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Riding the Energy Transition: Oil Beyond 2040

by Reda Cherif, Fuad Hasanov, and Aditya Pande

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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.

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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 (Hubbert 1956). Progress in oil extraction and continuing discoveries of new reserves, however, have brought this idea into question.[2] In fact, 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." 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 (Schurr and Netschert 1960).[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.

After examining recent developments in transportation and renewable energy 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 not too distant a future. In our projection, this switch could happen in the next 10 to 25 years as electric cars replace motor vehicles like 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 another 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] (Slaughter 1996). This could be the last age of oil, in which oil would become the new coal.

Few would deny that the energy transition is underway. Technological progress has produced cost declines of 50 percent or better in photovoltaics, wind power, and battery production since 2008. Oil use per unit of global GDP has also fallen by 40 percent, essentially linearly, since 1980 (IMF 2016).[5] The International Energy Agency (IEA) projects a decline in the share of global energy coming from oil and coal reaching 26 percent and 25 percent, respectively by 2040, displaced by growing natural gas use (24 percent) and renewable energy (19 percent) (OECD/IEA World Energy Outlook 2015). Although consistently low

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[2] "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" (Covert, Greenstone, and Knittel 2016).
[3] Taken from Lipton (1962).
[4] Also known as Dator's second law.
[5] See Arezki, Bogmans, and Matsumoto (2016).

fossil fuel prices could delay the energy transition, the IMF's WEO (2016) raises the possibility of a faster shift today than historically (in the cases of wood and coal).

From wood to coal to oil, the transition patterns remain similar. Fouquet's (2010) study of the United Kingdom indicates that it takes around 50 years for energy transitions to take place. Wilson and Grubler (2011) find that global changes require 80-130 years, while Vaclav Smil estimates that it takes 50-70 years (Lacey 2010) for new resources to reach a significant level.[6] In a similar vein, Grubler's (1990) work *The Rise and Fall of Infrastructures* highlights consistent 55-year intervals between the development of the canal, railway, and surfaced road networks in the United States (Grubler 1990, p. 276).

Figure 1 illustrates the transition from wood to coal and from coal to oil in the U.S. Most noticeable is the rapid rise of coal as a major energy source, growing from 33 percent to over 70 percent of the U.S. total primary energy use in about 25 years (1875-1900). Wood was displaced by coal, falling from 66 percent to 21 percent share over the same period. So was coal as its share substantially declined from 1920 to 1970. Yet the shares of the new energy sources, oil and natural gas, have plateaued for the last three decades. Like oil in 1905, renewable energy made up 5 percent of the total primary energy use in 2015.

The similarity in adoption rates across time is also evident in terms of the growth of raw energy use. Starting from comparable relative positions, natural gas, petroleum, and renewable energy[7] have grown at almost the same exponential rate despite the vast differences in context for the three transitions (Figure 2). Such observations are not new (Marchetti and Nakicenovic 1979, and Grubler 1990), but they lend plausibility to the historical parallel we are making.

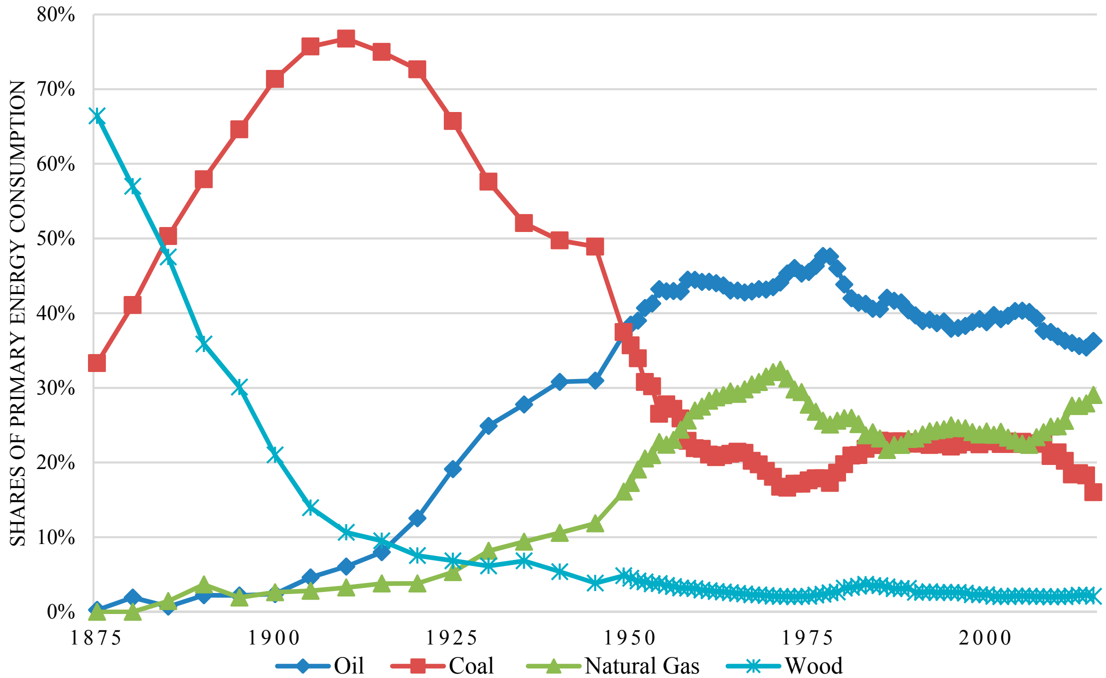
A process of technological transition could very well upend the oil sector. Nakicenovic et. al. (1999) summarize the critical technological transition process: a successful learning curve, which is based on learning-by-doing and economies of scale, allows for declining costs, while a logistic diffusion model exploiting network effects characterizes adoption, allowing technology to become "locked-in." There have been several recent analyses regarding the formative phases of new technologies (Bento and Wilson 2016), prospects for a future energy transition (Sovacool 2016), and resulting policy implications (Fouquet 2015). However, to the best of our knowledge, none of these engaged in assessing the implications of technological transitions on the oil market, proposing a possible future price of oil. We examine the United States as our main test case both because of its large size and the availability of data.

The sections of the paper are as follows: first, we describe the historical parallels and prospects for a technological transition in transportation, which we argue is the most critical component of oil demand. We then examine possibilities for renewable power generation: displacing a non-negligible fraction of oil use while meeting the increased electricity demand due to the rise of electric vehicles. Finally, we advance a plausible thesis regarding the future of oil prices.

[6] 25 percent in Smil's analysis.

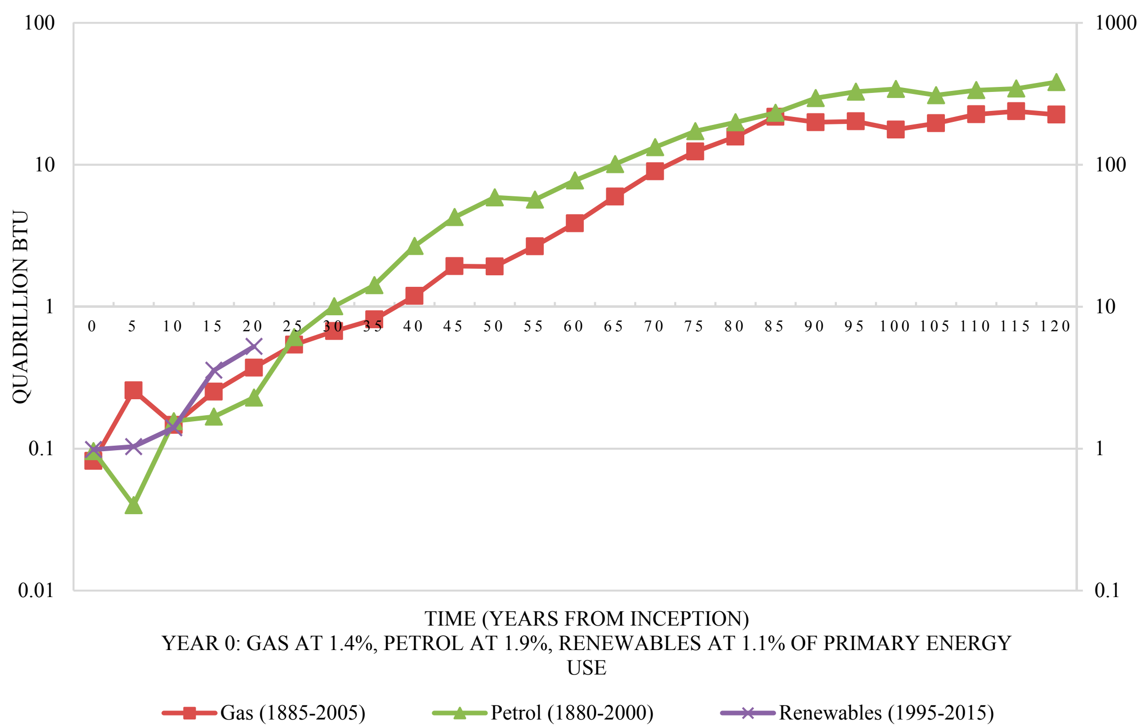
[7] "Renewables" data in this paper include only solar, wind, biofuel (excluding wood), and geothermal energy.

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



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

Figure 2: Natural Gas, Petroleum, Renewables Over Time (USA)



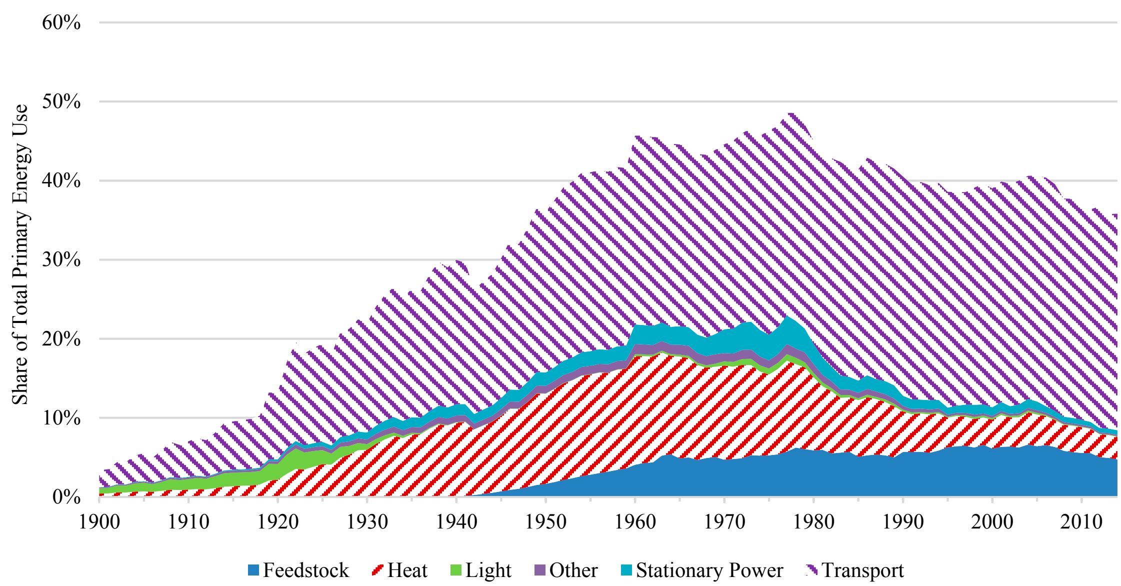
Note: The Y-axis is plotted on a logarithmic scale, and renewables are plotted on the right-hand axis.
Source: U.S. EIA (2012) and U.S. EIA Open Data.

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 swapped for 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 (76 percent in the U.S. in 2014, Figure 3). Road transportation alone accounts for 44 percent of oil use.[8] In absolute terms, the penetration of the electric car in the U.S. follows that of the motor vehicle[9] remarkably closely in the early stages despite a century time difference (Figure 4).

Figure 3: Oil Share of Primary Energy Use, Sectoral (USA)



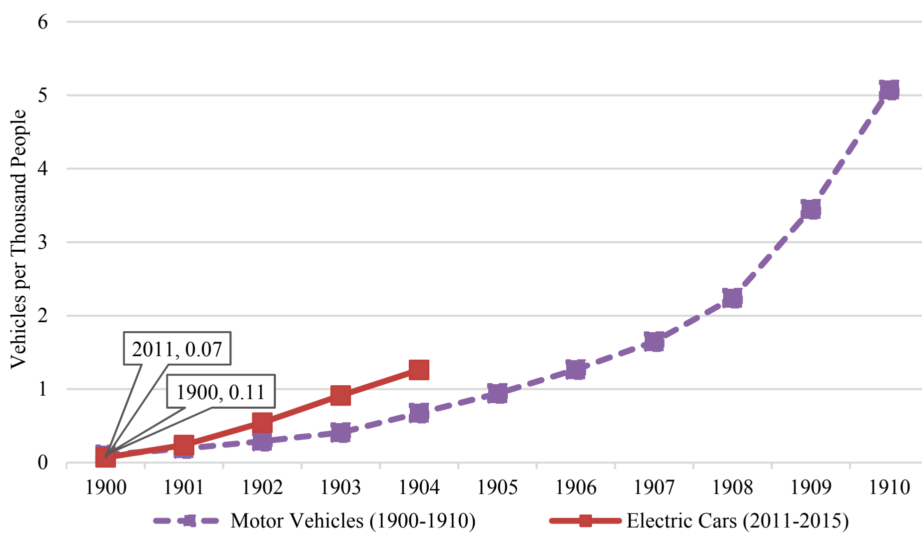
Source: International Institute for Applied Systems Analysis (De Stercke 2014).

Interestingly, electric cars, in the year 1900, made up one-third of the total automobile stock of the United States. 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

[8] 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) (OPEC World Oil Outlook 2015).
[9] The stock of motor vehicles is approximated by the total number of motor vehicle registrations (including buses and light trucks).

new oil discoveries that made oil relatively cheap—the electric car could not compete. It had essentially disappeared by 1935 (Matulka 2014). Yet the electric car appears poised for a comeback.

Figure 4: Electric Cars and Motor Vehicles (USA)



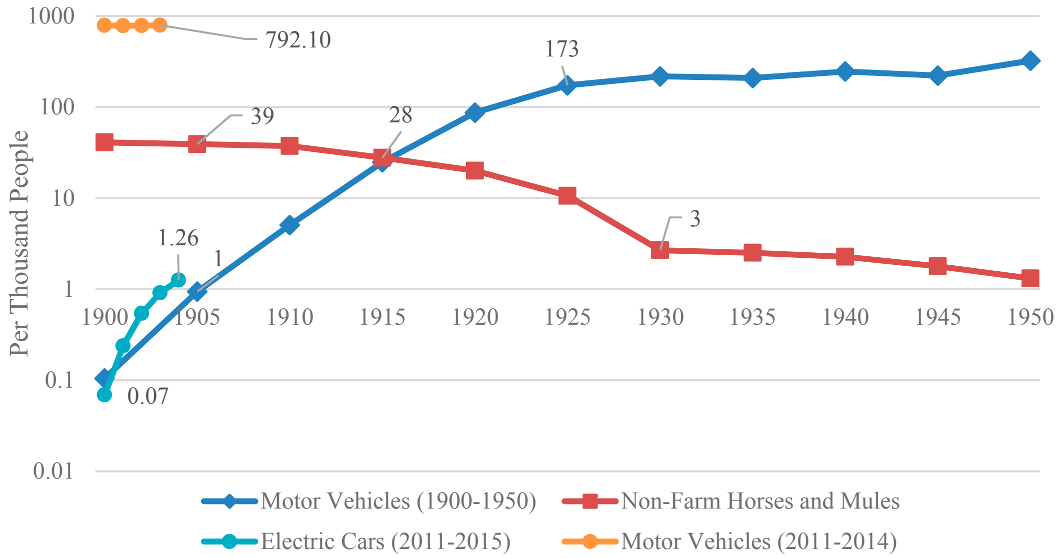
Note: "Electric cars" in this and all other figures include purely electric as well as plug-in hybrid vehicles.
Source: OECD/IEA (2016) and U.S. Federal Highway Administration (FHWA), various years.

The disappearance of cart horses gives us some insight into what a transportation transition could look like (Figure 5). 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 (OPEC 2015), coal consumption a century ago was only 20 percent reliant on the transport sector—mainly steamships and rail (De Stercke 2014).

Although projections of the number of electric vehicles (EVs) on the global level 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. Its 2016 WOO report significantly revised that figure to 22 percent. Bloomberg New Energy Finance (BNEF) estimates 7.4 million electric vehicles on the roads by 2020, eventually representing 25 percent of all cars by 2040.[10] BNP Paribas estimates 25 percent displacement by 2030 (*The Economist* 2017). Another report by Carbon Tracker and the Grantham Institute at Imperial College London (2017) projects a 19 percent share of electric vehicle by 2030 and 55 percent by 2040 (see "Weak_EV" scenario). Becker et. al. (2009), using a diffusion model, predict that EVs would represent about a quarter of the total stock of vehicles by 2030. When explained explicitly, most projections use the data available on EV adoption and battery cost reduction in recent years to extrapolate into the future (e.g. BNEF).

[10] *Global Trends in Renewable Energy Investment* (2016).

Figure 5: 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, various years, and OECD/IEA (2016).

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 2015. 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 and 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.

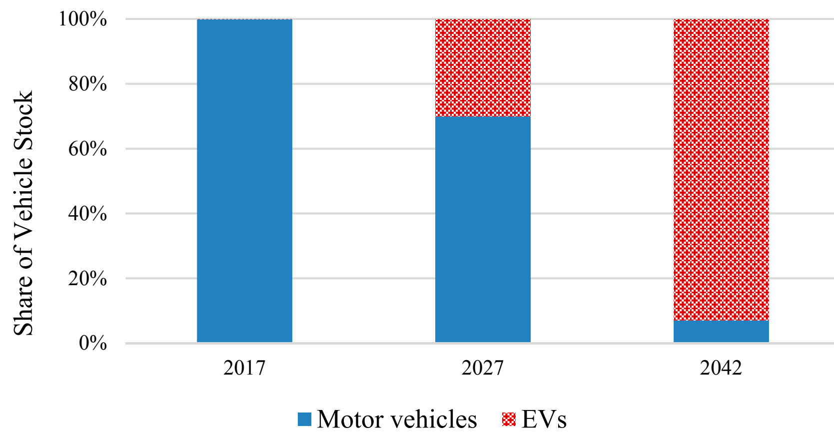
We study the horse-car transition that mostly started taking place about a century ago between 1905 and 1930. Our main goal is to project the ownership of motor vehicles in the next few decades. In Method I (Figure 6), the fast adoption scenario, we translate the horse displacement in the early 20th 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 2017, 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).[11] These projections are

[11] Reaching the EV price threshold of around $35,000 in 2018 discussed below could trigger a motor vehicle displacement rate similar to that of horses starting in 1915. In this case, motor vehicle ownership would fall by

consistent with the recent growth of EVs. Between 2011 and 2015, the average annual growth rate of ownership was 120 percent (Figure 5). 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.[12]

Figure 6. Electric Vehicle Penetration Projection: Method I



In Method II (Figure 7), the slow adoption scenario, we project motor vehicle ownership using the growth rate of motor vehicles at the beginning of the 20th century to project the rise of EVs starting in 2017. This method would imply an average annual growth rate of EV ownership of 24 percent over 25 years. The method yields much lower estimates of motor vehicle displacement (an average annual rate of decline of 2 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 30 percent displacement by the late 2020s and 93 percent by early 2040s. Method II yields slower displacement rate (5 percent displacement by late 2020s and 36 percent by early 2040s), which is closer to most of the other studies cited above.[13] The 90 percent market saturation would be reached after about twenty years based on the growth rate of motor vehicle adoption over 1945-1955, instead of 1930-1945, to exclude the Great Depression and WWII.

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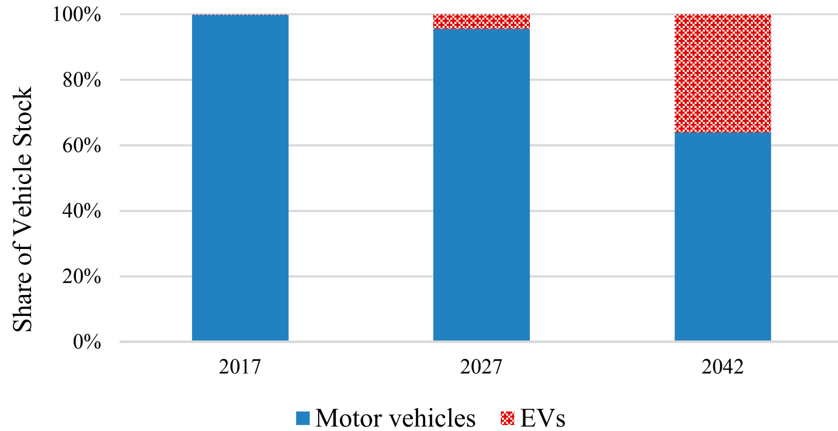
90 percent between 2018 and early 2030s, while electric vehicles would grow at an average annual growth rate of 53 percent over 15 years.

[12] Alternatively, we can use the evolution of the shares of horses vs. motor vehicles between 1905 and 1930 to project the EV and motor vehicle shares for 25 years until the early 2040s. The share of horses (respectively, motor vehicles) is computed as a ratio of the total number of horses and motor vehicles combined or total major means of personal transportation. If the total vehicle (motor vehicle and EV) ownership per capita remains constant, this method yields similar displacement rates as Method I.

[13] The OECD/IEA Global Electric Vehicle Outlook (2016) projects EV penetration levels to keep a global temperature rise below 2°C. This will require about 65 percent annual growth rate between 2015 and 2020 to put 15 million electric cars on the road by 2020, about 30 percent growth between 2020 and 2025, about 20 percent growth in 2025-2030, and 10 percent growth in 2030-2050. Such a transformation would result in 60 million EVs by 2025, 150 million EVs by 2030, and 1 billion EVs by 2050 (then 40 percent of total light vehicle stock), which is well below the predicted numbers according to Method I and close to Method II if the global adoption is similar to that in the advanced countries.

Figure 7. Electric Vehicle Penetration Projection: Method II



Method I and II projections provide a range for EV adoption, but we argue that the future is more likely to be closer to Method I than Method II. There is a large difference in the market scale between horse ownership in the early 20th century and motor vehicle ownership in the 21st century (Figure 5). It follows that the potential market for adoption of EVs is much larger than that for motor vehicles in the past. Motor vehicles and EVs are much closer substitutes than horses and motor vehicles, and the choice between owning an electric car or a motor vehicle is rather akin to the switch to the smartphone from an ordinary cell phone, which happened swiftly (Figure 10). As EV prices converge to the average motor vehicle price, the substitution could take place very fast (see Section C). Beyond the price, EV producers such as Tesla could succeed at branding their cars the way Apple succeeded at branding the iPhone. In addition, the ability to scale up the production of motor vehicles in the early stages of the automobile industry was far less than the capability of automakers in the 21st century.[14] Also, in the early 20th century, the lack of roads and gasoline distribution network could have slowed down the adoption of motor vehicles. The environmental consciousness of consumers and climate change concerns further lend credence for a fast adoption of EVs.[15] Our projections under Method I are also supported by the prediction of a standard diffusion model and the pace of the electric vehicle adoption that is matching that of other modern rapid technological adoptions (Figure 9).

[14] The average age of automobiles and light trucks in the U.S. was 11.4 years in 2014 (Bureau of Transportation Statistics 2017), and annual sales in 2015 in the U.S. were more than 17 million vehicles for a stock of about 250 million (NADA 2015 and FHWA 2016). McKinsey estimates a full stock turnover of 15-20 years (Becker et. al. 2009).

[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 (Kolbert 2009). New York in 1900 had 100,000 working horses (Tricks 2016), 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 (Kolbert 2009).

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 (Bass 1969).[16] 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. In the context of the displacement of MVs by EVs, $F(t)$ represents the fraction of EVs of the total of all 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.[17] 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] 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. 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.

[16] 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 (Bass 2004).

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

[18] 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.

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 6). 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 6). 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 7). 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 (*The Economist* 1999). The actual number turned out to be 120 times larger than forecast at 109 million phones (Seba 2016).[19]

Similar obstacles such as 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 8.[20]

Figure 8 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 time when motor-vehicle ownership matched that of horses before MVs completely displaced horses within a decade or so (Figure 5). In comparison, unsubsidized prices for Tesla (and other EVs) seem to be converging towards

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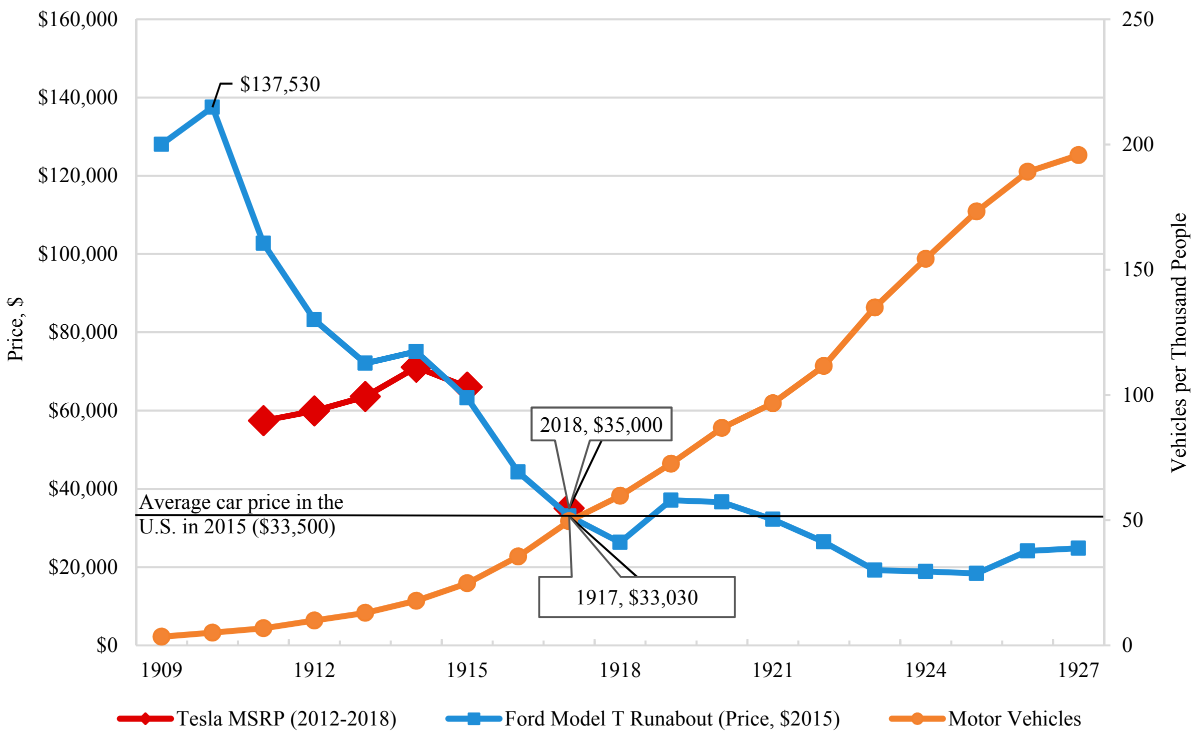
[19] The data source is CTIA, the wireless association.

[20] In other words, prices are deflated using nominal GDP per capita (base of 2015), e.g.

$$\frac{\text{Nominal Model T Price, 1910}}{\text{Nominal GDP per capita, 1910}} * \$55{,}805_{\text{US Per capita GDP 2015}} = \$137{,}530$$

the Model T's price threshold.[21] 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" (Goldstone 2016, p. 330). The historical parallel—indeed, the Model S as precursor to Model "T"[hree]—is clear.[22] More important, the price of Model 3 at $35,000 is about the average price of a new car sold in the U.S. in 2015.[23] With comparable prices, it seems the electric car industry is about to pass a turning point, justifying further our extrapolation based on horse displacement.

Figure 8: Electric and Motor Vehicles Adoption and Prices



Note: See footnote 22 for the price indexation methodology of Ford Model T.
Sources: Collins (2007), FHWA, various years, OECD/IEA (2016), NADA (2015), and Tesla prices: Tesla (2012), Davies (2014), Quiroga (2015), Fleming and Peltz (2016), Randall (2016).

Battery costs, which represent the main barrier to electric vehicle commercialization, are rapidly declining. As Nykvist and Nilsson (2015) show in their widely-cited metastudy, average vehicle lithium-ion battery costs have fallen from $1000/kWh in 2007 to $410/kWh in 2014—approximately by 14 percent per year. Market leaders like Tesla and Nissan are

[21] The Runabout was consistently the Model T's cheapest version, presenting the least-favorable comparison for Tesla.
[22] See also Bloomberg New Energy Finance and Randall (2016).
[23] The average price was about $33,500 in 2015 (NADA 2015).

already in the $300/kWh range. Such an exponential trend is expected to continue, as further learning coupled with economies of scale make Li-ion batteries at $150/kWh by 2025 a serious possibility. Plug-in hybrid batteries fare even better, with the U.S. Department of Energy reporting $268/kWh in 2015 and targeting $125/kWh by 2022.[24] 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.[25] 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 (UT News 2017).

Lifetime cost competitiveness is also paving the way for the adoption of electric vehicles. The IEA[26] estimates that it has already been achieved. Analysts at Bloomberg New Energy Finance and Cambridge Econometrics predict cost competitiveness for battery electric vehicles by 2022[27] and 2025, respectively. 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.[28] The mpg of Tesla was about 90. In addition, as EVs contain much less moving parts than motor vehicles, the maintenance cost for EVs is 10 to 100 times cheaper than that for MVs (Seba 2016).

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. 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.

Finally, recent research (Needell et. al. 2016) 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.

Furthermore, several major automakers have announced concrete commitments to electric vehicles. Honda announced its aim to have plug-in hybrid EVs (PHEVs) and battery EVs make up 2/3 of global sales by 2030 (Kubota 2015). Volkswagen has pledged 25 percent of

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[24] The U.S. Department of Energy, "Revolution Now," 2015 Update.
[25] 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 (Bradley and Jaskula 2014 and OPEC 2015). Given the current world reserves of over 39 million tons, 2.4 billion EVs could be potentially produced (Bradley and Jaskula 2014).
[26] Nykvist and Nilsson (2015).
[27] Carrington (2016).
[28] 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.

sales as EVs by 2025 (Campbell 2016). GM's Chevy Volt, Nissan's Leaf, Toyota's Prius Prime, and Tesla's Model 3, already have prices in the $25-$35 thousand range (and GM's Bolt is about $37,000), before tax incentives.

Even if the number of EVs does not increase as fast as predicted, the advent of autonomous vehicles may still displace a significant number of motor vehicles. Ford recently announced a plan to mass-produce fully self-driving cars by 2021 (Fields 2016). CEO of Lyft Travis Zimmer predicts that self-driving cars could dominate the Lyft fleet within five years. A study of the potential effect of autonomous driving showed that the fleet of more than 13,000 yellow cabs in Manhattan could be replaced by 9,000 self-driving vehicles, about 30 percent decline, while substantially decreasing the cost per mile from $4 to $0.5 (Burns et. al. 2015).[29] Eliminating drivers would instantly make ride-sharing cheaper than car ownership, increasing the scope for electric car diffusion (see Hook 2016).

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 9). 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 also 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 (Cox and Alm 2008). Motorbikes and electric bikes tell a similar story, with diffusion of recent technologies outpacing diffusion in the past. The fast adoption scenario for the U.S. EV market (Method I) shows a pattern that resembles more the most recent technological adoptions.[30]

Sector-specific transitions can be quite rapid and could be even faster with a strong state push. Brazil's signature ethanol program is a case-in-point. Flex-fuel cars (able to use both ethanol and petroleum) went from 20 percent to 90 percent of new cars sold in the five years between 2004 and 2009 (Sovacool 2016). By the mid-2010s, 64 percent of all Brazilian cars on the road were flex-fuel (Forero 2016). Cheap ethanol and expensive gasoline made it easier, but tax incentives played a critical role as well.

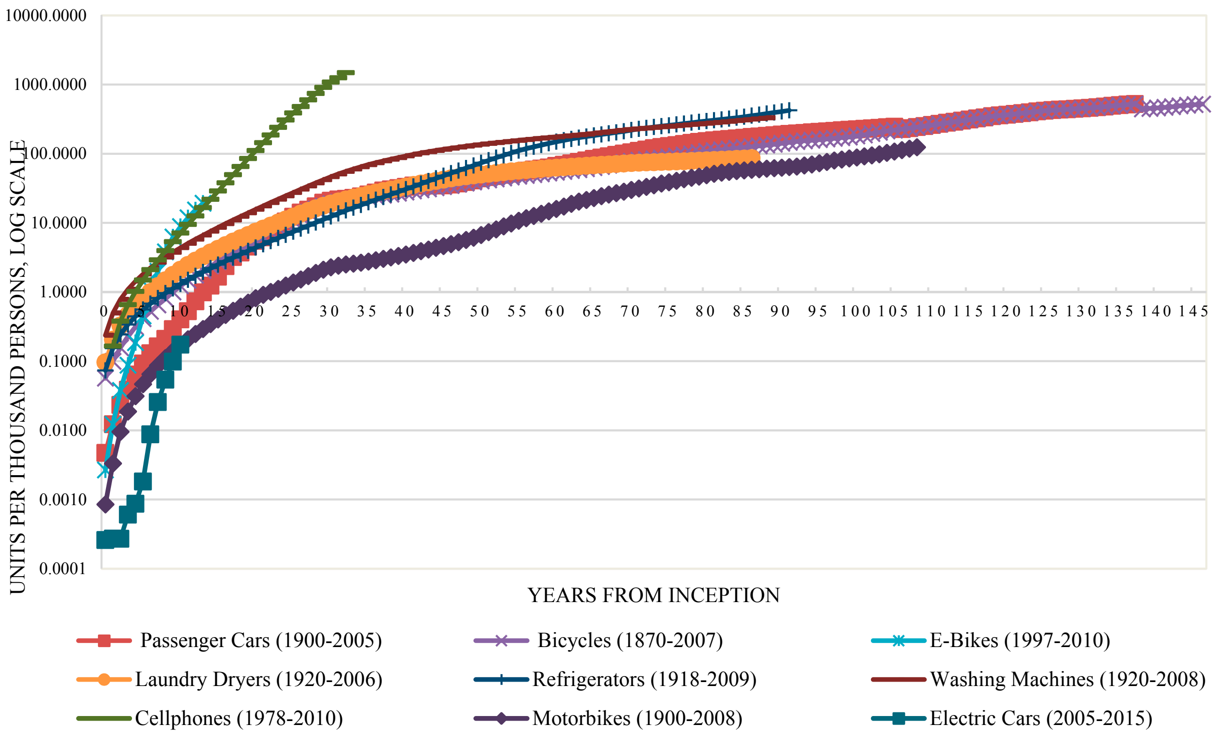
The spread of smartphones—albeit far easier to adopt than transportation innovations—shows how rapid direct substitution of a superior technology can be. Sales witnessed a rapid rise from 10 percent to 75 percent of the market in a mere 8 years (Figure 10). Widespread

[29] An MIT study estimates that 3,000 cars could serve 98 percent of taxi traffic in New York City based on a new ride-sharing algorithm (Conner-Simons 2016). Relative simplicity of highway driving and labor cost provide an incentive for America's $700 billion trucking industry to eliminate its more than 3 million drivers in favor of autonomous trucks (Hook 2017).

[30] 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.

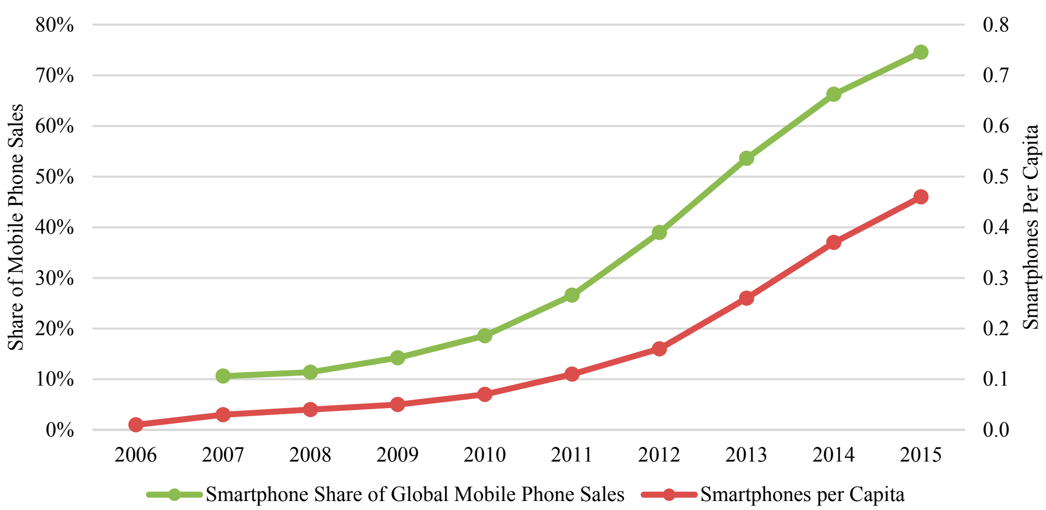
smartphone substitution seemed no more imminent in the early 2000s than large-scale energy substitution seems today. The disappearance of established major mobile phone producers, replaced by companies known for personal computers within a few years, is a reminder of the swift adoption of a superior technology. The rise of smartphones also shows that the adoption rate in developing economies closely trailed that of advanced ones.

Figure 9: Global Consumer Technology Penetration



Source: Bento and Wilson (2016) and OECD/IEA Global Electric Vehicle Outlook (2016).

Figure 10: Global Spread of Smartphones



Source: Gartner (2009, 2015, 2016), Heggestuen (2013), and Ericsson Mobility Report (2015, 2016).

III. GENERATING ELECTRICITY: THE SWEEP OF RENEWABLES

If the electric car were to take over road transportation, one would expect an increase in demand for electricity to be quite substantial. Fossil fuels could still play a major role in the electricity generation as does coal today. However, renewables are growing rapidly enough to provide the increasing demand for electricity and potentially replace existing fossil energy sources.

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.[31] 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[32], 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[33], it would require 5.4 million barrels per day (mbd), compared to 9 mbd used to produce gasoline in 2015.[34] 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.

The prospects of renewables as a primary energy source are gaining ground. Renewable energy capacity seems to be following the log-linear trend of previous power technologies (Figure 11). 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 (Clark 2016b). 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 (World Economic Forum 2016). Solar power could become the leading source of electricity worldwide by mid-century (OECD/IEA 2014) 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 (BNEF New Energy Outlook 2016). Although oil use mostly involves the transportation sector, power generation still plays a significant role, making up 7 percent of total oil consumption (OPEC WOO 2015). Most current generation takes place in the oil-rich Middle East, but even this is disappearing as the Gulf states begin to transition to

[31] 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 (Barnard 2015).

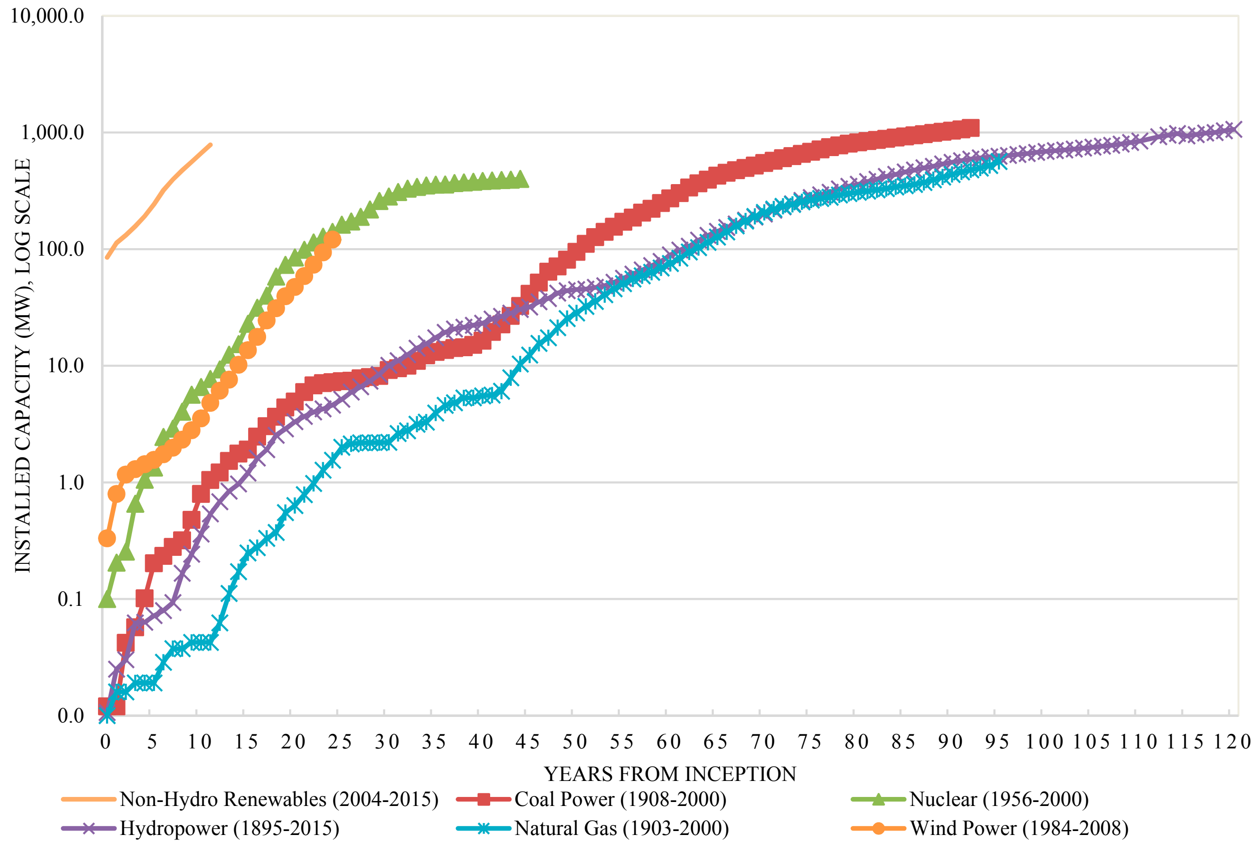
[32] See U.S. EIA: https://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3.

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

[34] See U.S. EIA: http://www.eia.gov/energyexplained/index.cfm?page=oil_use.

renewable energy, especially as low oil prices force cutbacks in domestic consumption in favor of increased export volumes (Goldenberg 2016).

Figure 11: Global Diffusion–Power Technologies



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

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[35] has fallen 80 percent since 2009 (Lazard 2015). Wind power's levelized cost has also fallen approximately 60 percent; both technologies are competitive *without* subsidies in some areas of the U.S.[36] MIT's Energy Initiative (2015) finds that a full 65 percent of utility-scale solar costs today are 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.

[35] It represents the average price of electricity needed to break-even over the lifetime of the generating asset.
[36] Notably Texas, the Midwest, and the Southwest (Bloomberg New Energy Finance 2016, p. 36).

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 (Martin 2016). McKinsey projects that stationary storage prices will be halved by 2020, at roughly $200/kWh.[37] Combined with demand-response policies, a more interconnected grid, and complementary natural gas plants, this could effectively eliminate the intermittency problem.

Europe and some developing nations are leading the adoption of renewables. Germany's *Energiewende* has allowed it to generate over 35 percent of its electricity from (non-hydro) renewables, while the UK, France, and Italy have reached more than 19 percent. In 2015, the G-20 derived 8 percent of its electricity from renewables, about 70 percent increase since 2010 (Clark 2016a). Perhaps more important, renewable non-hydropower capacity addition in emerging nations outstripped that of developed ones in 2015 (Randall 2015). Uruguay presents a notable case—55 percent of the country's total primary energy and 95 percent of its electricity comes from renewable sources, including hydropower (Watts 2015). China, of course, is advancing fast with the sheer scale of its transition. It accounted for nearly half of global wind[38] and a third of renewables capacity growth in 2015 (Clark 2016a). On the transportation front, China also became the world's largest market for electric vehicles in 2015.[39] 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[40]), and plans to add 6-7 million hybrid and electric vehicles per year by 2020.[41] 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.[42]

As Grubler (2012) shows, late adopters of energy technology are often faster in shifting energy sources (Table 1).[43] The current energy transition is already underway in China, India, and Sub-Saharan Africa, which may well "leapfrog" investing in fossil-fuels altogether in favor of renewable energy. Rubio and Folchi (2012), similarly, find more rapid transitions in developing countries. Whereas the coal-oil transition took nearly 70 years in the U.S., Argentina experienced it in 30 years—from 1913-1941, the coal share of domestic consumption dropped from about 94 percent to 11 percent. Furthermore, oil surpassed coal earlier in many Latin American countries—after 1925, coal was still dominant only in Brazil. In other countries, even where coal was widely used (e.g. Chile) the coal's share was not much greater than 50 percent.

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[37] D'Aprile, Newman, and Pinner (2016).
[38] Hornby (2016).
[39] *Global Trends in Renewable Energy Investment* (2016).
[40] Bloomberg New Energy Finance, *100GW solar by 2022: India's target or aspiration?* (2016).
[41] OECD/IEA World Energy Outlook (2015).
[42] Ibid.
[43] Grubler measures diffusion speed as the time (in years) from 10% to 90% of peak primary energy share.

Table 1: Transition Rates by Country

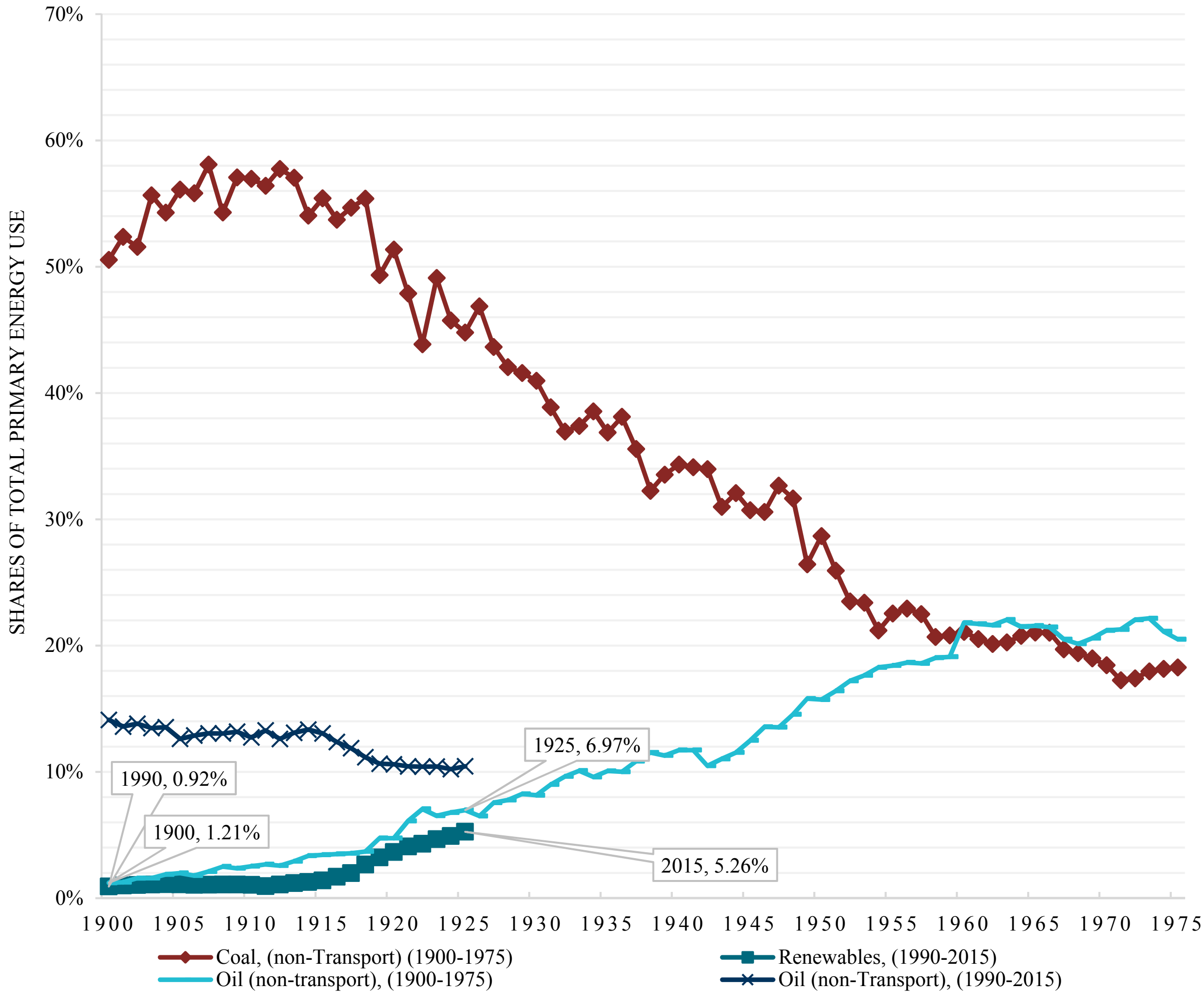
		Diffusion Midpoint	Diffusion Speed (years)
Phase out wood/biomass, phase in coal			
Core	England	1736	160
Rim	Germany	1857	102
	France	1870	107
	Netherlands	1873	105
Periphery	Spain	1919	111
	Sweden	1922	96
	Italy	1919	98
	Portugal	1949	135
Phase out coal, phase in oil/gas/electricity			
Core	Portugal	1966	47
	Italy	1960	65
	Sweden	1963	67
Rim	Spain	1975	69
	Netherlands	1962	62
	France	1972	65
Periphery	Germany	1984	50
	England	1979	67

Source: Grubler (2012).

If we exclude energy used for transport[44], historical and modern trends are similar (Figure 12). 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. 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.

[44] We assume that renewables are mostly used in electricity generation. Other series are from IIASA database (De Stercke 2014).

Figure 12: Comparing Transitions (Excluding Transport), United States



Source: IIASA (De Stercke 2014) and EIA Open Data.

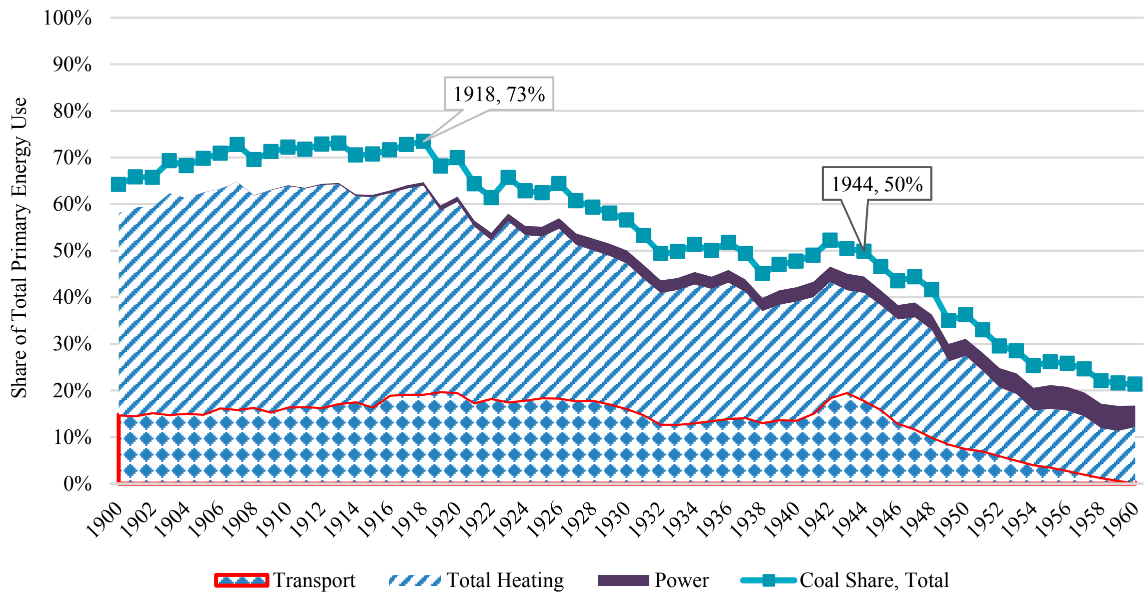
IV. Oil as the New Coal?

We further draw a parallel between today and the energy transition in the early 20th century when the dominant energy source was coal. The decline of coal can be viewed as occurring in two stages.[45] The first phase, lasting from 1918 to 1944, saw coal fall from 73 percent to 50 percent of total primary energy use (Figure 13). This decrease was driven essentially entirely by the 22 percent fall in coal-based heating, due to the expansion of petroleum and natural gas. The second phase was heralded by the collapse in coal-powered transportation within the 15 years from 1945 to 1960. As the coal share was declining, the oil share was rising (Figure 14). The newly discovered oil in the early 20th century provided cheap fuel for automobiles. Following the automobile boom after WWII, the oil share surpassed the coal share of total primary energy use (O'Connor and Cleveland 2014).

[45] Data from IIASA PFU Database (De Stercke 2014).

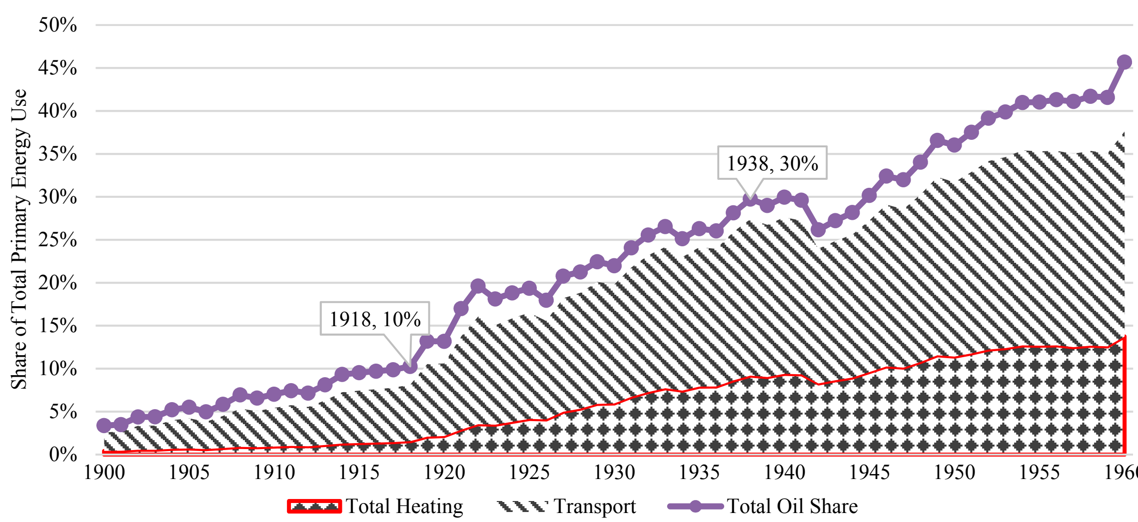
The advent of oil-based motor cars seems to initially have opened an entirely new market for energy use rather than substituting directly for coal. Coal-based transport (mainly steam-ships and coal-powered trains) remained essentially constant as a share of energy use until the 1940s. Horses and then automobiles, by the early 20th century, were used mainly for urban rather than long-distance travel. It was only after WWII that the United States became a car-centric society. Although it could be difficult to disentangle the effects of ship and train conversion to diesel (Smil 2010) versus the expansion of motor car transport even post-1945, today's transportation revolution would depend mostly on the transition from gasoline-powered cars. Once the end-use technology shifts, the primary energy shares would adjust.

Figure 13: The Decline and Fall of Coal (United States)



Source: De Stercke (2014).

Figure 14: The Rise of Oil (United States)



Source: De Stercke (2014).

Looking at the price and shares of oil and coal over almost the past 150 years, we can see two striking features[46] (Figure 15). 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. Secondly, despite the substantial shift in energy use away from coal, the value of heat provided by coal (a barrel of oil equivalent, approximately 6 million BTU) has fluctuated narrowly at about $10-15 for a century and a half.[47]

The differences in the quality of energy service and in the market structure between coal and oil could explain the differences in the price patterns. First, the difference in price levels could be due to the quality of the energy service (i.e. transportation, heat, electricity). Although the price of oil has been significantly higher than that of coal per BTU, oil-based *energy services* are qualitatively better and more efficient. Second, coal is widely available, both in quantities and geographically[48], and it is relatively easy to adjust the scale of production suggesting that its supply should be relatively elastic, especially in the medium run. In contrast, until recently before the advent of shale oil, the supply of oil has been relatively inelastic compared to coal, as increasing oil supply requires risky and expensive exploration projects. In a survey of empirical studies estimating the supply elasticities of different energy products in the U.S., Dahl and Duggan (1996) conclude that oil supply appears to be less elastic than coal but more elastic than natural gas. In addition, no major coal producer has held the ability to influence prices in the same fashion as OPEC in the oil market, especially in the 1970s (see Hamilton 2009).

In terms of demand, coal is mostly used for heating and power generation (Figure 13), and there are other energy sources (e.g. natural gas and oil) that are close substitutes for coal. As a result, demand for coal could be more elastic than oil. A large share of oil is used for transportation (Figure 14), for which there has been no viable alternative until recently, making oil demand more inelastic. The estimates of the price demand elasticity for oil and coal vary (see Parry 2016). In their survey, Dahl and Roman (2004) find that the average short term demand elasticity of coal is -0.21. Dahl (2012) surveys more than 200 country studies of gasoline demand elasticity and finds that the elasticity is in the range of -0.1 to -0.4. Given that the cost of crude oil represents more than half of the cost of gasoline production, the demand elasticity for crude oil would be around -0.2 to -0.8.[49] Several studies such as IMF (2011) find that the short-term oil demand elasticity is very low or about -0.02, and the long-term one is about -0.07, suggesting the demand for oil is very inelastic (see also Dahl 1993 and Cooper 2003). Hamilton (2009) argues that these lower estimates of the demand elasticity for oil are more convincing given the historical patterns of oil consumption.

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[46] 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.

[47] McNerney et. al (2011) attribute this pattern to the “random walk” nature of commodity prices. See also Hamilton (2009).

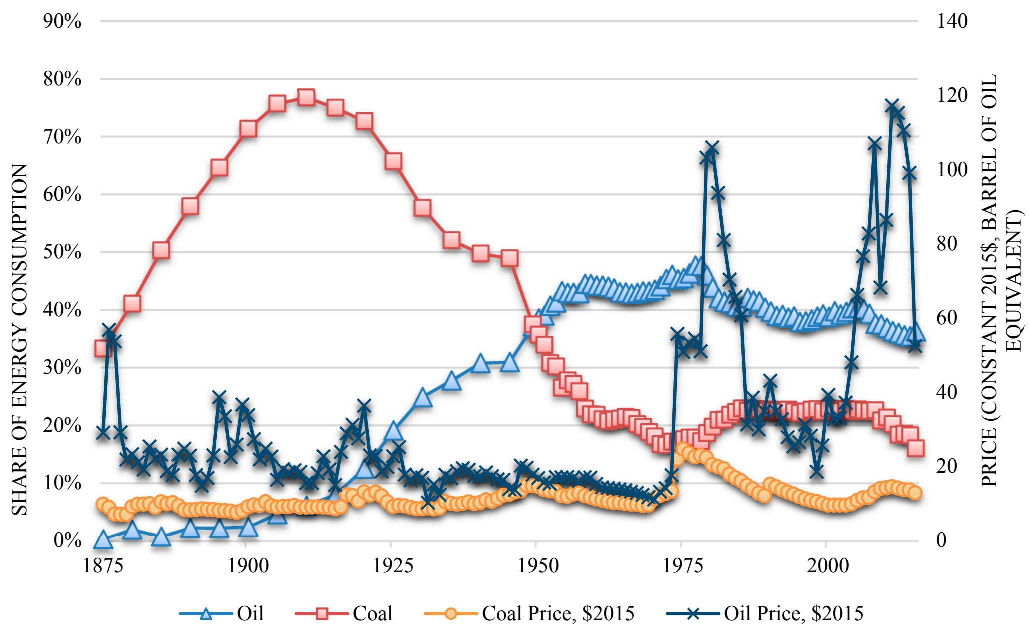
[48] As noted by Mitchell (2006), there is enough coal in major producing countries such as the US, Russia, Canada, China, Australia, Colombia, Venezuela, and India, to meet the needs beyond the current and potential future demand.

[49] See Parry et. al. (2016) and Charap et. al. (2013) for further discussion.

These differences in the market structure could explain the relatively low and stable price markup for coal compared to oil. The effect of shocks would be larger in the oil market and would contribute to larger variations in the oil price compared to the price of coal.

Moreover, 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 18, 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 15: Quantities and Prices of Coal and Oil (USA, 1875 – 2015)



Source: EIA (2012), EIA Open Data, BP Statistical Review, and McNerney et. al. (2011).

What are the implications for oil? As argued earlier, by the late 2020s the stock of motor vehicle in the U.S. (and by extension in other advanced—OECD—economies) would potentially decline by 24 percent (Method I). Then in the next 15 years, the stock of motor vehicle could fall by another 90 percent (Figure 6).[50] In terms of oil consumption in the transportation sector in advanced countries, this represents a decrease of about 6 million barrels per day (mbd) by late 2020s and a further decrease of 15 million barrels per day by early 2040s.[51] Method II would imply a slight increase of about 1 mbd by late 2020s and then

[50] We assume a population growth rate of .08 beyond 2017 (corresponding to the average annual growth rate between 2004 and 2014).

[51] Given an initial demand for oil of 46 mbd for OECD countries (OPEC WOO 2016), one-half of which goes to road transportation. This is a conservative assumption since the aviation industry, for example, is not immune to the advent of electric planes, which are being developed by NASA, Airbus, and Boeing.

a fall of 6 mbd by early 2040s. The implied total drop in oil demand coming from transportation in advanced countries is about 21 mbd under Method I and 5 mbd under Method II by early 2040s. We also assume that oil demand for non-transportation sectors in OECD economies remains constant, which is conservative. Under both methods, we project a large drop in oil demand in OECD economies (Figures 16 and 17).

Figure 16. Global Oil Demand Projections, Method I

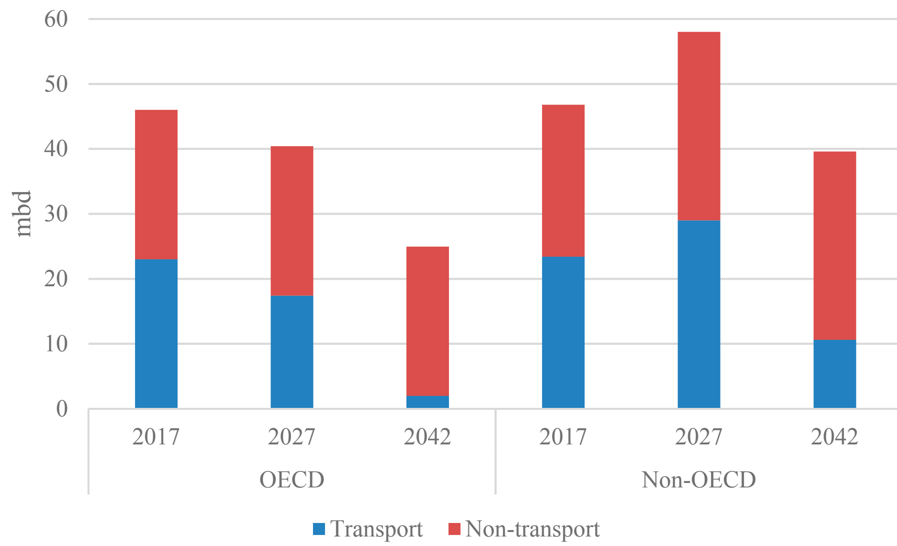
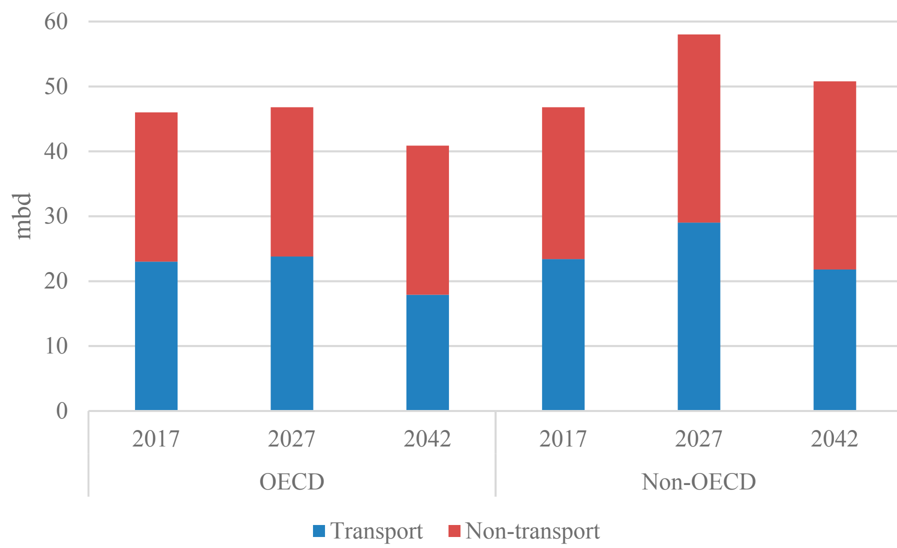


Figure 17. Global Oil Demand Projections, Method II



We further argue that the substantial drop in OECD oil demand may not be compensated by an increase in demand coming from emerging markets. We examine projections made by others and provide arguments against a large increase in oil demand in non-OECD countries.

The US EIA (2016) and OPEC (2016) project about 24 percent increase in oil demand in non-OECD countries between 2015 and 2025, 35 percent over 2015-2030 and 54 percent over 2015-2040. In contrast, the consultancy Wood Mackenzie predicts a global oil demand peak at 2035[52], while the World Energy Council forecasts the year of 2030. Royal Dutch Shell considers 2021 as a possible oil demand peak (Ward 2016a), and OPEC considers the prospect of oil demand peaking in 2029 if COP21 targets are fully implemented (OPEC WOO 2016).

To examine potential increase in oil demand in non-OECD economies, we compute the implied GDP growth rates in non-OECD economies based on projected oil demand and oil demand elasticities from the literature. IMF (2011) shows that for non-advanced economies the long- term oil demand income elasticity varies between 0.2 and 0.6 (median of 0.4). Consequently, (using the median elasticity), the associated annual GDP per capita growth in non-OECD countries would have to be 4.3 percent over 2015-2030 and 3.5 percent over 2015-2040.

Given their large weight in non-OECD economies, China and India would play a crucial role in the future of oil demand. Over the period 1980-2005, China and India grew by 5.7 percent and 3.5 percent, respectively, in per capita terms (Feenstra, Inklaar, and Timmer 2015). The needed growth in non-OECD countries to counteract the rise of EVs in OECD economies is in line with historical averages (at least for the two biggest economies). However, particularly given the slowdown in growth between 2008 and 2015, the growth needed may not necessarily materialize. More important, even if we assume that such sustained growth over 25 years is achievable, it ultimately contradicts the assumption that EVs will not displace motor vehicles in non-OECD economies as these economies become richer.

Indeed, if non-OECD economies grow at 3.5 percent per capita over 2015-2040, their living standards would increase such that a widespread use of motor vehicles would be implausible. Motor vehicles would be an obsolete technology in the OECD by the early 2040s, according to the fast adoption scenario (Method I). In particular, China and India, if they both grow at the 3.5 percent rate, would move from 24 percent and 10 percent, respectively, relative to U.S. GDP per capita around 2015, to 40 percent and 17 percent in 2040.[53] Under our scenario, by the early 2040s, OECD economies would have completely switched to EVs (or at least to a significant extent, depending on Method I or II), while China and India, a high middle-income economy and a middle-income economy, respectively, by then, would still be relying on a 25-year-old transportation technology. It is equivalent to say 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 (Figure 13).[54] Or to use another analogy, it is as if cars in middle-income countries in 2015 were still equipped with manual windows instead of power windows (see Cherif and Hasanov 2015 or World Bank for a classification of countries by income categories).

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[52] Ward (2016b).

[53] The most recent data on GDP per capita in PPP terms from Penn World Table 9.0 is for 2014. We assume that GDP per capita in the U.S. grows at 1.5 percent over 2015-2040.

[54] Ireland and Greece were around 40 percent of U.S. GDP per capita in PPP terms in 1970 (Penn World Table 9.0). Argentina and Taiwan Province of China were close to 20 percent.

In fact, the EV penetration rate globally is not largely different from that in the U.S. (Figure 9). More tellingly, China in 2016 was already the biggest market for EVs (OECD/IEA 2016). Moreover, as shown previously, late adopters of energy technology are often faster in shifting energy sources. There is no reason to assume that high and sustained growth in non-OECD countries would take place without a fast adoption of both energy and transportation technologies, i.e. renewables and EVs.

What should we expect for oil demand growth in non-OECD economies over the next 25 years? If we assume conservatively an adoption lag of 10 years, we can use the US EIA and OPEC projections for the first ten years after 2017, which implies an increase in non-OECD total oil demand of about 24 percent (from about 47 mbd to 58 mbd). In the following 15 years, we use the fast adoption scenario (Method I), which implies a drop in oil demand for transportation of 7 mbd by early 2040s (compared to the 2015 level).[55] Applying the slow adoption scenario of Method II after 10 years implies a decrease of oil demand for transportation of about 24 percent for the following 15 years. In this case, oil demand would increase by 4 mbd by early 2040s relative to the 2015 level (Figures 16 and 17).

Oil demand may or may not decline much in the next 10 years through late 2020s depending on Method I or II, and other factors could mitigate the effect on prices, for example a drop in supply (although the development of shale technologies makes this possibility unlikely).[56] However, over the long run, from the late 2020s to the early 2040s, in the fast adoption scenario, global oil demand would fall substantially, about 28 mbd, and in the slow-adoption scenario, by about 1 mbd. In comparison, Carbon Tracker/Grantham Institute project about 16 mbd displacement while BNEF projects about 13 mbd displacement globally by 2040.

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 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 an elastic demand.

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 18). 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 twenty years depending on whether the lower end of the confidence interval for parameter q in the Bass Model or Method II is used. Moreover, renewables could take over the whole energy market, driving the price of oil and other fossil fuels even lower.

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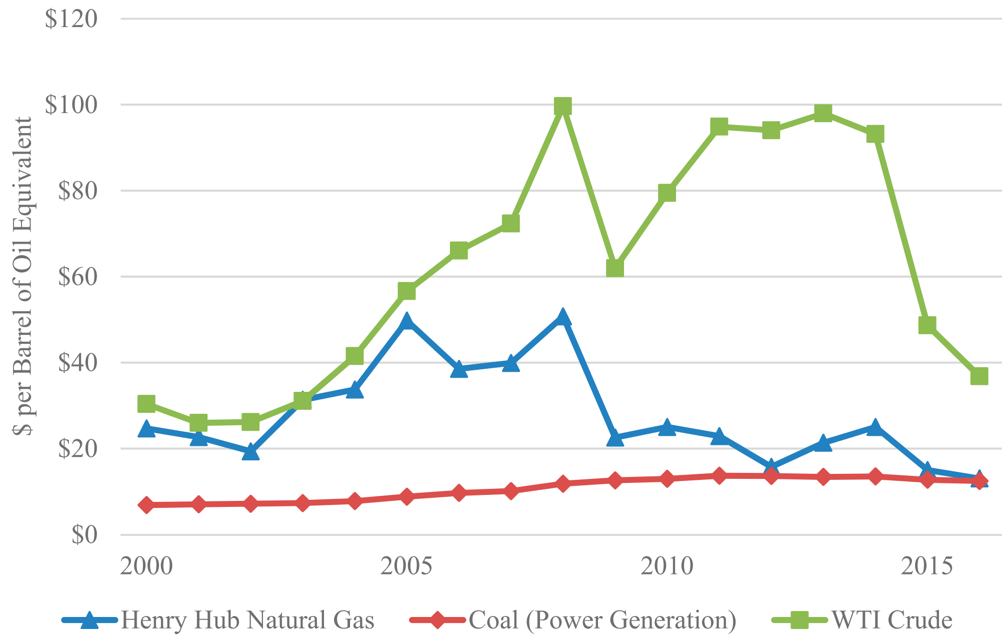
[55] In the projection after 10 years, oil demand in the non-transport sector (one-half of total) is assumed to be constant and the demand in the transport sector falls by 24 percent in the initial 10 years followed by another 48 percent in the subsequent 5 years (a prorated decline of 90 percent in 15 years, according to Method I).

[56] 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.

Figure 18: Convergence of Energy Prices in the U.S.?



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

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 could upend the role of fossil fuels in the energy mix altogether.

Under the fast adoption scenario, 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. If the penetration of electric cars follow the early-20th century transition to motor vehicles from horses, the next decade could witness a large increase in the use of electric vehicles and the beginning of the decline of the motor vehicle share in personal transportation. The following 15 years could then witness a substantial fall in motor vehicles. With road transportation accounting for one-half of the oil use globally and a sole role for oil as the essentially the only fuel source, a substantial drop in the oil price could occur. In the slow adoption scenario, this transition could be delayed by ten to twenty years. As we have observed in this paper, coal did not disappear after 1960. However, it did become much less economically and geopolitically relevant. The same fate might await oil once it loses its exclusive role in fueling cars.

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. If all the extra demand in electricity to power EVs were to be generated from oil solely, the demand for oil would still fall substantially even with current technology. Moreover, renewable technology seems to have reached a threshold in terms of costs and efficiency due to massive investments, particularly in Europe and China. If this trend continues, renewables would represent a sizeable share in the global energy-mix and more than compensate for the additional demand in electricity to power the EVs.

A sizeable increase in car ownership is expected in emerging markets. However, the assumption that these countries would still use motor vehicles while advanced economies would have made the transition to EVs is unrealistic. Indeed, the associated expected rapid economic growth in emerging markets would lead to large improvements in living standards relative to advanced economies to the extent that keeping a 25-year-old transportation technology would be implausible. Moreover, relatively cheap oil is no guarantee for the continuous use of motor vehicles in emerging markets. Indeed, coal is still available and relatively cheap; yet steam boats and steam trains disappeared completely many decades ago.

Some authors have expressed concerns about a possible "sailing-ship" effect sustaining the demand for fossil fuels.[57] Just as sailing ships improved and managed to briefly compete in the face of steam power, the fall in oil prices may allow fossil fuels to continue to dominate temporarily. Lower oil prices—even around $50-60 for the next decade or two[58]—due to, for instance, increased shale production,[59] might delay the energy transition mainly by depressing alternative fuel transportation penetration. EV sales have indeed declined slightly with the 2014-2016 fall in oil price. However, EV producers have also cut their costs even faster (IMF WEO 2016). The car industry is about to reach a turning point in terms of cost of EVs relative to average income, similar to that of the Ford Model T a century ago. With comparable prices of electric and motor vehicles and much lower cost to charge and maintain an electric car compared to a motor vehicle, oil price would have to fall substantially to keep motor vehicles economically competitive. Moreover, cost is not the only factor determining technological adoptions. For instance, coal was cheaper and more easily available than oil throughout the 1920s-1940s, and yet this did not prevent coal's swift displacement. Lastly, although our scenarios are based on the adoption of EVs displacing motor vehicles, other alternative technologies such as hydrogen cars could take over transportation. However, this should not alter our conclusions.

The transition away from oil has deep implications. The economic model of many oil-exporting nations would not be sustainable in such a world. Even if one believes that the probability of such a future is low, the decline in oil revenues for many oil exporters would be so large that the expected loss would nevertheless be sizable. Such low oil prices would obviously have major implications on the macroeconomic stability, including fiscal sustainability, of these countries. To prepare for such a future, diversification away from oil

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[57] Fouquet (2010).
[58] OECD/IEA WEO (2015), see "Low Oil Price Scenario."
[59] Aguilera and Radetski (2016).

should be the most crucial policy item on policymakers' agenda in oil-exporting economies (Cherif, Hasanov, and Zhu 2016). Investment in sectors such as renewables and alternatives to motor vehicles would be natural hedges against the fall in oil prices. For oil-importing countries, low oil prices would reduce the pressure on current accounts but would lead to a shift in tax policy for countries that rely heavily on fuel taxes toward other forms of taxation.

A transition to EVs would also disrupt the auto industry, both in production and maintenance, with much shorter value chains and more reliable vehicles. The production of EVs requires a much smaller number of parts and much less maintenance in comparison to motor vehicles, and the possibility of on-shoring into advanced economies would be likely. Eventually tens of thousands of jobs in advanced and emerging markets could see a transition into new sectors: power charging networks, battery production, and autonomous driving, just to name a few.

Finally, the most important implication of our fast adoption scenario is that the pace at which EVs would replace motor vehicles would meet the conditions to keep global temperature rise below 2°C. There is a strong rationale for coordinated government intervention to make this transition in transportation even swifter to combat the effects of climate change.

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VI. 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."