Interesting relationship of EVs versus a diesel car weighing about 2900 lbs.[1] Estimate the mechanical work at measured average 47mpg at average speeds, at 35% efficiency.[2]

**Diesel car:**

Fuel cost per gallon divided by fuel mileage (in MPG) gives *fuel cost per mile*:

$\frac{\$/gal}{mileage} = \frac{\$}{mile}$. At $5/gallon, this comes to $0.11 / mile.

Assume an EV runs at about 90% efficiency, so if we calculate the mechanical work for the diesel car, and equate that to be the same work as moving an EV of similar size, design and weight, we can estimate the cost of electricity that would make the energy cost for the diesel and the EV the same. First mechanical work:

$EC_{diesel} = 139{,}000\frac{BTU}{gal}$, diesel fuel energy; $\frac{EC_{diesel}}{mileage}$ = energy expended, per mile.

Now, apply efficiency:

$\left(\frac{EC_{diesel}}{mileage} eff_{diesel}\right)$ = mechanical work, per mile. This comes to about 0.303 kWh/mile.

The above result is consistent with how economical the Cruze is to drive. A Tesla Series 3 weighs significantly more, as a mid-size car, not a compact, at between 3800 to 4200 pounds, but most losses at highway speeds are due to wind drag, not rolling friction.[3] 2022 Series 3 Long Range AWD published at 0.26 kWh/mi; 90% of that is 0.23, less than the Cruze. [4] I suspect this is a bit of an understatement, so make all comparisons at the Cruze mechanical work, at 0.303 kWh/mi. That's about a 24% error, possibly due to testing the Tesla with all the lights, A/C, and heating off.[5]

**EV:**

$\frac{\$}{kWh}\left[\left(\frac{EC_{diesel}}{mileage} eff_{diesel}\right)/ eff_{EV}\right] =$ *cost per mile for EV*, using the same mechanical work per mile as above, but with EV losses included. The idea is to find where cost per mile is equal for both cases. Let $x = \$/gal$ for the cost of diesel fuel. Let $y = \$/kWh$ of the equivalent cost for the EV, equating costs per mile:

$\frac{x}{mileage} = y\left[\left(\frac{EC_{diesel}}{mileage} eff_{diesel}\right)/ eff_{EV}\right]$, notice *mileage* cancels.

Solve for $y$: $y = \frac{x\, eff_{EV}}{eff_{diesel}\ EC_{diesel}}$

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[1] 2017 Chevy Cruze diesel, compact, an efficient Internal Combustion Engine (ICE).

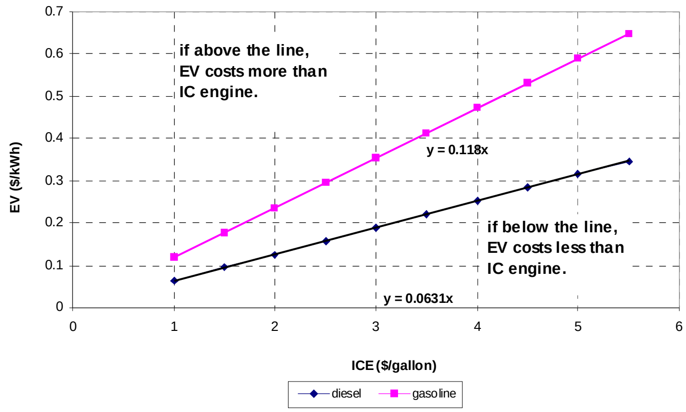
[2] https://rentar.com/efficient-engines-thermodynamics-combustion-efficiency/ This source lists 50% possible efficiency for modern diesel cars; I assumed 35%. $eff_{diesel}$ = 35%.

[3] 2022 Series 3: Lithium Ion Traction Battery w/11.5 kW Onboard Charger, 10 Hrs Charge Time @ 220/240V and 82 kWh Capacity, mid-size sedan. 82kWh/(0.26kWh/mi) = 315 mi. range, est. Tesla also publishes equivalent fuel mileage (MPGe) as combined/city/highway = 131 / 134 / 126, but I have no idea what that means. It's the cost that matters, not the quantities. One huge advantage of EV over ICE type is no idling at stop signs; also regenerative braking, which may enter into energy per mile values.

[4] At $0.37/kWh, this comes to $0.09/mi. Using 0.303 kWh/mi mech work, it's $0.13/mi.

[5] A/C from 1 hp to 10 hp, depending on load. Average speed of 44mph, 5 hp equates to 0.085 kWh/mi, a very large fraction (35%) of the Tesla calculated mech. work (0.23 kWh/mi). The Cruze values are from my own car's average computer readouts, mixed driving with plenty of either A/C or heating.

With the above assumptions, with the units of \$/gallon for $x$, and \$/kWh for $y$, it's a linear relationship with a slope of 0.063. At 28 mpg, 21% efficiency and 124,000 BTU/gal, a gasoline curve can also be made using the same basis, (\$0.11/mi at \$3/gal):




## Charging an EV

Below are some electrical rates for EVs. There are slow chargers and fast chargers, with the fast chargers being quite a bit more expensive and not very good for your battery:[6]

*On average, it costs between \$0.30- \$0.60 / kWh to charge an electric vehicle. Therefore, this means that a small car could cost about \$11.50 to \$23 to fully charge while a bigger or long-distance vehicle could cost between \$22.50 to \$45.*

*Level 3: These types of chargers are much more potent*[7] *than levels 2 and 1. It takes less time to charge at these stations, but not all cars can charge at these ports. Your car charge also needs to be below 80% charge to be charged at these ports. After your vehicle is at 80% of charge, the car starts charging a little slower. Level 3 chargers could take about fifteen minutes to charge your vehicle with 7kWh, covering around forty-five kilometers.*

*Level 2: These charger types are the most typical ones easily found anywhere in public. If your car is at 80% charge, it is better to charge it at a level 2 because it will charge at the same speed as a level 3 charger but at a cheaper cost. Level 2 chargers take between 5 to 12 hours to charge your car entirely.*

*Level 1: These chargers are ones you can have in your garage. It takes several hours to charge your car to 100% at home since the outlet has only 120 volts. If you have time, this would be a cheaper option. Charging at home will take between 8 to over 40 hours, depending on your car's battery size.*

For long distance, it's hard to imagine driving 300 miles, finding a Level 3 charger, and then having to wait 15 minutes for 45km (28mi), or in other words, around 2-1/2 hours before the next 300 miles. But I guess the inconvenience is worth the nearly insignificant difference in energy cost (sarc). Very different story with city driving, with Level 2.

[6] https://www.mach1services.com/costs-of-using-car-charging-stations/

[7] Higher voltage, as much as 800VDC. Some claim full charging to 80% in as little as a half an hour, at which point the power tapers off in order to limit damage to the battery.

**Anything to learn?**
From the preceding, it would seem electric cars might be a good solution for cities, for people who can charge their own cars (have a garage or carport, in other words) and work reasonably close to where they live (~25mi.), and can afford such a car. One thing to keep in mind is if demand is increased, costs go up, and one would expect the same for electricity. How much will demand go up?

It's estimated that 80% of the US population lives in cities. Half the city population would qualify for the above criteria, as a guess. It seems pretty clear from the previous information that EVs are not very appropriate for outside the cities. So, perhaps 40% of motor vehicles and the accompanying fuel demand could be replaced by EVs. Total gasoline consumption is between 370 and 390 million gallons per day the last few years, so assume 40% of 380 million gasoline demand is converted to electrical power.

$40\% \times 380\ million\ gallons \times EC_{gasoline} = 5.524 \times 10^3\ GWh$, per day.

where $EC_{gasoline}$ is 123,000 BTU/gal, and GWh is Gigawatt-hours of energy.

This energy in gasoline is therefore $2.016 \cdot 10^3$ tWh per year, tWh being terawatt-hours.

We can do the same sort of thing as earlier, and use the ratio of ICE efficiency to EV efficiency to calculate electrical demand, but this time EV efficiency is 84%, not 90%, since we are talking about power generation, and have to include line losses from the plants to the vehicle, plus the vehicle's efficiency itself.[8]

$2.016 \times 10^3 tWh \dfrac{gasoline_{eff}}{EV_{eff}} = 527 tWh$ of new generation required to replace gasoline.

It's admittedly a rough estimate, but it could be compared to both installed power and produced power, mostly to dispell the notion that electricity is infinitely abundant. As of 2020, the EIA reported 4010 tWh per year being generated and consumed.

527 / 4010 = 13.1%

This is the amount of power generation that is needed to be added to supply the new electrical demand based on this limited replacement of gasoline vehicles. Moreover, one of the reasons given for using EVs, given their inconvenience, is to slow down or stop climate change, so this only makes sense if renewables are what supplies the new demand. As of 2020, EIA has renewables (wind and solar) supplying about 20% of the power, or 802 tWh. (It has doubled since 2018!)

527 / 802 = 65.6%

This is the increase in generation required with existing renewables. This does not include eliminating diesel, of course. EIA projects that solar will eventually eclipse wind for the major share of renewable power.

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[8] 90% X 93% = 84%. Multiply this by 38%, for fossil fuel plant avg. efficiency, and average EV efficiency from fossil fuel plant sources (from the combustor) is only 32%! 60% are fossil fuel generators at present, so weighted average efficiency comes to 0.4 X 84% + 0.6* X 0.38 = 53%.

**Battery Charging**

This is more of a description of natural limits, than any specific charger or battery. Batteries are subject to hysteresis and wear, just like about everything else. A high rate of charge can damage a battery, especially if it's already near full charge, usually taken as more than 80%. The chargers are subject to limits, too, such as current in a 120V wall plug charger probably shouldn't be more than 15 amps (breakers are usually about that; don't want high current in an extension cord!). High voltage Level 3 needs particular care, since they can cram a lot of electricity into a battery very quickly; and if they are more than 500V, have their own special safety requirements. A Level 2 probably would never exceed 50 amps, 30 amps is often given as a charging limit for some batteries.

Based on that, below are estimated charging times for a 15 *A* Level 1, a 30 *A* Level 2, and a 60 *A* Level 3 at 600V. This is based on the 82 kWh Series 3 Long Range battery capacity. (No power factors taken into account; fast chargers taper off after 80%, which is not shown here.)

| | | | |
|---|---|---|---|
| Level 3 at 600V | $60\,A \cdot 600\,V = 36 \cdot kW$ | $\frac{82\,kWh}{36\,kW} = 2.3 \cdot hr$ | $L3 = 140 \cdot mph$ |
| Level 2 at 240V | $30\,A \cdot 240\,V = 7.2 \cdot kW$ | $\frac{82\,kWh}{7.2\,kW} = 11.4 \cdot hr$ | $L2 = 28 \cdot mph$ |
| Level 1 at 120V | $15\,A \cdot 120\,V = 1.8 \cdot kW$ | $\frac{82\,kWh}{2.4\,kW} = 34.2 \cdot hr$ | $L1 = 9 \cdot mph$ |

long range, 75kWh
shorter, 38kWh
Tesla LR Series 3, 82kWh

$$\frac{128.8\,kW}{0.16\,\frac{kWh}{km}} = 500 \cdot mph$$

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Anecdotally, I was told by one electric car fan that it only took 20 minutes to charge his car at home, and it only cost $20,000 new. Not sure where you get a $20k electric car nowadays, but OK. I would assume it is the smaller 38kWh battery. How much power is that?

$\frac{Energy}{time} = Power$, or $\frac{38kWh}{20min} = 114kW$. Wow! When asked about difficulties of infrastructure to make such a thing widespread, he just said it was an "engineering problem." Obviously he is not an engineer.

To put this in perspective, the average monthly usage for a typical home in the US is about 800kWh, or 26.3kWh per day, or 1.1 kWh/h. In other words, average power is 1.1 kW. A typical home is set up with a 200amp electrical service. At 240volts, his power draw is 475 amps! This is more than two times the nominal rating. This suggests some pretty radical rewiring is necessary wherever a car owner wants to have a quick charge in his house. Or it suggests this person wasn't telling the complete story.

Charging a Tesla on 120V AC power—the power that comes from a standard U.S. wall socket—would take days. In Europe, 230V is the AC standard, according to Germany's ZVEI electronics-industry association. European chargers installed on street corners, at supermarkets, places of work and in home garages can charge a powered down Tesla battery overnight.

The supercharger networks run on DC power, requiring at least 480 volts of power, and can charge up to around 200 miles of range within 15 minutes.

Tesla cites .16kWh / km
Also, 82kWh battery

$rate := 0.16 \dfrac{kWh}{km}$

$batt := 82\ kWh$

$\dfrac{82\ kWh}{rate} = 318 \cdot mi$

So this implies 200 / 318 = x / *batt*

$x := batt \cdot \dfrac{200}{318}$ $\quad x = 52 \cdot kWh$

Using the Power = VA equation ($i$ = A to not mess up units):

$$\frac{x}{15 \cdot min} = (480\ V) \cdot i$$

$$i := \frac{1}{7200} \cdot \frac{x}{(min \cdot V)} \qquad i = 430 \cdot A$$

$480 \cdot V \cdot i = 206 \cdot kW$

$480 \cdot V \cdot i = 277 \cdot hp$

That's a heck of a lot of current, and $Vi = Power$

And a lot of power!

Assuming "overnight" is 12 hours, for 240V case:

$$\frac{x}{12\ hr} = (240\ V) \cdot i$$

$$i := \frac{1}{5760} \cdot \frac{x}{(hr \cdot V)} \qquad i = 9.0 \cdot A$$

$240 \cdot V \cdot i = 2 \cdot kW$

$240 \cdot V \cdot i = 3 \cdot hp$

A 100-mile ride cost the Mini EV owner €26.35 at the Allego fast-charging network, which charges €0.85 per kWh. The conventional Mini cost €20.35 to pump enough fuel to accomplish the same journey.

How much energy?

$$\frac{€ \cdot 26.35}{\left(\frac{€ \cdot 0.85}{kWh}\right)} = 31 \cdot kWh \qquad \frac{31 \cdot kWh}{100\ mi} = 0.19 \cdot \frac{kWh}{km}$$

$$\frac{.19 - .16}{.16} = 19 \cdot \%$$

19% less efficient than Tesla published data.

In Germany, Tesla has raised supercharger prices several times this year, most recently to 0.71 euros in September before falling somewhat, according to reports from Tesla owners on industry forums. There is no public source to track prices on Tesla superchargers.

At that price, drivers of Tesla's Model 3, the most efficient all-electric vehicle in the Environment Protection Agency's fuel guide in the midsize vehicle category, would pay €18.46 at a Tesla supercharger station in Europe for a charge sufficient to drive 100 miles.

By comparison, drivers in Germany would pay €18.31 for gasoline to drive the same distance in a Honda Civic 4-door, the equivalent combustion-engine model in the EPA's ranking.

$$\frac{€ \cdot 18.46}{\left(\frac{€ \cdot 0.71}{kWh}\right)} = 26 \cdot kWh \qquad \frac{26 \cdot kWh}{100\ mi} = 0.16 \cdot \frac{kWh}{km}$$

same as published data

https://www.wsj.com/articles/rising-power-prices-in-europe-are-making-ev-ownership-more-expensive-11671719724?cx_testId=3&cx_testVariant=cx_164&cx_artPos=1&mod=WTRN#cxrecs_s