchfield, Overman, Puga, & Turner, 2006; Glaeser & Kahn, 2004). The latter has serious environmental and socioeconomic consequences in the form of increased ecosystem fragmentation (Radeloff, Hammer, & Stewart, 2005), loss of arable land (Tan, Li, Xie, & Lu, 2005), higher CO_2 emissions (Wu, Lin, Oda, & Kort, 2020), water pollution (Arnold & Gibbons, 1996; Jacob & Lopez, 2009), more urban energy use (Güneralp et al., 2017), an increase in vehicle miles traveled (Ewing & Cervero, 2010; Ewing & Hamidi, 2015) and related health problems (e.g. obesity) (Rundle et al., 2007; Sallis et al., 2016), reduced community stability (i.e. higher home foreclosure rates) (Chakraborty & McMillan, 2018), and augmented cost of infrastructures (Burchell, Downs, McCann, & Mukherji, 2005) and service provision (Carruthers & Ulfarsson, 2003; Hortas-Rico & Solé-Ollé, 2010). The key question then is whether EVs, given their peculiar characteristics, will contribute to slowing down the endless expansion of impervious surfaces, will just let it go unchecked or, paradoxically, accelerate it.

This study aims to start a discussion on the topic by exploring three aspects of EV technology that might strongly affect the magnitude of its impacts on land use: operating costs, charging requirements and energy production. For each of these, we explore the linkages with land use and attempt a simplified quantification of related impacts for various degrees of EV adoption. Three adoption levels are considered – 10 %, 20 %, 40 % – that reflect progressively increasing shares of BEVs on the roads, in line with some of the global forecasts to 2040–2050 (BNEF, 2019) yet not tied to specific years of achievement given huge uncertainty in this respect. Although the level of adoption is a function of several factors, including the first two aspects analyzed in this study, it is treated here as an exogenous variable. The decision to focus solely on BEVs is justified by the fact that PHEVs do not fully run on electricity, while hydrogen fuel cell vehicles (HFCVs) are still a big unknown owing to efficiency issues in hydrogen production and lack of infrastructure. We particularly refer to the European Union (EU) (including the UK) and North America (Canada and USA), where the share of BEVs is predicted to grow considerably in the years to come and large datasets for analysis are available. To our knowledge, this is the first study to systematically explore the impacts of electric mobility on land use and to provide some rough estimates of the extent to which the diffusion of EVs might affect the extension of impervious surfaces. As such, it sets the stage for new research targeting the specific aspects highlighted here.

The paper is organized as follows. Section 2 presents the theoretical and conceptual underpinnings of the impact of EVs on land use owing to the three above-mentioned aspects (i.e. operating costs, charging, energy production), and describes the methodology used to estimate such impacts. Section 3 presents figures of land use impacts associated with each of these aspects. Section 4 discusses the findings and the limitations of the proposed methodology. Section 5 outlines some relevant themes for future research on the impact of EVs on land use.

2. Concepts and calculation methods

2.1. Operating costs

Transportation costs are a key determinant of urban size. According to the well-known Alonso-Muth-Mills model (Alonso, 1964; Mills, 1967; Muth, 1969), in a monocentric city (i.e. all employment and amenities are located in the city center), a household's earnings to be spent on land declines as the distance from the center increases because of progressively increasing transportation costs. In other words, if y is income, t is commuting cost per unit distance and d is distance, then the possible expenditure at any given distance will be $y - td$. At distance d^*, $y - td^*$ equals the agricultural land rent r and city expansion stops (Fig. 1). All else (e.g. population, income, agricultural land rent) being equal, when t increases, commute trips become more expensive and the city shrinks (i.e. city boundary shifts to d_A), whereas if t decreases commuting is easier and the city boundary moves outward to d_B (Brueckner, 1987). While the monocentric assumption seems outdated for today's world, the

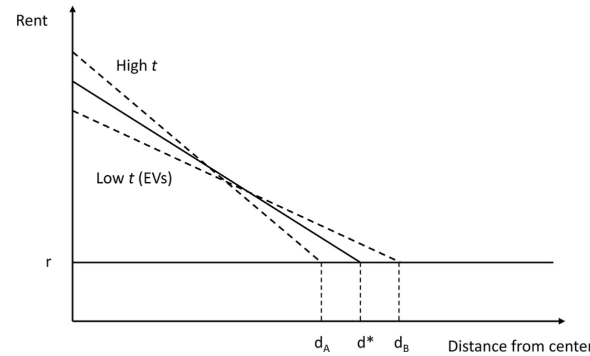

Fig. 1. Bid-rent curves for a monocentric city under different per unit distance transportation costs (t). Initially, the city boundary is found at distance d* from the center: this is the place where income net of transportation costs equals the agricultural land rent r. If t increases, commuting gets more difficult and the city boundary shifts to d_A. Conversely, if t decreases (as in the case of cheap electricity for EVs), commuting becomes easier and the city expands to d_B.

model's rationale and basic conclusions have been proven robust in polycentric contexts too (Henderson & Mitra, 1996). In fact, declining transportation costs due to the diffusion of automobiles, investments in freeways and cheap fuel have greatly contributed to the phenomenon of sprawl by cutting commuting costs and making suburban locations attractive to the average citizen (Brueckner, Mills, & Kremer, 2001; Glaeser & Kahn, 2004).

From a household's standpoint, the monetary cost of car-based transportation, also referred to as total cost of ownership (TCO) (Dumortier et al., 2015; Hagman, Ritzén, Janhager Stier, & Susilo, 2016), is primarily given by the purchase of the vehicle (and associated down payment and interests), insurance and ownership taxes, maintenance and fuel. While BEVs are still much more expensive to buy than comparable ICEVs, forecasts suggest that by 2024–2032 they might cost essentially the same (BNEF, 2019; Seixas et al., 2015; Weiss et al., 2012) owing to economies of scale, technological learning (Weiss et al., 2012) and constant decline in the price of Li-ion battery packs (Nykvist & Nilsson, 2015). Rapid depreciation, a major drawback of today's EVs, may become less of an issue as EVs stop being an emerging technology and ICEVs get increasingly limited by environmental policies (e.g. restrictions on access to city centers) (Danielis, Giansoldati, & Rotaris, 2018). Assuming the sum of insurance, taxes and maintenance costs to be more or less similar for BEVs and ICEVs (although the incidence of taxation may in fact vary considerably between countries because of incentives) and considering that battery replacement (a rather expensive procedure) may only be required by high-intensity users after 8–10 years of use (Weldon, Morrissey, & O'Mahony, 2018), it is then fuel that will largely determine the difference in cost between the two technologies.

Fuel wise, BEVs are currently much cheaper than ICEVs. In Europe, for example, considering an average gasoline price of euros 1.4 L^{-1} (EC, 2018), an average electricity price of euros 0.2 kW h^{-1} (Eurostat, 2018), a gas mileage of 40 mpg (17 km l^{-1}) and an electricity mileage of 3.6 miles kWh^{-1} (5.8 km kWh^{-1}) (Offer, Howey, Contestabile, Clague, & Brandon, 2010), driving 100 km would cost 8.2 euros of gasoline with an ICEV compared to a mere 3.4 euros of electricity with a BEV. Nearly 60 % less. Savings would be similar in the US where both gasoline and electricity are roughly half as expensive (on average, \$ 0.75 L^{-1} and \$ 0.13 kW h^{-1}, respectively) (EIA, 2018a, 2018b).

The extent to which cheaper fuel would encourage BEV owners to drive more, therefore favoring more spread out settlements, depends, among other things (e.g. appeal of suburban life, land use policies, recharging scheme, vehicle range), on their willingness to reinvest fuel savings into additional driving. The elasticity of vehicle-km (both total and per vehicle) with respect to fuel price has been roughly estimated at around -0.1 in the short term (about a year) and -0.3 in the long term (about 5 years) (Brand, 2009; Goodwin, Dargay, & Hanly, 2004; Litman, 2013). These elasticity values were used to estimate the likely variation in a household's car usage after switching to an EV, considering various electricity prices and different levels of ICEV fuel economy (km l^{-1}), while holding EV fuel economy (5.8 km kWh^{-1}) and the price of gasoline (1.4 euros l^{-1}) constant. Electricity prices were varied between the current level (i.e. euros 0.2 kW h^{-1}) and the level that would make EV and ICEV equally expensive on a per unit distance basis at current fuel efficiency level (i.e. euros 0.48 kW h^{-1}), to simulate the possible introduction of charges on electricity, similarly to what happens today with gasoline excises. The fuel economy of ICEVs was varied between the current average level (i.e. 17 km l^{-1}) and a level 50 % higher (i.e. 25.5 km l^{-1}) to reflect projected technological improvements over the next 30 years (EIA, 2020).

Quantifying the impact of BEVs' lower fuel costs on urban size is very difficult given the multitude of variables to account for (e.g. housing preferences, income distribution, zoning policies, etc.) and the relatively limited bulk of relevant empirical studies to rely upon (McGibany, 2003; McGrath, 2005; Ortuño-Padilla & Fernandez-Aracil, 2013; Tanguay & Gingras, 2012). A simplified calculation was nonetheless attempted using estimates of fuel price elasticity of the share of low-density housing out of all housing by Ortuño-Padilla and Fernandez-Aracil (2013) for Europe and Tanguay and Gingras (2012) for North America (Canada and USA). The percent increase in artificial land cover was estimated combining the above-mentioned elasticity values, fuel savings for a given ratio of electricity cost to gasoline cost on a per unit distance basis (f_{BEV}/f_{ICEV}), the share of BEVs on the roads, rate of low-density housing, areal fraction of low-density neighborhoods out of all residential neighborhoods and areal fraction of residential neighborhoods out of artificial land. The f_{BEV}/f_{ICEV} parameter was assumed to range between the current 0.4 and 0.9, therefore accounting for possible increases in electricity prices due to the introduction of charges. Values of 1 and above were disregarded, assuming price equality ($f_{BEV}/f_{ICEV} = 1$) to cause no significant changes in land use patterns and costlier-than-gas electricity ($f_{BEV}/f_{ICEV} > 1$) to be unlikely. The rate of low-density housing, the fraction of low-density neighborhoods and the fraction of residential neighborhoods were estimated as average values from the analysis of geospatial land use and zoning data for 15 EU and 15 North-American mid-sized cities (for details about land use data and the list of cities, see the Appendix A).

2.2. Charging requirements

The diffusion of EVs depends on the presence of a reliable network of charging points at a variety of locations including homes, workplaces, public parking lots and so-called corridors such as highways (Biresselioglu, Kaplan, & Yilmaz, 2018; Hardman et al., 2018). The installation of charging points in the last two contexts, however, although key to guaranteeing the mobility of those who cannot charge at home or workplace (Pan, Yao, Yang, & Zhang, 2020) and long-distance travel (Biresselioglu et al., 2018), might require considerable amounts of land.

Public charging is possible at dedicated parking spaces using normal power (generally up to 7.4 kW), which has minor impacts on the electric grid but is rather slow, providing 100 km of range in 3 or 4 h. It is exactly the long charging time, rather than the required infrastructure (essentially a cable and control unit per parking space), that might push the demand for land. In fact, a very high number of dedicated parking spaces must be provided across a city to guarantee a certain throughput, namely to make sure EV owners can easily find an empty spot when needed (Gnann & Plötz, 2015). As to the appropriate number, current guidelines suggest 10–15 EV s per charging point (EU, 2014; IEA, 2017), equivalent to about 70−100 m^2 of dedicated parking space every 100 EVs.

Charging along corridors is performed via direct current (DC) fast chargers (power above 40 kW), which can typically provide 100 km of range in 20−30 min or less, therefore ensuring a relatively quick stop-and-go. Lower charging times (compared to normal charging facilities) allow for the installation of a much lower number of charging points – between 80 and 150 EVs per charging point considering 50 kW of power rate and 100 km of electric range (Gnann et al., 2018) – which are grouped in stations to be wisely spaced along highways and other fast road corridors (He, Kockelman, & Perrine, 2019). Studies suggest that, in order to provide adequate support to travelers, stations along a given road should be placed no more than 60 km apart (Donati et al., 2015). The land area requirement of these stations, though limited, is generally larger than the mere size of charging spaces because energy storage facilities may have to be installed to mitigate the effects of high power demand charges on the grid, especially when several EVs are charged simultaneously (Yunus, Zelaya-De La Parra, & Reza, 2011; Zheng, Shao, Zhang, & Jian, 2020).

The area occupied by public charging facilities was computed starting from today's number of light duty vehicles in urban settings (for details about how this number was calculated, see the Appendix A) and assuming a target of 15 vehicles per charging point, each of which would cover 14 m^2. The area occupied by fast charging stations was estimated considering two stations (one per direction) every 60 km on all highways (motorways and state roads) and assuming a basic station size of 200 m^2, which doubles and quadruples when BEV share increases to 20 % and 40 %, respectively.

Although public and corridor charging facilities, by reducing range anxiety and guaranteeing the completion of long trips in due time, can greatly contribute to the diffusion of EVs, there is no doubt that the possibility to charge at home is a major motivation to purchase an EV (Patt, Aplyn, Weyrich, & van Vliet, 2019). Unfortunately, home charging is very easy when owning a house because of direct access to a personal charging point, but less so when living in a flat, especially in large apartment complexes (Axsen & Kurani, 2012). While no empirical studies (as far as we are aware) exist on the topic, it is plausible to believe that a strong societal orientation towards electric mobility may increase the appeal of detached and semi-detached houses in suburban locations for their greater "compatibility" with EVs (Kester, Sovacool, Noel, & Zarazua de Rubens, 2020; Newman, Wells, Donovan, Nieuwenhuis, & Davies, 2014; Ulrich, 2020). After all, the ensemble of a single family home, a green lawn and an EV charging outside is a powerful image, which may be easily, yet naively, interpreted by many as a symbol of modern sustainable living, and be used by developers to reinvigorate the demand for this housing type. The effects of such dynamics on land use might be significant. In order to roughly estimate such effects, the per capita artificial land cover of European and North American countries was regressed against the share of people living in detached houses (details about data sources are in the Appendix A).

2.3. Energy production

The ability of EVs to cut greenhouse gas emissions depends on whether and to what extent the electricity that powers them comes from renewable sources. In fact, the zero emission scenario (not considering the manufacturing of EVs and energy-producing facilities as well as their disassembly) is only possible if all of such electricity is generated through renewables, typically solar and wind. Yet, achieving this goal may have considerable impacts on land use given the very low power densities of photovoltaic power plants and wind farms (Miller & Keith, 2018).

The land area required for the satisfaction of electric mobility's energy demand was estimated based on the assumption that 10 %, 20 %, 40 % of today's light-duty vehicle kilometers would be traveled by BEVs with an average electricity mileage of 6 km kWh^{-1}, and that mean power densities of photovoltaic power plants and wind farms are 5.4 W m^{-2} and 0.5 W m^{-2}, respectively (Miller & Keith, 2018). Details about the computation of light-duty vehicle kilometers traveled are presented in the Appendix A.

3. Main findings

3.1. Operating costs

Owing to their respective fuel efficiencies, as well as the prices of gasoline and electricity, shifting from an ICEV to a BEV might lead to significant variations in a household's kilometers traveled, both in the short and the long term (Fig. 2). Given current ICEV efficiency and electricity prices, a household's total mileage might increase by 6% in the short term and up to 18 % in the long term when shifting to a BEV. For a household driving 20,000 km a year, this is equivalent to a weekly increment of up to 70 km (i.e. 14 extra km every weekday), which, in a mid-sized city, is compatible with a move to a more suburban location. Considering the current ICEV efficiency, the possibility of driving more when shifting to a BEV would only be excluded if electricity prices were raised by a staggering 150 % through taxes. Things would be less extreme in case people shifted to BEVs from more efficient ICEVs. Yet, electricity prices 80 % and 60 % higher than today's would still be needed to prevent more driving among people shifting to BEVs from ICEVs 25 % and 50 % more efficient than today's average, respectively. In the absence of any special tax on electric mobility, BEVs would be so much more economical than even the most efficient ICEVs that a shift to electric mobility might induce the owners of cars with a gas mileage of 25.5 km l^{-1} to drive 4% and 11 % more than they used to in the short and the long term, respectively.

The expected increase in artificial land cover because of EV adoption, assuming constant population, is going to be much stronger in American cities, where the areal fraction of low-density residential out of total artificial land is very high (on average 42 % in our sample), than in European ones, where that fraction is generally negligible (on average 9% in our sample) (Fig. 3). Considering medium electricity price (f_{BEV}/f_{ICEV}) and presence of BEVs – 0.7 and 20 %, respectively – a European city characterized by an artificial land cover of 100 km^2 would have it increased by 0.17−0.27 km^2 (17−27 ha) compared to 0.72−1.1 km^2 for an equivalent American city (upper and lower values reflect ratios of high density to low density of 2 and 4, respectively). Under extreme conditions (0.4 f_{BEV}/f_{ICEV} and 40 % BEV share), the expansion of artificial land would rise up to 0.72−1.14 km^2 in the hypothetical European city and 3-4.57 km^2 in the American equivalent.

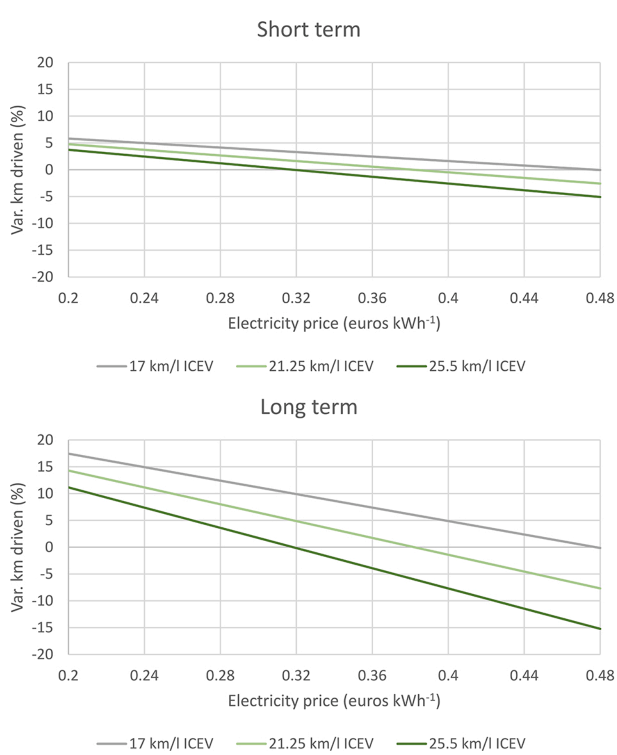

Fig. 2. Variation in km traveled when shifting from an ICEV to an EV for different values of electricity prices and ICEV fuel efficiency, holding EV efficiency and gas price constant (5.8 km kWh^{-1} and euros 1.4 L^{-1}, respectively). Elasticities of vehicle-km with respect to fuel price of -0.1 and -0.3 are considered for the short and the long term, respectively.

3.2. Charging requirements

The extent of land required by adequate networks of public and corridor charging points for different shares of BEVs (i.e. 10 %, 20 %, 40 %) in EU, Canada and USA is shown in Fig. 4. Numbers suggest charging facilities would in fact cause rather limited impacts on land use. In fact, under the assumption that BEVs get to represent 40 % of the overall vehicle fleet, the amounts of land the EU and USA should devote to charging facilities are around 87 and 104 km^2, respectively.

Fig. 5 illustrates the relatively strong correlation between the share of people living in detached houses and per capita amount of impervious surfaces (m^2) in EU countries, Canada and USA. The coefficient of the independent variable is 8.392 ($p < 0.05$), meaning that a one percent increase in the proportion of people living in detached houses is roughly associated with an 8 m^2 rise in the amount of artificial land cover per inhabitant. Hence, all else being equal, should the transition to electric mobility contribute to increase the share of people preferring detached houses to other housing types by 1% in a country of twenty million, the overall amount of built-up land would increase by about 165 km^2: an area roughly the size of Gothenburg, Sweden (built-up area only).

3.3. Energy production

Estimates of the overall amount of land that would be needed to satisfy the energy demand of BEVs in the EU, Canada and USA using only solar or wind are presented in Fig. 6. While the extra demand of electricity associated with the use of EVs would be generally limited compared to current overall production, the amount of land needed to meet such demand via renewables would be substantial, particularly in the EU and USA. In order to run 40 % of their vehicles with electricity, the EU should devote over 5000 km^2 of land (twice the size of Luxembourg) to photovoltaic panels or almost 56,000 km^2 (about the size of Croatia) to wind turbines, whereas the US should devote over 6000 km^2 (roughly the size of Delaware) to solar or almost 70,000 km^2 (more than the area of West Virginia) to wind. Canada, owing to a much smaller population, could satisfy the demand reserving slightly more than 400 km^2 (the area of Montreal) to photovoltaic panels or approximately 4500 km^2 (slightly less than the size of Prince Edward Island) to wind farms. Clearly, a mix of the two energy sources would require amounts of land that are in between the all-solar and all-wind scenarios, and depend on the shares of the two.

4. Discussion

From a spatial planning perspective, the amazingly low operating costs of EVs compared to ICEVs on a per unit distance basis are a major concern as savings accrued when shifting to electric mobility may stimulate more driving and therefore sprawl. In fact, our estimates suggest EV owners might drive way more (up to 18 % more) than they used to, even when shifting from very efficient ICEVs, unless ad hoc taxation is imposed on EVs. The subsequent increase in urban impervious surfaces, though possibly limited percent-wise, might be considerable area-wise, especially in large cities. For example, in a city with 300 km^2 of impervious surfaces (e.g. Lyon, France; Tampa, FL, USA), a mere 0.5 % increase of these would imply the loss of 1.5 km^2 of natural land: an asset that, if covered with trees, could capture 900 tons of CO_2 annually (Valentini et al., 2000) and, if cultivated, could yield around 600 tons of cereals per year (World Bank, 2019). Impacts would be particularly bad in North American cities, where increases in artificial

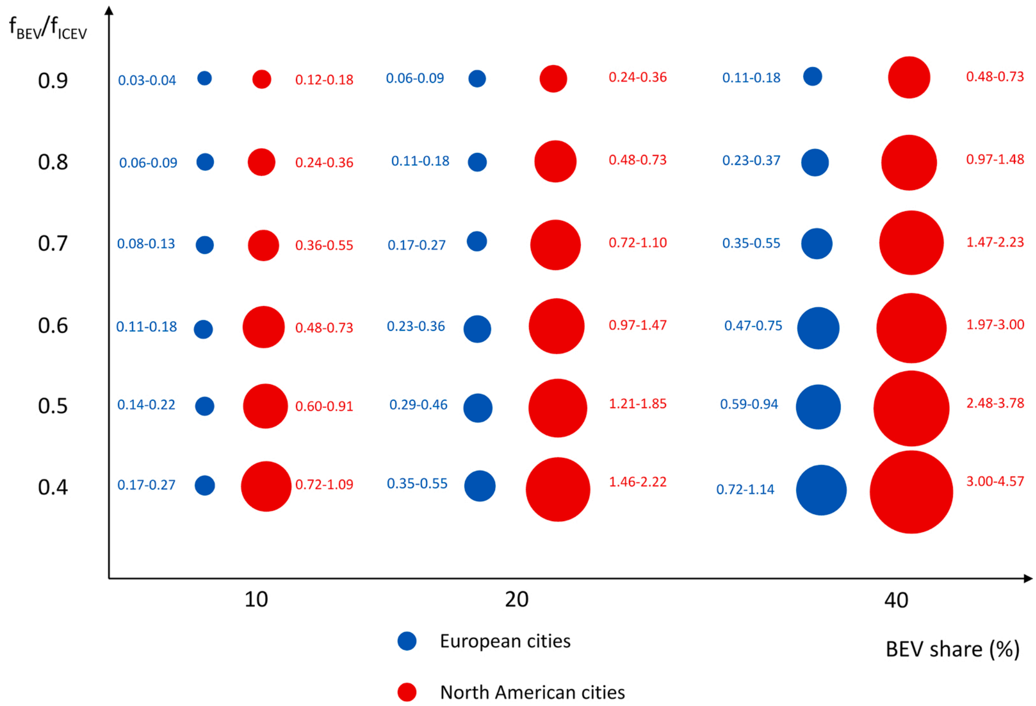

Fig. 3. Predicted percent increase of the built-up area of European and North American cities for various shares of BEVs out of the total vehicle fleet (10 %, 20 %, 40 %) and different ratios of electricity price to gas cost on a per unit distance basis (f_{BEV}/f_{ICEV}). Upper and lower values reflect ratios of high density to low density of 2 and 4, respectively.

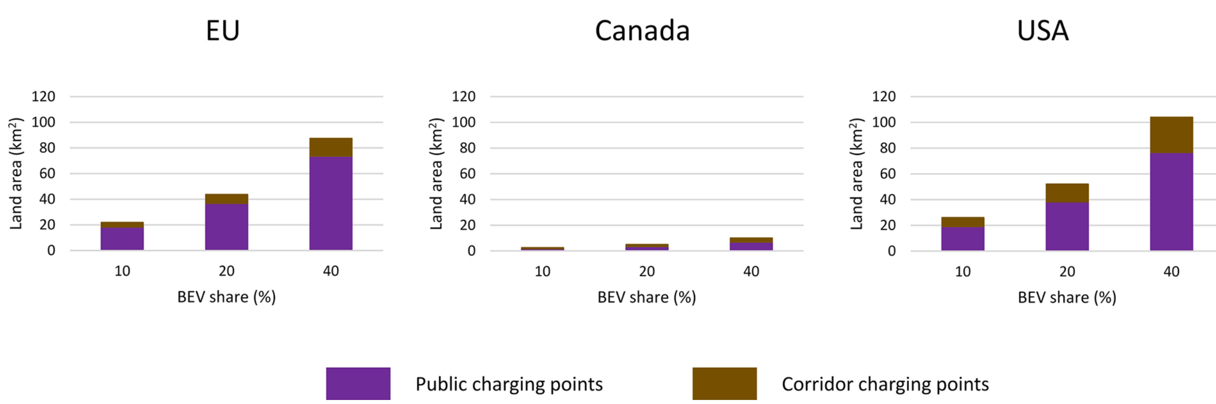

Fig. 4. Land area requirements for the creation of public charging points (i.e. parking spaces for normal power charging) and corridor charging points (i.e. fast charging stations along highways) in the EU, Canada and USA.

land area of 1% or more would be almost inevitable if BEV use became widespread, and still probable if their diffusion were moderate and electricity cheap.

Such predictions are possibly affected by a considerable degree of uncertainty, owing not just to the simplified calculation method, but also the impossibility to account for the influence of policy and technological factors in the years to come. First of all, elasticities generally hold true only over a limited range of values around the status quo: people's reaction to much cheaper fuel may be markedly different from what existing studies suggest. For example, actual elasticities might prove higher than expected in Europe, where low-density housing and the associated demand for fuel are a premium good, and lower in North America, where they are mostly perceived as basic assets. If that were the case, the expansion of impervious surfaces would then be greater than predicted in Europe and narrower than predicted in America.

The idea that cheap electricity would necessarily encourage people to drive considerably more than they currently do, therefore stimulating a major expansion of urban agglomerations, may be overstated in the face of the limited range of some EVs and, more importantly, the so-called range anxiety, which reduces people's willingness to embark on long commutes if recharging during the day is not possible (Neubauer & Wood, 2014; Pearre, Kempton, Guensler, & Elango, 2011; Yang, Yao, Yang, & Zhang, 2016). Moreover, relocating to a suburban (or more suburban) location generally requires a household to own more than one vehicle: fuel-related savings would then be guaranteed only if all of them were electric, yet this may prove impracticable for many. These concerns, however, may largely disappear as EV technology improves in terms of range and purchase price, and local administrations encourage electric mobility through incentives and tax cuts.

Cheap fuel may contribute to land consumption via other pathways too. For example, by actually encouraging households to own more vehicles. Given a long-term price elasticity of vehicle stock of -0.25 (Goodwin et al., 2004), values of f_{BEV}/f_{ICEV} comprised between 0.4 and 0.9, and a BEV share between 10 % and 40 % might lead to a 0.25–6%

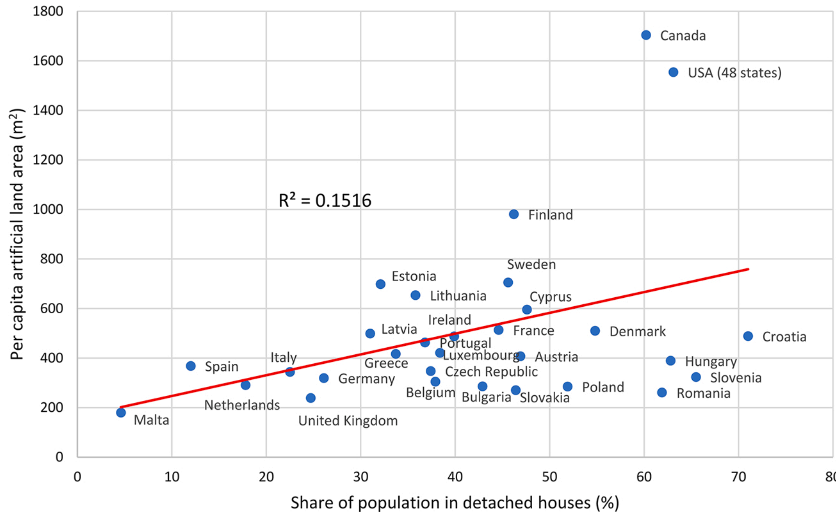

Fig. 5. Regression of per capita amount of artificial land (*al*) against the share of population living in detached houses (*pdh*) in EU countries, Canada and USA. The regression line is: $al = 162.82 + 8.392 * pdh$ ($R^2 = 0.1516$).

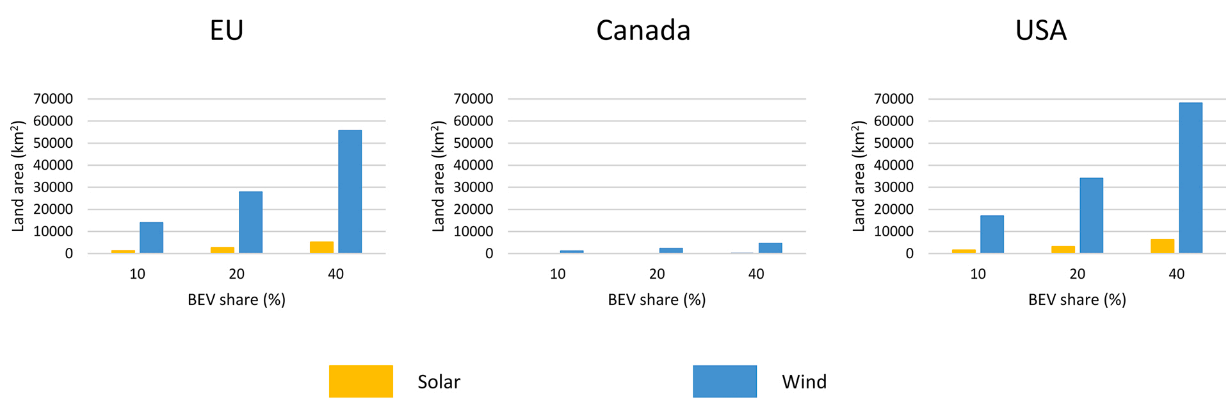

Fig. 6. Overall amount of land to be devoted to photovoltaic power plants and wind farms to satisfy the energy demand of BEVs in the EU, Canada and USA, assuming an average electricity mileage of 6 km kWh^{-1}.

increase in the overall number of vehicles, therefore stimulating additional demand for parking and road space. Clearly, the boost cheap fuel can give to car ownership may be heavily diminished if battery packs and their replacement keep being expensive, especially under a likely scenario of rapid depletion of lithium resources.

Another thing cheap fuel can do is to make private vehicles ever more attractive than public transit. Assuming a cross-elasticity of transit use with respect to fuel price of 0.34 (Goodwin, 1992; Nowak & Savage, 2013), the above-mentioned conditions of fuel savings and BEV share may encourage between 0.34 and 8% of current transit users to shift to the private vehicle, exacerbating the land use implications of private mobility.

Finally, the combination of increased car ownership and reduced transit ridership may induce (or accelerate) a “vicious cycle” by which the shift to private mobility favors land consuming low density patterns over compact development and this in turn stimulates the reliance on private vehicles and the flight from transit, and subsequently further urban expansion (Cervero & Kockelman, 1997; Glaeser & Kahn, 2004).

The amount of land required for public charging facilities (87 and 104 km^2 in the EU and USA with a 40 % share of EVs) is definitely extended in absolute terms (annual CO_2 storage: 52,200−62,400 tons; annual cereal yield: 34,800−41,600 tons), but still negligible in terms of percentage of the entire territories. Moreover, not all charging facilities would be created by sealing currently natural land: some would simply be obtained through conversion of existing gas stations or the redefinition and optimization of a city’s parking supply. Technological improvement, in terms of more extended ranges and faster charging, may reduce the number of public and corridor charging points required, further lowering the associated demand for land.

One risk nonetheless exists: that city administrations’ attempts at favoring EVs over ICEVs may result in zoning codes requiring developers to set aside excessive amounts of space for the charging of EVs in new residential complexes, therefore expanding cities significantly (Moroni & Minola, 2019; Shoup, 1999). Smart design, including the construction of underground charging points, can help limit the unintended consequences of such policies, though it may hardly be implemented where land prices are particularly low.

A strong hypothesis advanced in this study is that EVs might contribute to making lower-density settlements more attractive as they facilitate charging operations (e.g. detached and semi-detached houses generally have private parking spaces) (Axsen & Kurani, 2012), therefore increasing the extent of impervious surfaces. In fact, while existing literature only considers the opposite direction of causality (i.e. living in low-density areas favors the ownership of EVs) (Campbell, Ryley, & Thring, 2012; Morton, Anable, Yeboah, & Cottrill, 2018), it is not too far-fetched to believe that people holding pro-environmental beliefs and a fascination for green technologies might regard suburban life with an EV as very appealing (Axsen, TyreeHageman, & Lentgz, 2012). The regression analysis performed in this study was simply meant to provide an idea of the per capita increase in impervious surfaces associated with a stronger preference for lower-density housing: things in the real world can get way more complicated than that, however, owing to individual decision-making and policies in place.

Regarding the impacts of energy production on land use, the figures presented in this study should be interpreted as upper reference values, which may in fact be dramatically lower in practice for a number of reasons. First of all, technological progress may lead to an increase in both EV mileage, therefore reducing energy demand on a per unit distance basis, and solar and wind power densities, hence enabling the extraction of more energy from the same unit of land in a given time span. Second, a smart allocation of charging time slots during the day may ensure that most EVs are charged when energy demand from other utilities is lowest. Moreover, calculations are based on average power densities that may be slightly lower than what can be achieved even today if all solar or wind power plants are installed in the most suitable locations available across a territory (i.e. sunniest and windiest). Figures may also be misleading because they refer to the overall area that should be devoted to solar and wind production, not the extent of natural land that should be converted to photovoltaic panels or wind turbines. The latter is in fact much lower than suggested in Fig. 6, as photovoltaic panels can also be installed on existing artificial structures (e.g. large warehouses), whereas wind farms can coexist with other uses (e.g. agriculture) (Palmas, Siewert, & von Haaren, 2015) or be located offshore.

While numbers presented in this paper provide a comprehensive picture of the likely effects of electric mobility on the extension of impervious surfaces in Europe and North America, it is worth noting that, in addition to the specific methodological limitations presented above, they are also affected by two more general sources of uncertainty. On the one hand, the large scale of analysis imposed a great deal of simplifications and assumptions that inevitably reduced the accuracy of calculations. For example, no attention was paid to topographic and socioeconomic characteristics, which may nonetheless largely affect the impact of electric mobility on the landscape (Burchfield et al., 2006; Liu, Yamamoto, & Morikawa, 2017; Westin, Jansson, & Nordlund, 2018). On the other hand, there is some inherent uncertainty as to how EVs will impact the automobile market, how EV technology will improve in the near future and how new technologies and dedicated policies will redefine the transportation scene in the next decades (Liu & Lin, 2017; Wanitschke & Hoffmann, 2019). All of these elements of uncertainty affect not only the magnitude of our estimates, but potentially also the sign, meaning that the predicted increase in impervious surfaces might, under certain conditions, turn out not to take place. In fact, we cannot exclude that a mix of technological innovation, careful policies, increasing environmental conscience and unexpected socioeconomic trends might define a scenario in which increased EV penetration and the containment of impervious surfaces go hand in hand.

5. Conclusion

Pollution has been regarded as the main drawback of automobiles since their birth (Chapman, 2007), more than a century ago, and a reason, in recent times, for the adoption of targeted mitigation measures (e.g. carbon taxes). In this respect, today's EVs possibly represent the most extraordinary innovation ever, particularly for people living near major roadways. However, by eliminating pollution all together, EVs might also let citizens and administrators believe private mobility has eventually become clean, thus neglecting its other big, largely unavoidable, issues, including congestion, reduced physical activity and, of course, land use impacts. Regarding the latter, owing to cheap electricity, specific charging requirements and land-intensive renewable energy production, EVs might paradoxically perform worse than ICEVs.

This study has shown that cheap fuel and energy production may have the largest implications for land use as the former can induce a significant increase in urban size due to the expansion of low-density areas, especially in North America, whereas the latter may require potentially huge extents of land to be devoted to solar and wind power plants. The slow charging rate of EVs, and therefore the need for a very high number of charging points, does not seem to have significant direct consequences on land use, though it might potentially induce negative urbanization dynamics should low-density settlements become more attractive for their greater compatibility with EVs.

Despite all possible flaws and uncertainties, concepts and data presented here have the fundamental merit of shedding a light on a topic that is virtually disregarded in the scientific literature, outlining some of the key questions scholars will have to answer in the years to come to figure out the actual sustainability of electric mobility. Regarding operating costs, there is urgency of studies telling us how these will evolve, also because of dedicated policies (e.g. introduction of taxes on electricity for transport), and what their impacts on the size of urban areas could be given specific environmental and socioeconomic conditions. As to recharging requirements, we need to better understand what are the amount and spatial distribution of charging points that may encourage the adoption of EVs, without stimulating the overexpansion of mid-density residential areas. We also need economic and psychological studies informing us about the extent to which emphasis on EV ownership and use may foster a shift towards low-density living. Regarding energy production, it is crucial to assess whether and how the additional energy demand due to the use of EVs can be satisfied through renewables in a way that causes minimum losses in the provision of key ecosystem services for human well-being.

Cross-cutting all these issues and research questions is the diffusion of shared autonomous electric vehicles (SAEVs), given their potential to revolutionize car-based transportation in the next future (Chen, Kockelman, & Hanna, 2016; Fagnant & Kockelman, 2014). The fact that a considerable proportion of EVs are shared and autonomous in fact might have non-obvious consequences on land use, whereby a lower number of vehicles could help reduce parking areas in cities, but the elimination of transport-related opportunity costs (i.e. people would not have to drive and could engage in other activities while on the car) could encourage longer commutes and therefore lower density living. All of these issues and considerations unveil some exciting research niches that should be thoroughly explored by scientists in the near future if we want to understand the comprehensive impacts of electric mobility and be able to design policies that can guarantee its long-term sustainability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Operating costs

Land use and zoning data for EU cities were extracted from the 2012 Urban Atlas produced by the Commission Directorate-General for Regional and Urban Policy and the Directorate-General for Enterprise and Industry in the framework of the EU Copernicus programme, (http://land.copernicus.eu/local/urban-atlas/urban-atlas-2012/view), whereas data for US and Canadian cities were obtained from their GIS web portals.

The European cities are: Aalborg (Denmark), Bologna (Italy), Brno (Czech Republic), Debrecen (Hungary), Gothenburg (Sweden), Granada (Spain), Kaunas (Lithuania); Leuven (Belgium), Lyon (France), Nottingham (United Kingdom), Nurnberg (Germany), Porto (Portugal), Salzburg (Austria), Tampere (Finland) and Utrecht (Netherlands). The North American cities are: Austin, TX, Birmingham, AL, Fresno, CA, Lexington, KY, Minneapolis, MN, Pittsburgh, PA, Salt Lake City, UT, Spokane, WA, Tampa, FL, Tucson, AZ, Tulsa, OK, Worcester, MA in the United States, and Guelph, ON, Kelowna, BC, Regina, SK in Canada.

Charging requirements

Numbers of vehicles in urban settings were computed multiplying the total number of vehicles in each country by the urbanization rate of each country. The former was extracted from Eurostat (2017a) for EU countries, Statistics Canada (2018) for Canada and the Bureau of Transportation Statistics (BTS, 2017) for the USA. The latter was extracted from the World Bank (2018). The length of highway was extracted from Eurostat (2017b), Eurostat, 2017c for the EU, from Statistics Canada (2016a) for Canada and from the Federal Highway Administration (FHA, 2016) for the US.

The regression analysis between the share of detached houses and per capita artificial land cover was conducted on data about dwelling types from Eurostat (2015a), Statistics Canada (2016b) and US Census Bureau (2010), and data about artificial land cover from Eurostat (2015b); Statistics Canada (2011) and MRLC (2011).

Energy production

Light-duty vehicle kilometers traveled for the EU were computed multiplying the total number of light-duty vehicles (Eurostat, 2017a) by the average annual travel distance per vehicle (14,000 km), whereas for Canada they were extracted from Transport Canada (2009) and for the US they were obtained from EIA (2018c). Data about current energy production for comparison were extracted from Eurostat (2016) for the EU, from NRC (2016) for Canada and from EIA (2018d) for the USA.

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