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Riding the Energy Transition: Oil beyond 2040

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Riding the Energy Transition: Oil Beyond 2040

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Abstract

Recent technological developments and past technology transitions suggest that the world could be on the verge of a profound shift in transportation technology. The return of the electric car and its adoption, like that of the motor vehicle in place of horses in early 20th century, could cut oil consumption substantially in the coming decades. Our analysis suggests that oil as the main fuel for transportation could have a much shorter life span left than commonly assumed. In the fast adoption scenario, oil prices could converge to the level of coal prices, about $15 per barrel in 2015 prices by the early 2040s. In this possible future, oil could become the new coal.

JEL Classification Numbers: Q02, Q40, O33

Keywords: oil price, energy transition, electric vehicle, renewable energy

I. INTRODUCTION: ENERGY TRANSITIONS

The imminent demise of oil as the world's main energy source has been widely heralded since at least the 1950s, most famously by M. King Hubbert in his "peak oil" hypothesis [1]. Progress in oil extraction and continuing discoveries of new reserves, however, have brought this idea into question.[1] As noted by Sheikh Zaki Yamani, a former Saudi Arabian oil minister, "The stone age came to an end not for a lack of stones, and the oil age will end, but not for a lack of oil [2]." In other words, a demand-driven abandonment of oil would not be unprecedented—after all, wood and coal use in the 19th and 20th centuries did not diminish due to resource scarcity. Indeed, the U.S. energy and fuel mix went through two dramatic transitions within a century [3]. First, coal toppled wood as the main component of the U.S. fuel base roughly between 1850 and 1895. The share of wood in the fuel base went from about 90 to 30 percent, while coal's soared from 9 to 65 percent. In turn, oil and gas replaced coal between roughly 1910 and 1955. Within the span of four and one-half decades, the share of coal declined from 77 to 28 percent, while the combined share of oil and gas increased from 9 to 65 percent (Figure 1).

After examining recent developments in transportation as well as past technology transitions, we conclude that oil as the main fuel for transportation and a major energy source in general could have a much shorter life span than many assume. Like wood and coal in the past, a demand-driven switch away from oil could happen in the not-too-distant future. In our projection, this switch could happen in the next 10 to 25 years as electric cars replace motor vehicles just as motor vehicles displaced horses a century ago. Oil would lose its role as the main fuel for transportation. Coupled with the ascent of renewables for power generation, oil prices could converge to the level of coal prices, about $15 per barrel in 2015 prices by the early 2040s in the fast adoption scenario. In the slow adoption scenario, this could take a further 10 to 20 years. A fast energy transition may seem unlikely, but as the renowned futurist James Dator remarked, "decision-makers, and the general public, if they wish useful information about the future, should expect it to be unconventional and even shocking, offensive, and seemingly ridiculous [4]."[2] This could be the last age of oil, in which oil becomes the new coal.

A process of technological transition could very well upend the oil sector. Grubler, Nakicenovic, and Victor (1999) summarize the critical technological transition process: a successful learning curve, based on learning-by-doing and economies of scale, results in declining costs, while a logistic diffusion model exploiting network effects characterizes adoption, allowing technology to become "locked-in [5]." There have been several recent analyses regarding the formative phases of new technologies [6], prospects for a future energy transition [7], and resulting policy implications [8].

The first contribution of our paper is our forecast of electric vehicles (EVs) based on motor vehicle-horse displacement and further confirmed by the Bass diffusion model. We also examine the main hurdles to EV adoption, drawing a parallel with the hurdles facing mobile phone

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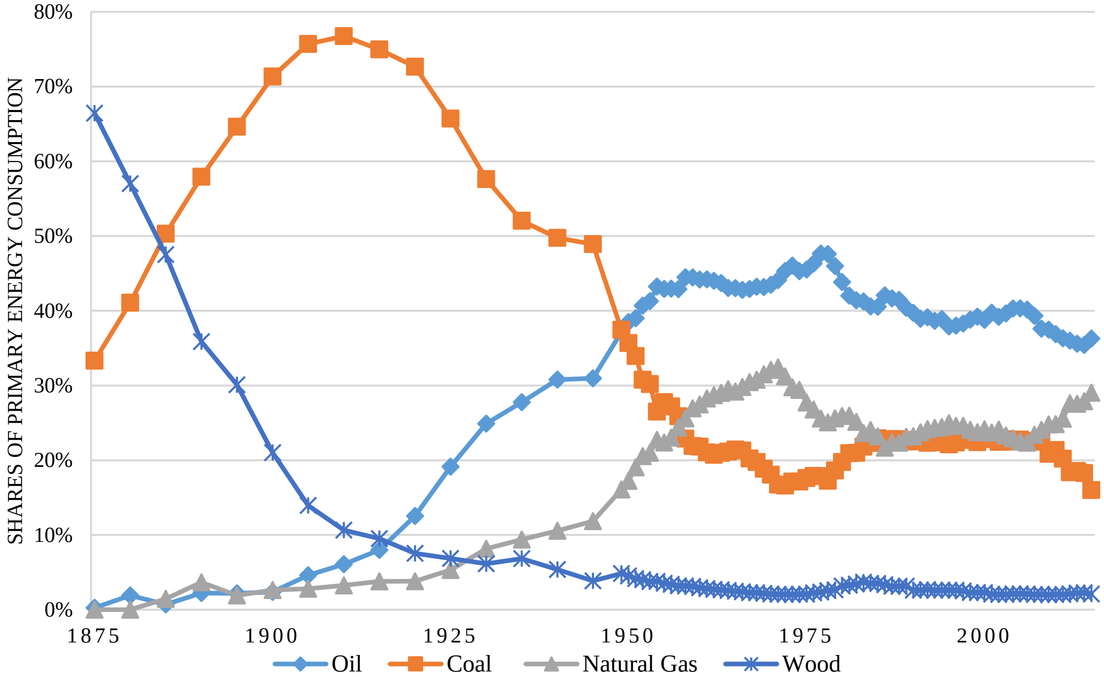
[1] "It is an empirical regularity that, for both oil and natural gas at any point in the last 30 years, the world has 50 years of reserves in the ground. The corollary, obviously, is that we discover new reserves, each year, roughly equal to that year's consumption. This phenomenon seems to be independent of the enormous variation in fossil fuel price changes over the last 30 years [55]."

[2] Also known as Dator's second law.

adoption in its early days. The second contribution of our paper is the quantification of the resulting impact of this technological transition on the global oil market, both in terms of long-term demand and prices. To the best of our knowledge this has not been done in the literature.

The sections of the paper are as follows: first, we describe the historical parallels and prospects for a technological transition in transportation, which we demonstrate is the most critical component of oil demand. We examine the United States as our main test case for EV adoption both because of its large size and the availability of data. We then advance a plausible thesis regarding the future of oil prices.

Figure 1: Primary Energy Consumption Shares (USA, 1875-2015)



Source: U.S. Energy Information Administration (EIA) (2012) and U.S. EIA Open Data [9,10]. See Appendix.

II. TRANSPORTATION REVOLUTION AND THE RETURN OF THE ELECTRIC CAR

A. Horse vs. Car: An Historical Parallel

A century ago, the rise of oil came largely as the result of a transportation revolution as horses were rapidly superseded by automobiles. The next transition away from oil is likely to come again via a transportation revolution as 57 percent of global oil demand comes from transportation (70 percent in the U.S. in 2018 [11]). Road transportation alone accounts for 44 percent of oil use.[3] In per-capita terms, the penetration of the electric car in the U.S. follows that

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[3] The rest, using Organization of the Petroleum Exporting Countries (OPEC) categorizations is petrochemicals (11 percent), industry (iron, glass, steel, cement, mining, and construction, 15 percent), residential/commercial/agriculture (10 percent), electricity generation (7 percent), and rail/shipping/aviation (13 percent, included in transportation) [13].

of the motor vehicle[4] remarkably closely in the early stages despite a century separating the two (Figure 2).

Interestingly, electric cars made up one-third of the total automobile stock of the United States in the year 1900. Quiet, easy to handle, and appropriate for urban transit, demand for electrics even drew the attention of luminaries like Thomas Edison and Ferdinand Porsche, the latter developing the first hybrid vehicle in 1901. Electric vehicles enjoyed prominence through 1910. It was the rapid rise of a new industry leader that pushed electric cars out of the market—the affordable Ford Model T. Faced with a Model T retailing at about 40 percent of the electric car's price by 1912—combined with a growing road network and the relative ease of expanding gasoline stations in rural areas compared to the electric grid, as well as new oil discoveries that made oil relatively cheap—the electric car could not compete. It had essentially disappeared by 1935 [12]. Yet the electric car appears poised for a comeback.

The disappearance of cart horses gives us some insight into what a transportation transition could look like (Figure 2). In the span of 15 years from 1915 to 1930, cart horse ownership fell by a factor of 10. Such a fall is not a commonly anticipated scenario for cars. However, it need not be so substantial to have a major impact on the oil market. Oil today is far more dependent on transportation than coal was in 1910 or 1930. While nearly 62 percent of oil use in the Organization for Economic Co-operation and Development (OECD) countries involves cars, trains, boats, and planes [13], coal consumption a century ago was only 20 percent reliant on the transport sector—mainly steamships and rail [14].

Although projections of the number of electric vehicles globally show a large increase, there are wide differences in the forecasts. In its 2015 World Oil Outlook (WOO), OPEC predicted only 6 percent alternative fuel cars worldwide by 2040 [13]. Its 2019 WOO report significantly revised that figure to 18 percent [15]. Bloomberg New Energy Finance (BNEF) estimated in 2016 that there would be 7.4 million electric vehicles on global roads by 2020, eventually representing 25 percent of all cars by 2040 [16]. Their 2019 report subsequently revised this figure up to 31 percent. For its part, the IEA projects 130 million global EVs by 2030 in its most recent central scenario (Global EV Outlook 2019). Another report by Carbon Tracker and the Grantham Institute at Imperial College London projects a 19 percent share of electric vehicle by 2030 and 55 percent by 2040 (in their "Weak_EV" scenario) [17]. Becker et. al. (2009), using a diffusion model, predict that EVs would represent about a quarter of the total stock of vehicles by 2030 [18]. When explained explicitly, most projections use the data available on EV adoption and battery cost reduction to extrapolate into the future (e.g. BNEF) or various multinomial logit and diffusion models [19,20].

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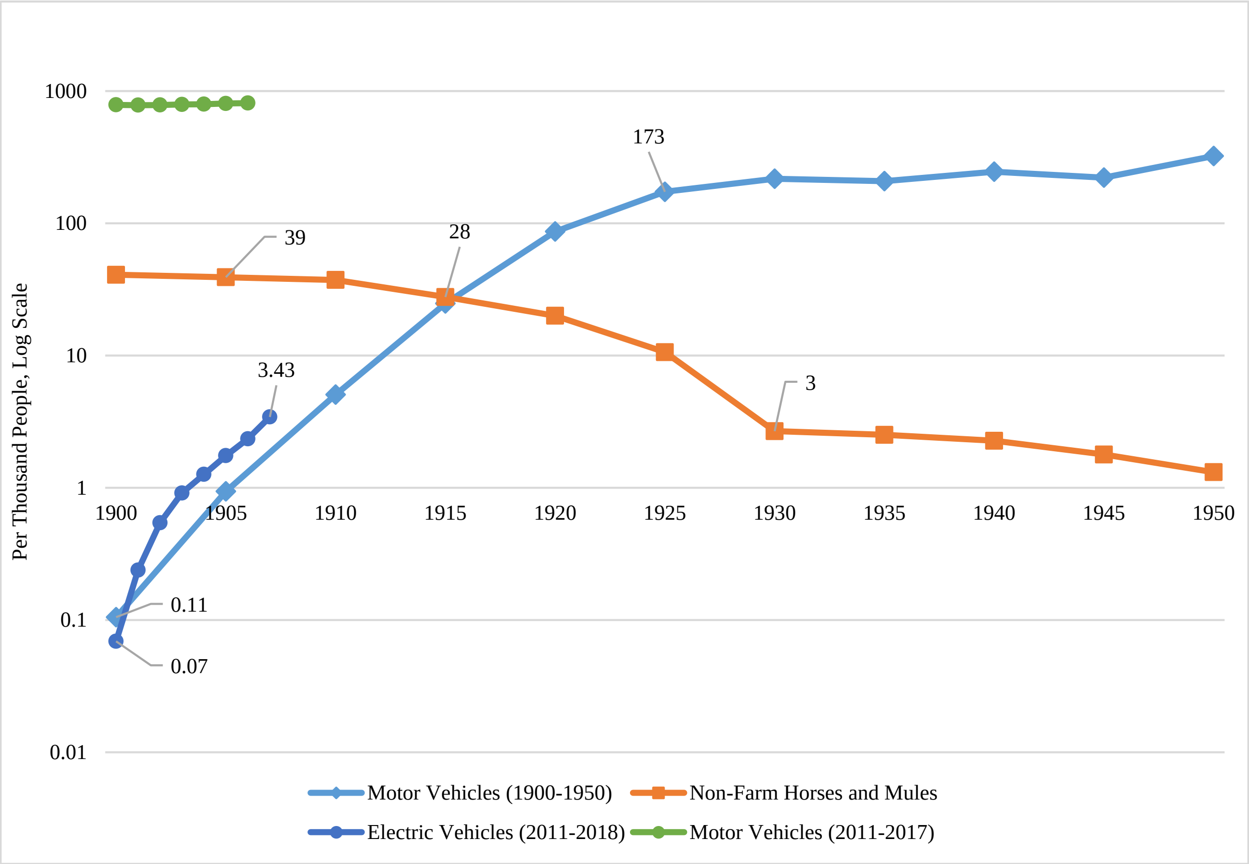
[4] The stock of motor vehicles is approximated by the total number of motor vehicle registrations (including buses and light trucks).

Figure 2: Motor Vehicles vs. Horses (USA)



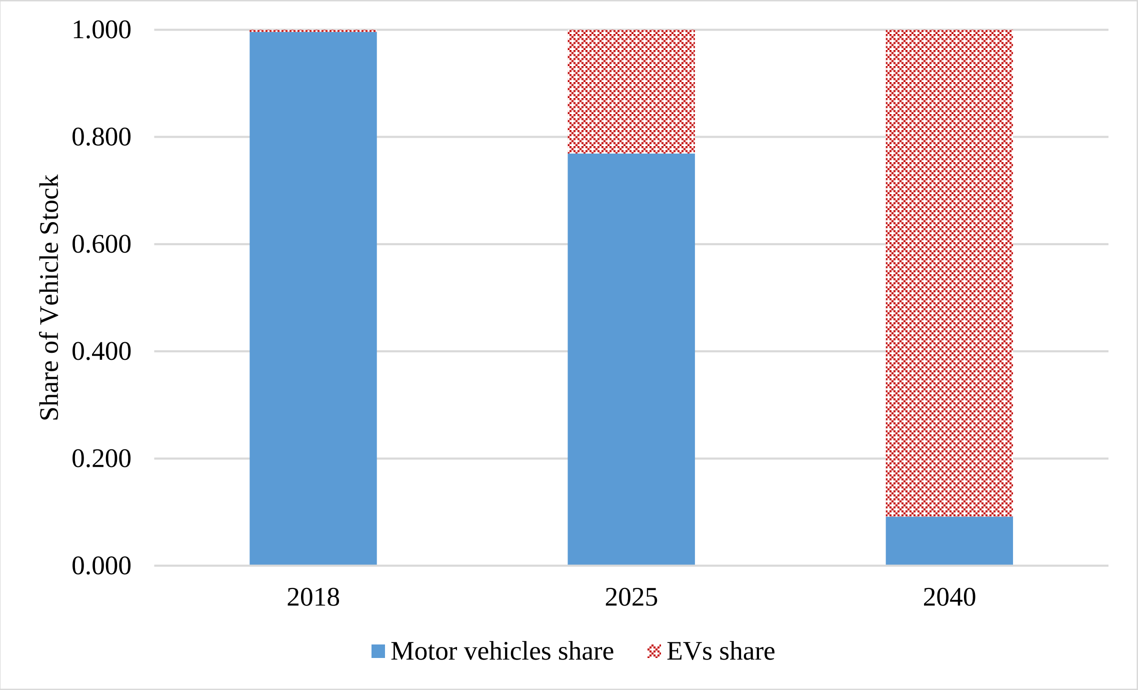
Note: Electric car graph line starts in 2011. Note the log scale on the Y-axis.
Source: Fisher (1974) for horse data, FHWA, OECD/IEA (2019), and Census Bureau [21–25].

We approach forecasting EVs from several perspectives. First, we use the horse-car transition pattern that happened a century ago to extrapolate EV adoption, and we verify that our extrapolation matches the data on EV adoption between 2011 and 2018. Second, we project the number of EVs using a diffusion model widely used in management science to predict the adoption of new technologies. Finally, we discuss the hurdles to adoption of EVs—in particular, the affordability of EVs compared to motor vehicles (MVs). We argue that these hurdles are disappearing, lending credibility to our conjecture that EVs could displace motor vehicles as motor vehicles displaced horses a century ago.

We study the horse-car transition that began about a century ago between 1905 and 1930. Our main goal is to project the ownership of motor vehicles in the next few decades. In Method I (Figure 3), the fast adoption scenario, we translate the horse displacement in the early 20th century to motor vehicle displacement today. Between 1905 and 1915 the ownership of horses per thousand people fell by about 30 percent. In the following fifteen years (1915-1930), horse ownership fell by 90 percent. If starting in 2016, the motor vehicle displacement follows the same pattern, we project that within a decade the ownership of motor vehicles in the U.S. would decline by 30 percent. Then in the next 15 years, the ownership would further fall by another 90 percent.

Considering one-to-one displacement of a motor vehicle by an electric vehicle, we compute the adoption rates of electric vehicles. This scenario implies an average annual growth rate of EV ownership per 1000 people of about 70 percent for the first ten years, followed by an average annual growth rate of about 8 percent for the following fifteen years (corresponding to an average annual growth rate of about 30 percent over 25 years). These projections are consistent with the recent growth of EVs. Between 2011 and 2018, the average annual growth rate of ownership was 75 percent (Figure 2). In addition, the adoption of EVs does not necessarily have to match the motor vehicle decline. The advent of self-driving cars, ride-sharing and improved public transportation could still contribute to the decline in motor vehicle ownership at the projected rates.

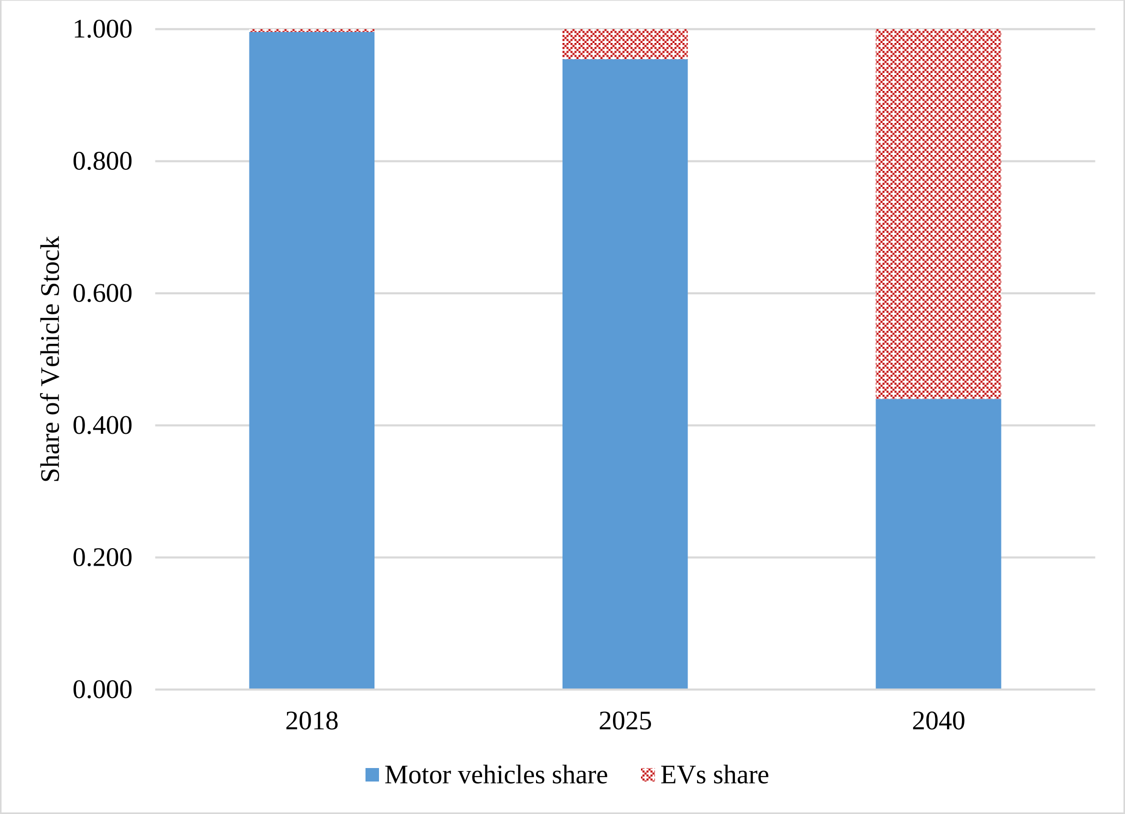
Figure 3. Electric Vehicle Penetration Projection: Method I



In Method II (Figure 4), the slow adoption scenario, we project motor vehicle ownership in the US using the growth rate of motor vehicles at the beginning of the 20th century to project the rise of EVs. This method yields an average annual growth rate of EV ownership of 26 percent from 2018 to 2040. As a result, this method implies much lower estimates of motor vehicle displacement (an average annual rate of decline of 3 percent).

In terms of shares of total vehicles, Method I yields a much faster decline in the shares of motor vehicles than Method II and most other studies. Method I implies 23 percent displacement by 2025 and 91 percent by early 2040s. Method II yields a slower displacement rate (5 percent displacement by 2025 and 56 percent by 2040), which is closer to most of the other studies cited above. Ninety percent market saturation would be reached after a further twenty years, using the growth rate of motor vehicle adoption over 1945-1955 (instead of 1930-1945, to exclude the Great Depression and WWII).

Figure 4. Electric Vehicle Penetration Projection: Method II



B. A Diffusion Model for Electric Cars

Our predictions based on the horse displacement by MVs are within the range of estimates of a standard diffusion model. The Bass Diffusion Model is widely used in the literature to predict the rise of new technologies and products [26].[5] In this model, adopters can be classified as innovators or imitators. Innovators lead the adoption of a new technology or a product, while imitators follow with increasing numbers over time. Eventually, the number of new adopters starts falling as the market reaches its full potential.

Modeling the behavior of each type, Bass (1969) arrives at a simple differential equation describing the overall adoption of a new product:

$$\frac{f(t)}{1-F(t)} = p + qF(t), \tag{1}$$

where *F(t)* represents the cumulative fraction of the potential market that is achieved at time t; *f(t)* represents the density function of adoption associated with *F(t)*, or the marginal change in adoption; *q* is the coefficient of imitation; and *p* is the coefficient of innovation [26]. In the context of the displacement of MVs by EVs, *F(t)* represents the fraction of EVs of the total of all

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[5] The Bass (1969) article is considered as one of the most influential papers in the 50-year history of *Management Science*, and one of the most widely used to forecast the adoption of new technologies [75].

vehicles (MVs and EVs combined). We assume that the potential market for EVs is the whole market for vehicles. The solution of the differential equation (1) is given by:

$$F(t) = \frac{1-e^{-(p+q)t}}{1+\frac{q}{p}e^{-(p+q)t}} \tag{2}$$

We estimate equation (1) to obtain coefficients *p* and *q* using the OLS regression on annual data from the U.S. EV market. The estimate of intercept *p* is close to zero (about 0.000017), and the estimate of slope *q* is equal to 0.44. Our 95 percent confidence interval is 0.34-0.53. The sample is very limited (10 years), but the estimates are in fact in line with the recent studies estimating the Bass model to project the adoption of EVs.[6] Becker et. al. (2009) and Davidson et. al. (2013) use a coefficient *p* between 0.01 and 0.02 and *q* of 0.4 [18,27].[7] They cite Mahajan et. al. (1995), who review numerous applications of the Bass model and find that *p* is typically between 0.01 and 0.03, while *q* is on average close to 0.4 [28]. Our estimate of *q* (0.44) is close to their finding. However, our estimate of *p* is conservative as it is several orders of magnitude below that of Becker et. al. (2009). The saturation of the market by EVs would happen much earlier if we were to replace our estimate of *p* by those in these studies. Becker et. al. (2009) model a low-oil price scenario that could delay the transition by assuming a smaller *p*, which is still several orders of magnitude greater than our estimate [18].

Using the point estimates we obtain for *p* and *q* and starting with the available data in 2015, the model predicts that by early 2040s, EVs would represent about 90 percent of the vehicles' stock, which is in line with the projections of Method I at the same horizon (Figure 3). Becker et. al. (2009) project EVs to represent 24 percent of the existing automobile fleet in the U.S. by 2030s, which is close to our Method I projection (Figure 3) [18]. Using instead the lower end of the confidence interval for *q*, which is 0.34, the share of EVs in the stock of total vehicles is projected at 44 percent by early 2040s, which is close to the EV share predicted by Method II (Figure 4). The market would reach 90 percent saturation around 2050. The only difference between the predictions of the historical model and the Bass diffusion model is that in the diffusion model, the ownership of EVs starts spiking only in the 2030s at a very fast pace. However, it does not affect our ultimate prediction for the price of oil by the early 2040s.

C. Disappearing Hurdles on the Road to Motor-Vehicle Displacement

In many ways, the skepticism towards the potential adoption of EVs is reminiscent of the early days of the cell phone market. In the early 1980s, McKinsey produced a report for AT&T on the potential world cell phone market. The report identified big hurdles to the adoption of cell phones such as bulkiness of the handsets, short duration of the battery charge, high cost per minute, and lack of coverage. The report predicted a market of 900,000 cell phones by 2000 [29]. The actual number turned out to be 120 times larger than forecast at 109 million phones [30].[8] In addition, the spread of smartphones—albeit far easier to adopt than transportation innovations—

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[6] See Massiani and Gohs (2015) for a survey of the literature estimating Bass diffusion models for the adoption of new automotive technologies, including EVs [76].

[7] Using Norwegian monthly data, Jensen et. al. (2014) find a coefficient *p* of 0.002 and *q* of 0.23 for the Bass model on a monthly frequency [77].

[8] The data source is CTIA, the wireless association.

shows how rapid direct substitution of a superior technology can be. Sales witnessed a rapid rise from 10 percent to 75 percent of the market in a mere 8 years [31–36].

Similar obstacles –high cost, lack of infrastructure, and short-range—face early adopters of EVs. However, these hurdles seem to be disappearing, lending support to the projected rise of electric cars.

Vehicle adoption is strongly associated with the ability to offer an affordable price. The large fall in prices in the early 1900s, thanks to the economies of scale and process innovations made by Ford, is closely matched by a rise in motor vehicle registrations. To make a relevant comparison of affordability across time, we compare the cost of motor vehicles of a representative model relative to a proxy for the average annual income, namely GDP per capita. By multiplying the ratios by GDP per capita in 2015, we obtain a measure of the affordability of motor vehicles given average income in 2015 as shown in Figure 5.[9]

Figure 5 confirms that the relative prices of Ford vehicles fell sharply from about $137,000 in 1910 to about $33,000 in 1917, coinciding with the onset of the rapid rise in motor vehicle ownership in the U.S. This was also the period when motor-vehicle ownership matched that of horses before MVs completely displaced horses within a decade or so (Figure 2). In comparison, unsubsidized prices for Tesla (and other EVs) seem to be converging towards the Model T's price threshold.[10] These prices suggest that Tesla seems to be better positioned compared to the Model T at a similar rate of market penetration. At about $35,000, the announced price of Tesla's Model 3 is at the threshold price of Ford Model T, at which the adoption started accelerating rapidly. The Model T was undoubtedly the anchor of the burgeoning American auto industry; by 1914, Model T production "topped 300,000, almost double the previous year's and greater than all other American automobile manufacturers combined [37]." More important, the price of Model 3 at $35,000 was about the average price of a new car sold in the U.S. in 2015.[11] With comparable prices, it seems the electric car industry is about to pass a turning point, justifying further our inference based on horse displacement.[12]

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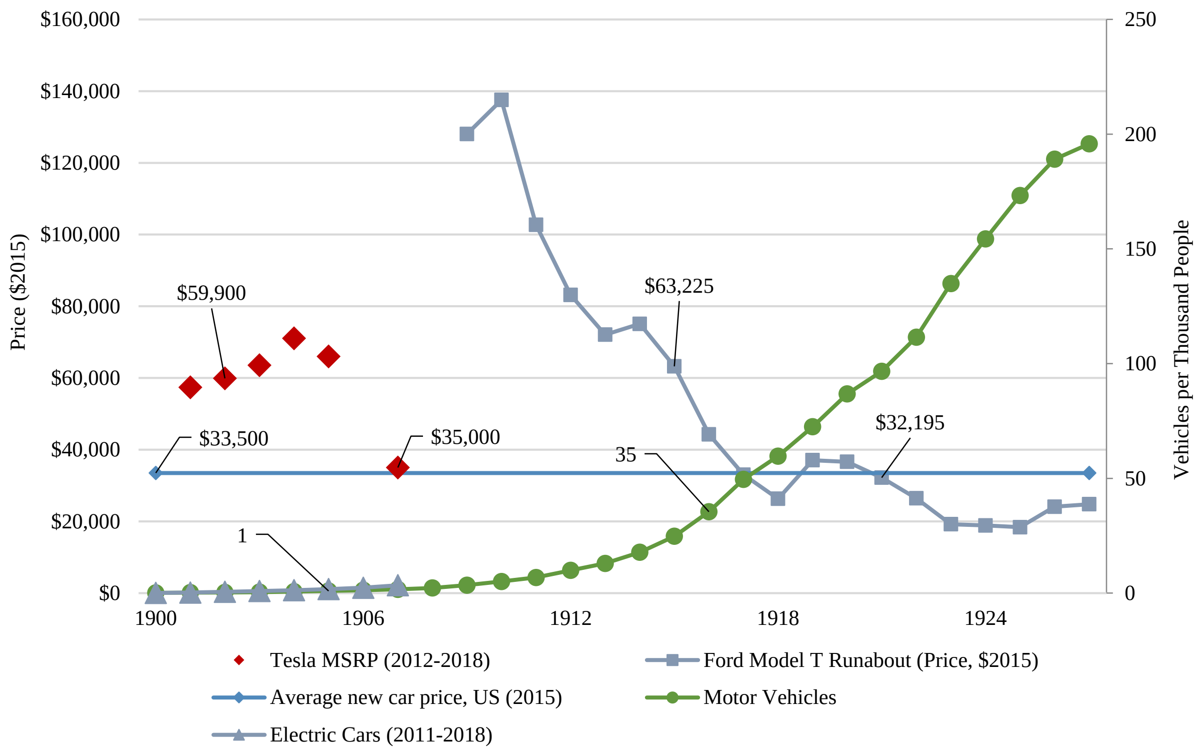
[9] In other words, prices are deflated using nominal GDP per capita (base of 2015), e.g.
$\frac{\text{Nominal Model T Price,1910}}{\text{Nominal GDP per capita,1910}} * \$55{,}805_{\text{ US Per capita GDP 2015}} = \$137{,}530$. [38,78,79]

[10] The Runabout was consistently the Model T's cheapest version, presenting the least-favorable comparison for Tesla [38].

[11] The average price was about $33,500 in 2015 [39].

[12] The average age of automobiles and light trucks in the U.S. was 11.4 years in 2014 [80], and annual sales in 2015 in the U.S. were more than 17 million vehicles for a stock of about 250 million [22,39]. McKinsey estimates a full stock turnover of 15-20 years [18].

Figure 5: Electric and Motor Vehicles Adoption and Prices



Sources: Collins (2007), FHWA, OECD/IEA (2019), NADA (2015), Census Bureau, and Tesla prices: Tesla (2012), Davies (2014), Quiroga (2015), Fleming and Peltz (2016), Randall (2016) [22,23,44,24,25,38–43].

Battery costs, which represent the main barrier to electric vehicle commercialization, are rapidly declining. As Nykvist and Nilsson (2019) show in their widely-cited metastudy, average vehicle lithium-ion battery costs have fallen from $1000/kWh in 2007 to $230/kWh in 2017—approximately by 16 percent per year (see also Andwari et. al. 2017, Kumar and Revankar 2017, and Manzetti and Mariasiu 2015) [45–48]. Such an exponential trend is expected to continue, as further learning coupled with economies of scale make Li-ion batteries at $100/kWh by 2025 a serious possibility. Bloomberg New Energy Finance's 2019 Battery Price Survey expects this milestone by 2024 [49], a critical one for electric vehicle cost parity with conventional vehicles, as does Nykvist & Nilsson (2019)'s central projection. Moreover, the availability of lithium needed for scaling up the production of EVs may not be a binding constraint given the current world lithium reserves and expected technological improvement in battery production and recycling.[13] In the medium to long run, lithium may not be even needed to produce batteries. For example, the co-inventor of the Li-ion battery, John Goodenough, and his team announced that they discovered a more efficient and safer battery technology that used widely available sodium as opposed to lithium [50].

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[13] With economically recoverable lithium reserves of 13 million tons and the average lithium needed per EV battery pack of 16 kilograms, about 800 million EVs could be produced compared to about 1 billion passenger cars worldwide [13,51]. Given the current world reserves of over 39 million tons, 2.4 billion EVs could be potentially produced [51].

Lifetime cost competitiveness is also paving the way for the adoption of electric vehicles. The IEA estimates that it has already been achieved [51]. Analysts at Bloomberg New Energy Finance and Cambridge Econometrics predict cost competitiveness for battery electric vehicles by 2022 and 2025, respectively [52,53]. In 2015, the average EV was already about 2.7 times cheaper to fuel compared to the average motor vehicle, with an equivalent 67 miles per gallon (mpg), compared to an average 25 mpg for motor vehicles.[14] The mpg-equivalent for a Tesla was about 90. In addition, as EVs contain many fewer moving parts than motor vehicles, the maintenance cost for EVs is 10 to 100 times cheaper than that for MVs [30].

The lack of supporting infrastructure may not be a major hurdle as it did not seem to have hampered the expansion of motor vehicles in the early 20th century. If today's problem is the lack of charging stations, the issue a century ago was far more challenging: the development of not only petrol stations, but also properly surfaced roads.[15] Nakicenovic (1986) indicates that fast growth of motor vehicles happened despite the lack of infrastructure when less than one-half of all U.S. roads were deemed useful for motor vehicles. In fact, the infrastructure growth came in parallel with the motor-vehicle growth after the 1930s [54].

The potential increase in demand for electricity because of a significant rise in EVs would have been only a fraction of electricity consumption in an advanced economy in 2015. Covert, Greenstone, and Knittel (2016) estimate that, on average, 15,000 miles/year driven by a vehicle with a fuel economy of 0.3 kWh/mile yields 4,500 kWh/year/vehicle [55].[16] The total electricity needed to power about 100 million electric vehicles (about the number of EVs in the U.S. by the early 2040s, according to Method II) would represent about 450 TWh of electricity (1 TWh is equivalent to 1 billion kWh). For comparison, the U.S. generated about 4,000 TWh of electricity in 2015[17], which means that in 2015, generating electricity to power 100 million EVs in the U.S. would require increasing the U.S. electricity production by about 11 percent. This is not a negligible increase, but it is certainly feasible. By the same reasoning, if the whole stock of motor vehicles in the U.S. were transformed into electric vehicles in 2015 (about 253 million vehicles), it would require increasing the production of electricity by about 30 percent. Moreover, if all this extra electricity were generated by oil[18], it would require 5.4 million barrels per day (mbd), compared to 9 mbd used to produce gasoline in 2015.[19] In other words, with the available technology in 2015, switching all motor vehicles to electric vehicles and generating all the electricity needed to power them from oil alone would still have decreased U.S. demand by 3.6 mbd in 2015 (see also Poullikkas 2015) [56].

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[14] Calculations are based on an average retail price of electricity of 12 cents per kWh, an average efficiency of 0.3 miles per kWh for the Nissan Leaf, and an average retail gasoline price of $2.40 per gallon.

[15] A looming environmental crisis—the veritable sea of horse manure blanketing the world's cities—was the subject of the first global urban-planning conference in 1898 [81]. New York in 1900 had 100,000 working horses [82], each producing 22 pounds of manure daily. Commentary of the time predicted a Manhattan laboring under manure piles, towering three stories high by the year 1930. Then, almost magically, the problem disappeared—thanks to the automobile [81].

[16] Trancik et. al. (2016) find that the Nissan Leaf has a fuel economy of 0.3 kWh/mile. Nissan Leaf is estimated to be between Chevy Volt and Tesla when it comes to fuel economy [57,83].

[17] See U.S. EIA [84].

[18] Ibid. According to EIA, 0.00173 barrels are required to produce 1 kWh of electricity.

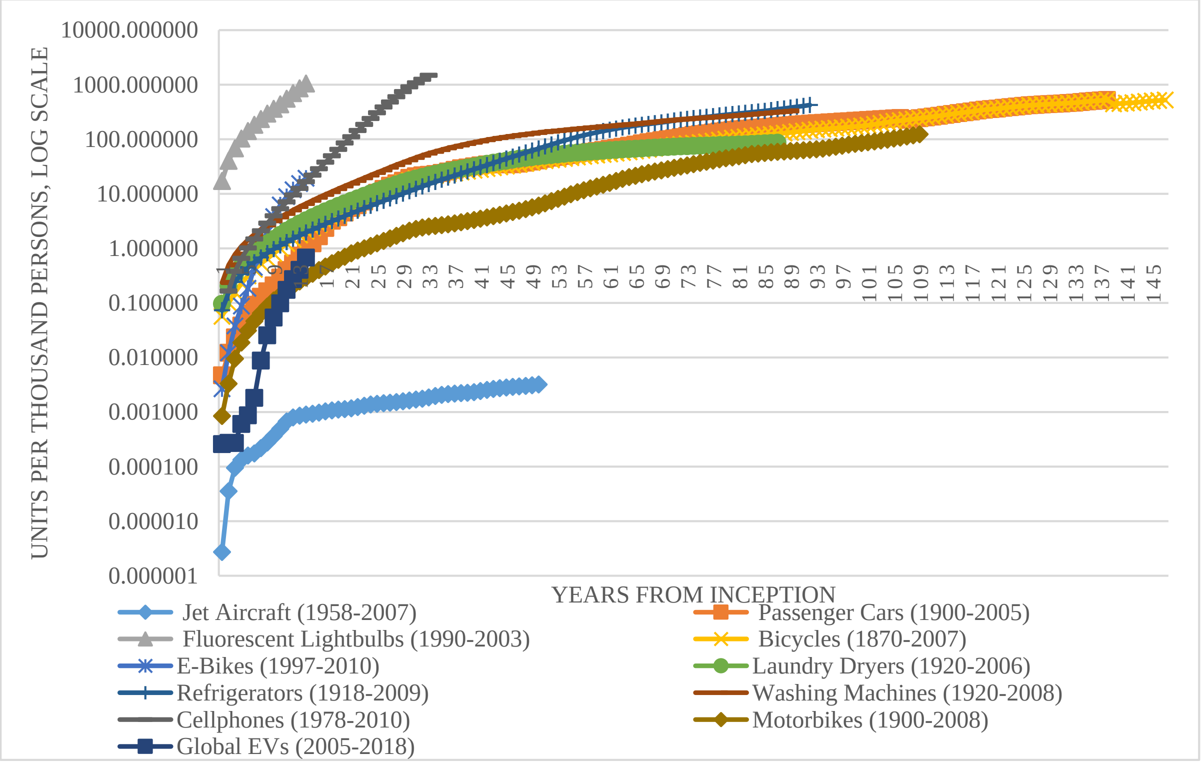
[19] See U.S. EIA [85].

Finally, recent research on micro-level driving patterns suggests that nearly 87 percent of daily trips taken in the U.S. are short enough to be made with an *existing* electric vehicle. Essentially, 60 percent of gasoline consumption, even without further improvements in electric vehicle range (and totally ignoring the penetration of partial hybrid EVs), could be theoretically replaced in 2016. "Range-anxiety", it seems, is a far more psychological than technical problem [57].

D. Electric Cars and Adoption of Other Technologies

In absolute terms, the expansion of global electric car stock has kept pace with the growth of other major consumer technologies. About a decade from inception, electric cars have expanded faster than motorcycles, motor cars, and electric bikes (Figure 6). It is true that global development levels are far higher than they were in the early days of the motorcycle or washer machine. But this offers cause for optimism—current innovations seem to diffuse faster than in earlier eras. VCRs, cell phones, and microwaves all went from 10 percent to 80 percent market penetration in the U.S. within a decade, a speed matched only by radio in the early 20th century. Color televisions did the same from 1970 to 1980, while refrigerators took two decades (1930-1950) to reach 80 percent of the population [58]. Motorbikes and electric bikes tell a similar story, with diffusion of recent technologies outpacing diffusion in the past. US EV penetration shows a pattern that resembles more the most recent technological adoptions.[20]

Figure 6: Global Consumer Technology Penetration



Source: Bento and Wilson (2016), OECD/IEA Global Electric Vehicle Outlook (2019), and Maddison (2009) [6,23,59].

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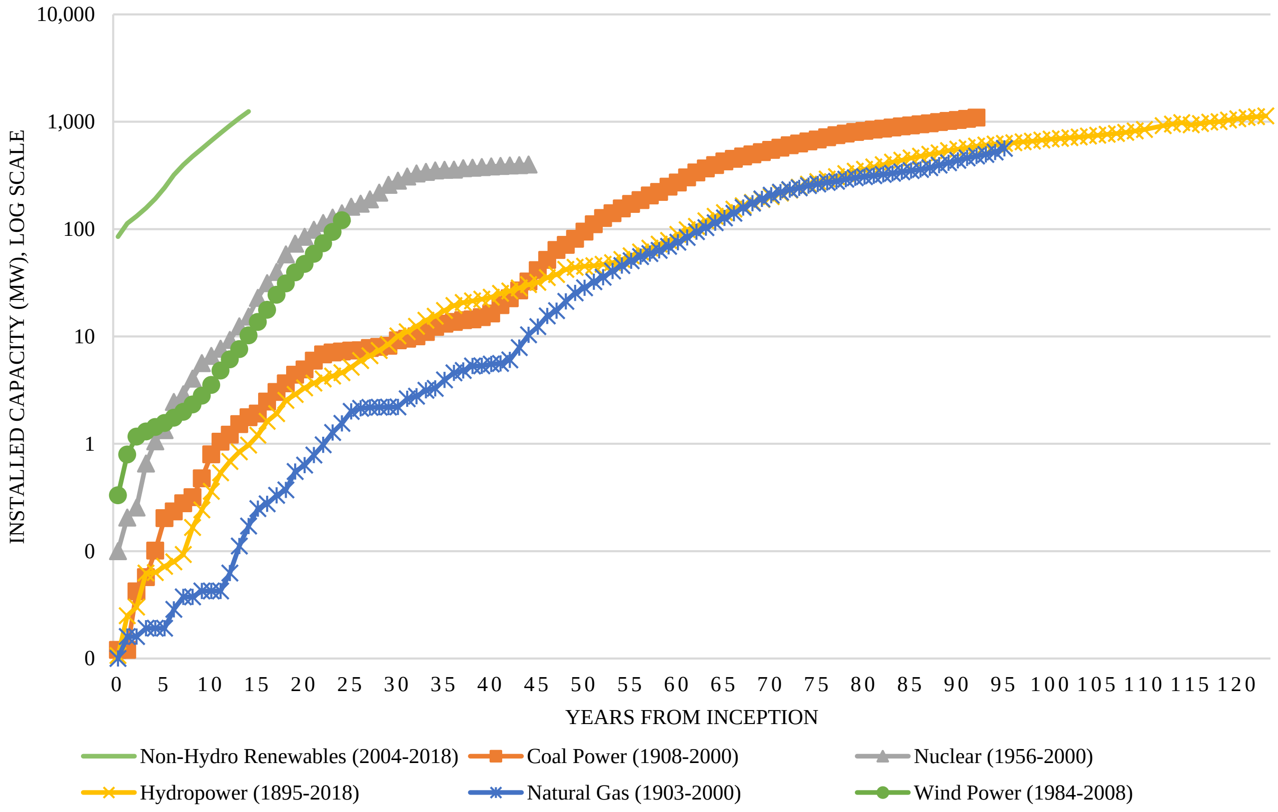
[20] Nagy et. al. (2013) estimate technological adoption using data for various technologies and show that the production increase broadly follows an exponential function. For instance, the annual average growth of DRAMs and hard disk drives was 26-28 percent while for wind electricity it was about 20 percent [86].

III. THE SWEEP OF RENEWABLES

Renewable energy capacity seems to be following the log-linear trend of previous power technologies (Figure 7). In 2015, total global renewable power capacity (inclusive of hydropower) finally outstripped coal-fired power capacity. Renewables are now projected to make up 28 percent of global power generation by 2021 [60]. Unsubsidized solar and wind, already competitive in 30 countries, is projected to become cheaper than coal and natural gas in over 60 percent of the world in the next few years [61]. Solar power could become the leading source of electricity worldwide by mid-century [62] with costs falling by 60 percent by 2040. Combined with a 40 percent reduction in wind energy costs, Bloomberg New Energy Finance projects 60 percent of global power capacity in 2040 as non-fossil fuel [63]. Although oil use mostly involves the transportation sector, power generation still plays a significant role, making up 7 percent of total oil consumption [13]. Most current generation takes place in the oil-rich Middle East, but even this is disappearing as the Gulf states begin to transition to renewable energy.

Figure 7: Global Diffusion–Power Technologies



Sources: Bento & Wilson (2016) , Renewable Energy Policy Network for the 21st Century [Ren21] (2014, 2016, 2017, 2018, 2019).

The main objections raised against solar and wind viability center around capital cost and the current lack of storage capability for such intermittently available electricity. Photovoltaic panels are already benefiting from economies of scale—photovoltaics' levelized cost of energy[21] has fallen 90 percent since 2009. Wind power's levelized cost has also fallen approximately 70 percent [64]; both technologies are competitive *without* subsidies in some areas of the U.S.[22] MIT's Energy Initiative (2015) finds that a full 65 percent of utility-scale solar costs in 2015 were non-module related expenses (module corresponds to panels, while non-module or "soft cost" corresponds to other installation costs). These installation and maintenance costs are expected to come down as the market grows—Germany, for example, provides solar power at a significantly lower cost even as module prices are roughly similar [65].

Intermittency concerns might also be surmounted in the foreseeable future. Lithium-ion battery costs continue to fall, and alternatives to lithium-ion (flow batteries, solid lithium) also look promising [66]. McKinsey projects that stationary storage prices will be halved by 2020, at roughly $200/kWh [67]. Combined with demand-response policies, a more interconnected grid, and complementary natural gas plants, this could effectively eliminate the intermittency problem.

Many countries are leading the adoption of renewables [68-70]. China, for instance, is advancing fast with the sheer scale of its transition. It accounted for nearly half of global wind [68] and a third of renewables capacity growth in 2015 [69]. On the transportation front, China alone has 40% of the world's electric vehicles, almost 2 million [70]. It remains to be seen how India handles the challenges of dizzying growth in energy consumption over the next few decades—total energy use is set to double by 2040. It has announced ambitious targets for wind and solar deployment (roughly 50 and 100 GW of additional capacity respectively by 2022 [71]), and plans to add 6-7 million hybrid and electric vehicles per year by 2020 [72]. But coal is still projected to make up 57 percent of power generation in 2040. Moreover, with passenger vehicle ownership at 2 percent of the population, transportation energy demand is set to more than triple by 2040, according to the IEA. Much will depend on the provision of public transportation and energy efficiency standards [71].

The rise of renewables follows the rise of oil. Although the coal share was substantial in the early 20th century, it nonetheless began falling over the following decades [75]. The dominant fuel can remain relatively stable for a significant period (about two decades in the case of coal), and the decline is (relatively) slow and linear in terms of energy use shares. Naturally, the decline in coal use for heating and power is not entirely attributable to oil—natural gas played an important role. But a shift in this sector can only worsen the prospects for oil as renewables take an increasing share of the electricity generation.

IV. OIL AS THE NEW COAL?

The advent of EVs would have profound implications for the global oil market in the future. As argued earlier, by 2025 the stock of motor vehicles in the U.S. (and by extension in other advanced—OECD—economies) would potentially decline by 23 percent (Method I). Then in the next 15 years, the stock of motor vehicles could fall by another 90 percent (Figure 3).[23] In terms

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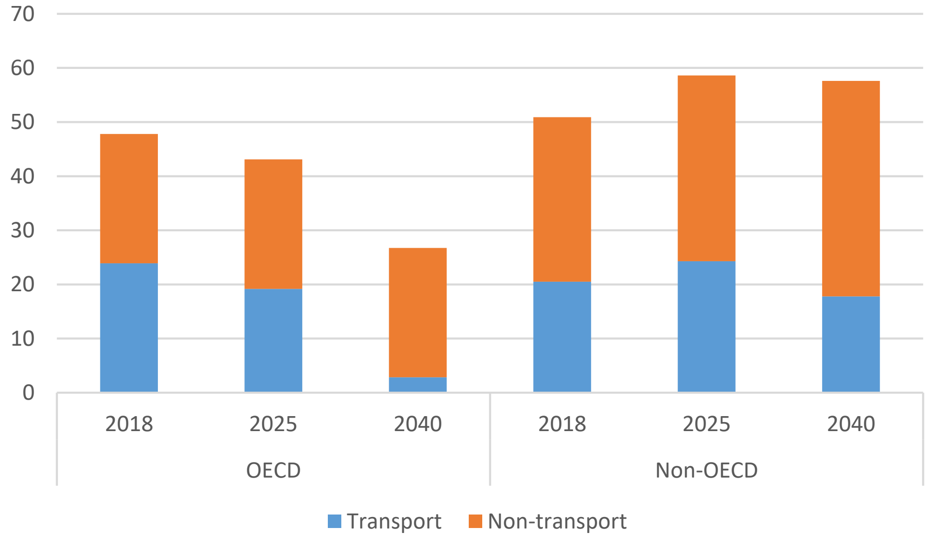
[21] It represents the average price of electricity needed to break-even over the lifetime of the generating asset.

[22] Notably Texas, the Midwest, and the Southwest [87].

[23] We use UN population projections for OECD and non-OECD countries, via OPEC (WOO 2019). We also use OPEC's total vehicle projections for the OECD. We assume a growth rate of 1% per annum for vehicles per-capita

of oil consumption in the transportation sector in OECD countries, this decline represents a decrease of about 5 million barrels per day (mbd) by 2025 and a further decrease of 16 million barrels per day by early 2040s.[24] Method II would imply constant transport oil demand through 2025 and then a fall of 13 mbd by 2040. The implied total drop in oil demand coming from transportation in advanced countries is about 21 mbd under Method I and 13 mbd under Method II by early 2040s. We also assume that oil demand for non-transportation sectors in OECD economies remains constant. Under both methods, we project a large drop in oil demand in OECD economies (Figures 8 and 9).[25]

Figure 8. Global Oil Demand Projections, Method I



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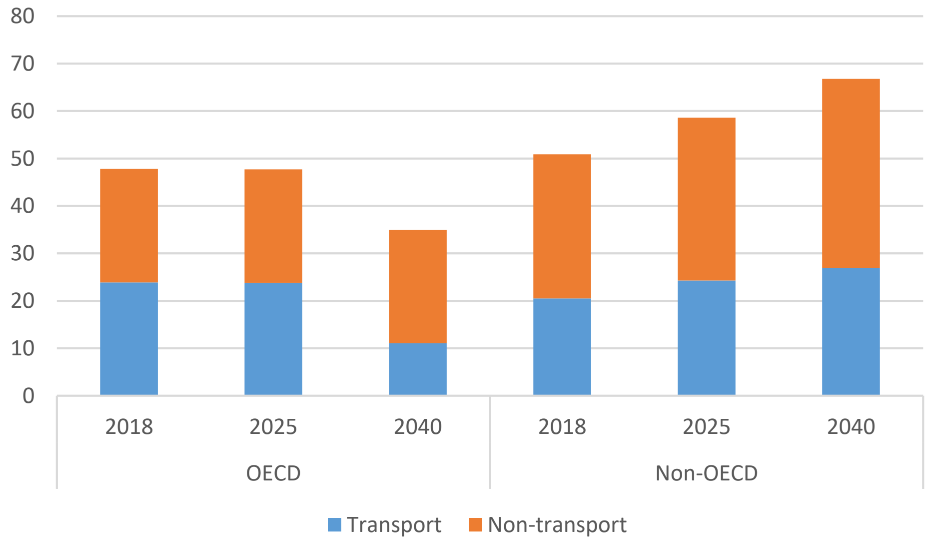
in the non-OECD countries from 2025 onwards (until 2025 we assume OPEC's total vehicle projections). Finally, we assume a growth rate of 1% p.a. for non-transport oil demand in the non-OECD after 2025, comparable to the WOO 2019's forecast of 1.2% for the same period.

[24] Given an initial demand for oil of 48 mbd for OECD countries, one-half of which goes to road transportation [88]. It excludes the aviation industry, which is not immune to the advent of electric planes, which are being developed by NASA, Airbus, and Boeing. Yet it includes heavy trucks, rail, and ships, which may be take longer to electrify than cars. If we exclude them from the oil consumption global share of road transportation, the share would be about 40 percent instead.

[25] The high energy density of oil is an important feature explaining its prevalent role in transportation. However, there is a trade-off between energy density and efficiency, maintenance cost, and pollution where EV technology is superior. These other characteristics could be a driving force in adoption going forward and in the long run innovation could in fact close the energy density gap.

Figure 9. Global Oil Demand Projections, Method II



We argue that the substantial drop in OECD oil demand may not be compensated by an increasing oil demand from emerging markets. If we assume conservatively an adoption lag of 10 years, we can use OPEC's (WOO 2019) projections for 2025, which suggest an increase in non-OECD total oil demand of about 15 percent (from about 51 mbd to 58 mbd).[26] In the following 15 years, using the fast adoption scenario (Method I) implies a drop in non-OECD oil demand for transportation of 3 mbd and a slight increase in total non-OECD oil demand by 7 mbd by the early 2040s compared to the 2018 level. Applying the slow adoption scenario of Method II after 10 years implies non-OECD oil demand for transportation would increase by about 6 mbd and total non-OECD oil demand would increase by about 16 mbd by 2040 relative to the 2018 level (Figures 8 and 9).

Oil demand could fail to decline by 2025 if Method II holds and other factors mitigate the effect on prices; for example, a drop in supply (although the development of shale technologies makes this possibility unlikely).[27] However, from 2025 to 2040, in the fast adoption scenario, global oil demand would fall substantially, by about 14 mbd from the 2018 level. In the slow-adoption scenario, it would rise by 3 mbd from the 2018 level.[28]

Beyond the expected decrease in the global demand for oil, the transportation revolution would also lead to a deep shift in the oil market configuration. Losing its role as

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[26] In fact, the EV penetration rate globally is not largely different from that in the U.S. In addition, China in 2016 was already the biggest market for EVs [23]. High-growth non-OECD economies, especially large economies such as China and India, would in fact adopt the latest energy and transportation technologies, i.e. renewables and EVs, as they would get richer, rather than rely on a 25-year old motor vehicle technology and continue consuming increasing amounts of oil (see Cherif, Hasanov, and Pande 2017 for more detail). It is equivalent to saying that economies like Ireland, Greece, Argentina or Taiwan Province of China were still using steamboats and steam trains in 1970, 25 years after the start of the decline of coal in transportation.

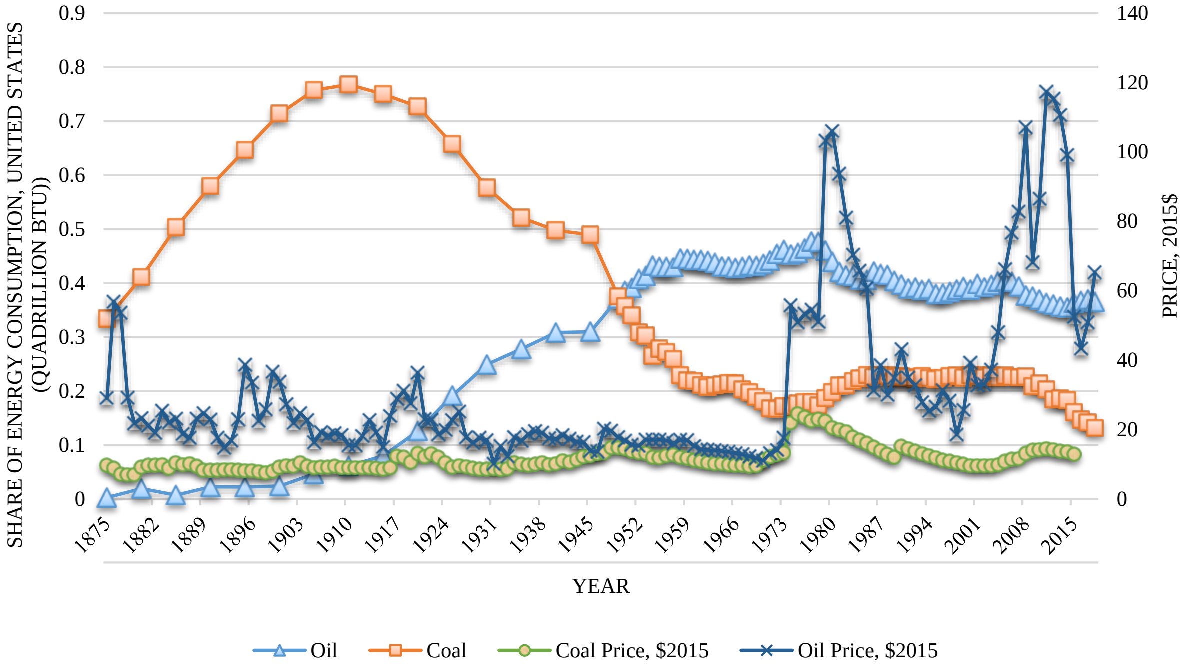
[27] For projections over the medium run, see for instance Benes et. al. (2012) and Arezki et. al. (2017), who use a model of global oil demand and supply and project an oil price increase by 2025 [89,90].

[28] In comparison, Carbon Tracker/Grantham Institute project about 16 mbd displacement while BNEF projects about 13 mbd displacement globally by 2040 [17,63].

essentially the only fuel source for road transport, oil would no longer be considered "black gold." While oil might still be used, it would have to compete as a close substitute in an already crowded energy market with natural gas, coal, nuclear, and renewable energy. Losing its exclusivity to fuel motor vehicles, oil could become the new coal, with ample recoverable reserves and elastic demand. In fact, at no point in history was the price of oil cheaper than the price of coal in terms of heat content per dollar—and yet, a major transition took place [29] (Figure 10).

Natural gas seems to have also become a widely available source of energy in the last decade due to huge discoveries of conventional gas all over the world, the rapid increase in LNG transportation that linked major markets, and the rise of shale gas in the U.S. and other economies since 2010. As coal and natural gas are close substitutes in heating and power generation, their prices should remain relatively close to eliminate any potential arbitrage opportunity. In fact, as shown in Figure 11, the premium of natural gas over coal has practically disappeared since 2010 in the U.S., and their prices seem to have converged in energy equivalent terms.

Figure 10: Quantities and Prices of Coal and Oil (USA, 1875 – 2018)



Source: EIA (2012), EIA Open Data, BP Statistical Review, and McNerney et. al. (2011) [9,10,73,74].

In a scenario where oil loses its role as the main fuel for transportation, oil price should eventually drop substantially and converge to a level around 15 dollars per barrel in 2015 prices, along with coal and natural gas (Figure 11). In the fast adoption scenario, we project that this could happen by the early 2040s, and in the slow adoption scenario, it may take another ten to

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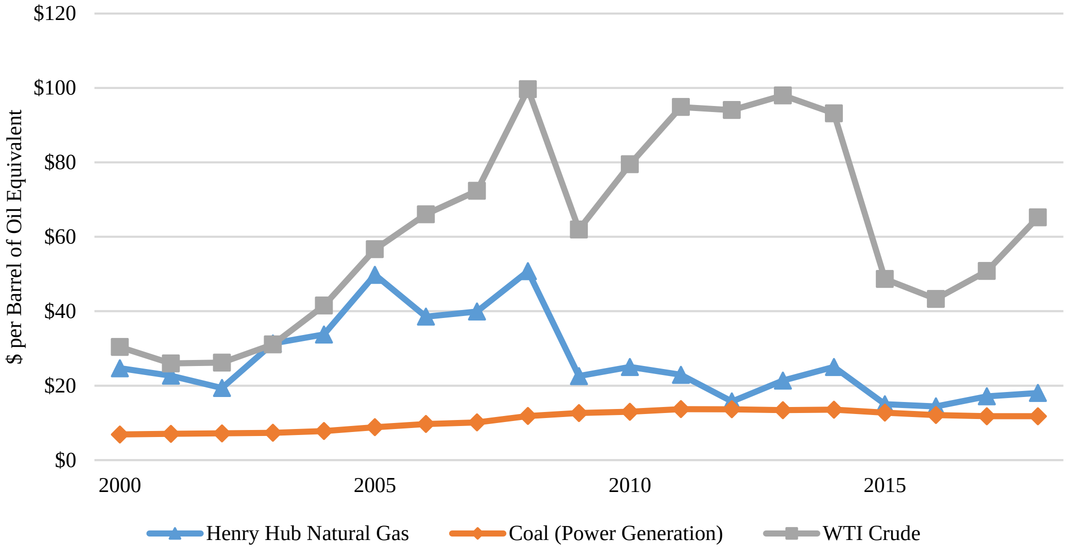
[29] Data from EIA, BP Statistical Review, and McNerney et. al. (2011). Note the small discontinuous jump in coal price in 1990. This represents the beginning of the EIA data series, which does not match exactly with those in McNerney et. al. (2011). The trends, however, still hold true [74].

twenty years depending on whether the lower end of the confidence interval for parameter *q* in the Bass Model or Method II is used.

Figure 11: Convergence of Energy Prices in the U.S.?



Note: One barrel of crude oil= 5.729 million BTU.
Source: EIA Open Data [10].

V. CONCLUDING REMARKS

What we envisage at the horizon of the early 2040s could be a completely transformed oil market as the result of a technological revolution in transportation. The displacement of motor vehicles by electric vehicles would take away the special role oil has enjoyed over transportation since World War II. The elasticity of oil demand would increase as it would have to compete with coal, natural gas, nuclear and renewables on the energy market. The rise of renewables could even upend the role of fossil fuels in the energy mix altogether.

As the transition from oil takes hold, by the early 2040s, oil could become the new coal and oil prices could converge to the level of coal and natural gas, about 15 dollars per barrel in 2015 prices. We have argued that neither the increase in energy demand to power EVs, nor the expected growth in emerging economies (in particular, in India and China) would prevent the displacement of oil and a subsequent decline in oil prices.

The transition away from oil has important implications on climate change. The latest IEA projections consistent with their Sustainable Development Scenario to keep global temperature rise below 2°C, require around 250 million electric cars by 2030 [82], which Method I achieves. The IEA's 2016 Global EV Outlook projected 1 billion EVs (40% of the total EV stock) would be necessary by 2050. This would be achieved a decade earlier under Method I and achieved by 2050 even under Method II. There is a strong rationale for coordinated government intervention to accelerate this critical transition in transportation to combat the effects of climate change.

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APPENDIX

Source	**Description**	**Variable**	**Units**
Fisher (1974)	Non-farm horses and mules (proxy for transportation-horses), annual data in 5 year intervals (1900-1950).	Non-farm horses and mules	Animals (millions)
Census Bureau (2000)	United States population estimates, July 1, 1900- July 1, 1999	US population, pre-1999	Persons
Census Bureau (2016)	United States population estimates, including armed forces overseas	US population, post-1999	Persons
IEA Global EV Outlook (2016)	Electric and plug-in hybrid vehicles, by country	Electric Cars	Cars (thousands)
U.S. Federal Highway Administration	U.S. motor-vehicle registrations (including trucks and buses), annual	"Motor cars"	Vehicles
Johnston & Williamson (2016)	US Nominal GDP per Capita, 1902-1927	Nominal GDP/Capita	Nominal US Dollars
U.S. EIA (2012)	U.S. Primary Energy Consumption by Source, 1875-2011, annual	E.g. Annual US coal consumption, 1875-2011	Quadrillion BTU
U.S. EIA Monthly Energy Review, August 2016	U.S. Primary Energy Consumption by Source, 2012-2015, annual	E.g. Annual US coal consumption, 2012-2015	Quadrillion BTU
De Stercke (2014)	US Primary Energy Consumption by source and usage, 1900-2014	E.g. Coal Consumption in Transportation	Terajoules/year
McNerney et. al (2011)	Nominal US coal price, weighted average of bituminous+anthracite coal for (1875-1957). Subsequently, weighted average of bituminous+subbituminous+lignite+anthracite coal for (1958-1989).	Nominal US Coal Price (1875-1989)	Nominal USD/short ton
EIA Open Data (Coal prices) (1)/ [STEO.CLEUDUS.A]	Cost of coal delivered to US electric generating plants, (1990-2015)	Nominal US Coal Price (1990-2015)	Nominal USD/million BTU
EIA Open Data (Natural Gas prices) [NG.RNGWHHD.A]	Henry Hub Natural Gas Spot Price, Annual (2000-2015)	Nominal US Natural gas price (2000-2015)	Nominal USD/million BTU
EIA Open Data (Crude oil prices) [PET.RWTC.A]	Cushing, OK WTI Spot Price FOB, Annual (2000-2015)	Nominal US Crude Oil Price (2000-2015)	Nominal USD/barrel
EIA Open Data (Renewable energy consumption) [TOTAL.WYTCBUS.A,TOTAL.BMTCBUS.A,TOTAL.SOTCBUS.A,TOTAL.GETCBUS.A,TOTAL.TETCBUS.A]	US renewable energy consumption decomposed by type (i.e. solar, wind, biofuels)/(2)	"Renewables"	Trillion BTU
EIA Open Data (Petroleum consumption) [TOTAL.PAICBUS.A, TOTAL.PACCBUS.A, TOTAL.PARCBUS.A, TOTAL.PAEIBUS.A, TOTAL.TETCBUS.A]	Petroleum consumption decomposed by sector (e.g. residential, industrial, commercial use) (1990-2015)	Petroleum Consumption, non-transport sector	Thousand barrels/day

EIA Open Data (Wood energy) [TOTAL.WDTCBUS.A]	Annual wood energy consumption (2012-2015)	Wood energy (2012-2015), later subtracted from renewables	Trillion BTU
Bureau of Labor Statistics	Consumer price index, 1800-2015	US CPI (used to deflate coal prices)	Unitless index
BP Statistical Review of World Energy (2016), data workbook	Oil price, combining various series. (1875-2015) (3)/	US oil price	Real $2015, deflated using US CPI
IMF WEO (2016)	US nominal GDP/Capita, 2015	US nominal GDP/capita (2015)	Nominal USD, 2015
Collins (2007)	Nominal Price (USD) of Model T Runabout	Model T Runabout price	US Dollars
Gartner (2009), (2015)	Global mobile phone sales to end users, (2008-2014)	Global mobile phone sales	Millions of units
Gartner (2016)	Global smartphone phone sales to end users, (2007-2015)	Global smartphone sales	Millions of units
Ericsson (2015), (2016)	Global smartphone subscriptions per capita (2014, 2015)	Global smartphone ownership	Units per capita
Heggestuen (2013)	Global smartphone penetration (active devices per capita)	Global smartphone ownership	Units per capita
["Tesla Motors sets…" (2012), Davies (2014), Quiroga (2015), Fleming & Peltz (2016), Randall (2016)]	Retail price for Tesla Model S and Model 3 (without tax credits) culled from various news sources, for lack of an available data series.	Tesla Model S (and prospective Model 3) MSRP	Nominal USD
Bento and Wilson (2016)	Annual data on global technological diffusion (1870-2008).	Consumer technologies (refrigerators, dryers, etc.) and Power capacity (Electricity from oil, hydropower, coal, etc.)	Consumer technologies (units) and Power technologies (megawatts of installed capacity)
Ren21 (2014), (2016)	Global total of solar, wind, biofuel, and geothermal electricity generation capacity (2004-2015)	Non-hydro renewables (2004-2015)	Megawatts of installed capacity
Maddison (2009)	Global population, annual (1870-2005)	Global population, annual (1870-2005)	Persons (thousands)
Census Bureau (2016)	Total mid-year global population, annual (2005-2015)	Global population, annual (2005-2015)	Persons

Description: where dates are given, these signify dates relevant for our use and not the full extent of the time series. For example, Fisher's non-farm horses data extends to 1850, but we use only 1900-1950.

(1)/ EIA Open Data series are constantly updated and available for bulk download from http://www.eia.gov/opendata/. Any Open Data series used here include unique series identifiers, enabling users to find the source data. There may be slight discrepancies as data is revised over time.

(2)/ We only include Solar, Wind, Biofuels (excluding Wood), and Geothermal Energy in our Renewables series.

(3)/ Series composition: "1875-1944 US Average, 1945-1983 Arabian Light posted at Ras Tanura, 1984-2015 Brent dated."