Introduction

Tesla is the vanguard of the electric vehicle (EV) industry, the world leader in manufacturing and selling EVs. Over the last two quarters, Tesla manufactured 163,650 vehicles at its Fremont, California, factory, equivalent to an annual pace of 327,000 vehicles per year. That capacity brings Tesla into the major leagues of auto manufacturing, exceeding the output of many North American auto plants. Tesla is constructing a new manufacturing plant in Shanghai that should start production in early 2020; it is on track to becoming a large automobile manufacturer, selling over a million vehicles per year in 2021 or 2022.

Per the technology adoption lifecycle that Geoffrey Moore's *Crossing the Chasm* made famous, it is clear that early majority buyers, in addition to innovators and early adopters, are buying EVs. Tesla's Model 3 sedan was 2018's best-selling premium vehicle in the U.S., besting models from Audi, BMW, Cadillac, Lexus, Mercedes and other premium brands, according to Tesla's January 2, 2019 press release. EV demand is booming.

All market segments will tip except three

Tesla and its competitors are steadily eliminating four disadvantages EVs have versus internal combustion engine (ICE) vehicles: purchase price, driving range, charging time (versus refueling time), and charging convenience (versus the convenience of gasoline stations). The strengthening economic and technological forces of electric motors and batteries are so compelling that all transportation segments will convert to electric forms within two decades — except for three where liquid fuels will still be used: transoceanic shipping, long-distance commercial aviation, and rocketry. A key insight is that battery energy density is doubling every ten years. By contrast, the energy content of gasoline, diesel, and other fossil fuels is fixed.

Oil markets and the ever-increasing EV effect

For now, the weekly and monthly vagaries of the oil market overwhelm the effect of EVs reducing the demand for gasoline and diesel fuel. Whether OPEC is boosting oil production or cutting it back, the rate of Venezuela's continuing production decline, the extent to which oil fracking companies are adding rigs in the Permian Basin, available pipeline capacity, China's economic growth rate, whether the Strait of Hormuz is open for commerce — these variables and others like them determine the market price of oil, which historically has been largely driven by supply. Oil is one of the world's most inelastic commodities, since in the short run there are few substitutes.

However, for the first time since the 1973 oil embargo, a powerful dynamic will affect oil demand that is unrelated to economic cycles. The EV effect is currently invisible. This situation is about to change. The electric miles driven by Tesla's fleet, and similarly that of all of its

competitors, is increasing *exponentially*, not linearly. Tesla first announced that Tesla customers had driven a total of one billion miles in June 2015. The global fleet reached ten billion miles by November 2018 and over twelve billion miles in April 2019.

Forecast: the EV effect will be as large as a typical OPEC production adjustment in 2024

OPEC production is currently over 31 million barrels per day. The average OPEC production increase or decrease, over the last 20 years, has been a little over one million barrels per day. An adjustment of two million or more barrels per day has only happened twice. When will the EV miles driven be equivalent to an OPEC move of one million barrels? My forecasting model predicts sometime in 2024. In subsequent years, OPEC's ability to influence the price of oil will steadily deteriorate. By no later than 2026, the EV effect will be at least two million barrels per day.

By comparison, ExxonMobil's oil production in 2018 averaged 2.3 million barrels per day. ExxonMobil is the world's largest publically traded oil company by market capitalization.

The model projects the miles driven by Tesla owners and assumes that Tesla will maintain a 20% EV market share worldwide.[1] This figure is consistent with an estimate of manufacturing capacity that Tesla should be able to add over the next several years. However, if Tesla's market share declines, it may occur because existing significant EV competitors such as BAIC, BYD, GM, Hyundai, Renault-Nissan-Mitsubishi, SAIC, and VW succeed in greatly increasing their EV manufacturing capacities.

In addition, automaker giants such as BMW, FCA, Ford, Honda, Mercedes, and PSA that today are largely absent from the market will be ramping up EV production in earnest starting in 2022.[2] In China, most major domestic automakers are already expanding EV production. Finally, many of the startups pursuing Tesla will not succeed. However, some will indeed achieve a defensible position in the market, further increasing EV sales volume. As EV sales continue to accelerate, Tesla's global market share should eventually decline. The forecast model also includes the effect of plug-in hybrid electric vehicles (PHEVs), which act as partial EVs, in

[1] Per EV-volumes.com's "Global EV Sales for 2018 —Final Report," global sales of plug-in vehicles in the light vehicle market segment were 2.1 million in 2018. EVs accounted for 69% of these sales, and plug-in hybrid electric vehicles (PHEVs) accounted for the rest. http://www.ev-volumes.com/country/total-world-plug-in-vehicle-volumes/, accessed May 23, 2019. Tesla sold nearly 245,000 vehicles in 2018, resulting in an EV market share of 17%. Given that Tesla continues to increase the Model 3 manufacturing rate at its Fremont, California factory and expects to manufacture vehicles in Shanghai in late 2019 or early 2020, its global market share may approach 20% in 2019 or 2020.

[2] Honda and Toyota have yet to make significant commitment to developing EVs. Instead, they are promoting hybrid vehicles and PHEVs.

reducing oil demand.[3] Two other important assumptions are the percent of a barrel of oil refined into gasoline or diesel fuel (60%) and the global average miles per gallon for light vehicles.[4]

The model is conservative in two dimensions. First, it forecasts the effect from vehicles that Tesla and its direct competitors are building or will build in the near future. Thus, the model does not include reduction in petroleum demand from market segments such as buses, electric barges and ferries, motorcycles and scooters,[5] or electric aircraft. Second, the model does not include the effects of electrification in non-transportation segments, such as construction, farm, or mining equipment.

Ways the forecast could be off track (but is unlikely to be)

Borrowing Nassim Nicholas Taleb's concepts of "black swans" and "gray swans," one can anticipate gray swans: events where a forecast is either wrong in direction or timing. (Per Taleb, black swans are nearly impossible to anticipate.) Gray swan events relevant to the EV effect are low-probability events. For example:

- Tesla reported very strong Q3 and Q4 2018 financial results and weak Q1 2019 results. In spite of its Q1 loss, Tesla is unlikely to fail. Nevertheless, if Tesla's financial struggles begin to hamper sales growth, then viable EV competitors, both incumbent automakers and startups such as Byton, Dyson, NIO, Rivian, and WM Motors will take advantage of a Tesla misstep. EV market prospects no longer substantially depend on one company's execution.

[3] The model assumes that PHEVs comprise 30% of total plug-in vehicle sales per footnote #1 and that they generate EV miles at 60% of the rate of (100%) EVs. Data compiled by the Argonne Laboratory comparing the miles traveled by PHEVs versus EVs in the U.S. during 2010-2018 results in a figure of 63%. David Gohlke and Yan Zhou, "Assessment of Light-Duty Plug-In Electric Vehicles in the United States, 2010-2018," Energy Systems Division, Argonne National Laboratory, March 2019, page 6. https://publications.anl.gov/anlpubs/2019/03/151081.pdf

[4] The International Energy Agency published a study on March 20, 2019, "Fuel Economy in Major Car Markets," and determined a value of 7.4 liters per 100 km (31.8 mpg) for light vehicles purchased globally in 2015. Using this figure in the model underestimates fuel consumption because the average age of the global light vehicle fleet is greater than five years and because it likely underestimates the extent to which vehicles idle or are stalled in traffic jams. https://www.iea.org/topics/transport/gfei/report/

[5] Per a recent Times of India story, the government is expected to mandate the sale of only electric three-wheelers from April 2023, while all new two-wheelers with engine capacity up to 150cc driving out of showrooms may have to be powered by electricity from April 2025. Dipak K. Dash, Sidhartha, "Only electric 2-wheelers may be sold in country after 2025," *Times of India*, May 22, 2019. In India, sales of these vehicles outnumber sales of four-wheeled passenger vehicles about 6.5 to 1. Society of Indian Automobile Manufacturers website, Domestic Sales Trends, http://siamindia.com/statistics.aspx?mpgid=8&pgidtrail=14, accessed May 23, 2019. In 2018, India was the world's largest two-wheeler market, besting China.

- A sustained reduction in oil price, which could delay the EV transition, is unlikely. Since 2008, when Tesla launched its first electric car, the price of oil (per the WTI benchmark) declined below $30 per barrel during only two months, January and February 2016. Moreover, as early majority consumers buy EVs en masse, the price of gasoline will cease to be a significant factor in their decision-making process.

- During the next ten years, further non-incremental advances in fracking technology, which could significantly lower the price of gasoline, are unlikely. The price of oil would have to decline to around $30 per barrel for gasoline to be equivalent to the average price of electricity in the U.S. At this price point, few oil firms would be profitable. Moreover, the spread between electricity and gasoline prices is, in general, much greater in other developed countries than in the U.S.

- The probability of non-incremental improvements in ICE vehicle technologies, to make them more competitive with EVs, is very low. In a November interview with *Automotive News* about ICE vehicles, VW's CEO Herbert Diess admitted, "The low-hanging fruits are gone."

- A reduction in the rate of battery energy progress would extend the EV transition time, but not halt it. Many companies and research organizations are pursuing dramatic improvements to lithium-ion batteries, involving chemistries using sodium-ion and other non-lithium elements, lithium solid-state, lithium-air, and lithium-metal, such as lithium-zinc. One of these approaches is likely to bear fruit.

- A recession could delay the EV transition, causing consumers to delay EV purchases. On the other hand, businesses could react to a recession by accelerating EV purchases, given their much lower operating and maintenance expenses versus those of ICE vehicles.

The transition away from fossil fuels—who will benefit?

The transition from vehicles run on fossil fuels to those run on electricity will be one of extraordinary magnitude, involving hundreds of billions of dollars per year of changing buying patterns. Those countries that anticipate and get ahead of this change will benefit, and those countries that ignore it will struggle. Countries that are large net oil importers, such as China, India, Japan, Korea, and most European countries, will benefit the most. In Asia, Thailand, Taiwan, and Singapore will also benefit, as they are also in the top fifteen net oil-importing countries. More generally, most African countries and some South American countries will benefit.

Which countries will struggle? The ones characterized by poorly diversified economies that rely on oil exports for a substantial portion of foreign earnings. These countries include Angola, Iraq, Iran, Libya, Kuwait, Nigeria, Russia, Saudi Arabia, and Venezuela. All of these countries, except

for Russia, are members of OPEC. Canada ranks fourth as an oil exporting country but benefits from a diversified economy. Several oil-producing countries, most notably Norway and the UAE, are anticipating the world's transition away from oil by aggressively promoting the domestic use of EVs and renewable energy. These actions maximize their export earnings.

How will the U.S. fare? U.S. oil production is now a little over 12 million barrels per day, and the U.S. is on the verge of being a net oil exporter. Only eight states (Texas, North Dakota, Alaska, California, New Mexico, Oklahoma, Colorado, and Wyoming) account for over 90% of U.S. oil production, excluding offshore production in federal waters. Two states, Texas and North Dakota, account for approximately half of total U.S. production.[6] Thus, most states will benefit economically from the EV transition. Fortunately, most oil-producing states can take advantage of a hedged bet. With the exception of California and Alaska, all of the major oil-producing states are located in the Great Plains region and can leverage excellent solar and wind energy opportunities. In their case, the transition away from fossil fuels will be disruptive. Yet with foresight, these states can adjust to declining employment in the oil sector by increasing employment in renewable energy and related fields.

Advent of EVs is, with high probability, inevitable

In conclusion, the probability is high that, in many transportation market segments, the transition from petroleum to electricity will soon accelerate into the steep portion of the technology adoption life cycle curve. This shift is inevitable and irreversible. The internal combustion engine likely is doomed.

The sperm whale industry, so well captured in Melville's 1851 novel *Moby Dick*, reached its heyday in the early 1850s. Per the Mystic Seaport Museum, revenues peaked around 1852. The price of sperm whale oil that year exceeded $60 per gallon (in 2010 dollars). Sperm whale oil's first use was for lighting, replacing candles, but the killer app was as a lubricant for the machines of the industrial age. However, as so often happens, enterprising business people found alternatives. Less than forty years later, the price dropped below $20 per gallon as demand declined. Sperm whale oil ceased being one of the world's most valuable global commodities.

We are about to witness the end of petroleum oil as the world's most important commodity. Countries, regions, cities, and companies that ignore this impending historic change do so at their peril.

[6] EIA website, Crude Oil Production, Annual-Thousand Barrels per Day, https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbblpd_a.htm, accessed May 23, 2019.