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Fermi Questions

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Solutions for Fermi Questions, December 2019

Question 1: Electric cars

How much more electrical energy will the United States need to generate if everyone drives electric cars?

Answer: If we all switch from gasoline-fueled to electricity-fueled cars, then we will need to generate more electrical energy. To estimate how much more, we need to estimate the number of cars in the United States, their average gasoline consumption, their energy efficiency, and, for comparison, the amount of electrical energy we currently (sorry about that) generate.

There is about one car for every driver in the United States. The U.S. population is about 3×10^8, but children, the very old, and Manhattanites don't drive, so we will estimate that there are 2×10^8cars. Each car is driven about 10^4 miles per year at 20 mpg (or 1.5×10^4 miles at 30 mpg), giving an average gasoline consumption of 500 gallons, 2×10^3 liters, or 2 m^3. This means that we consume about

$$V = (2\times10^8 \text{ cars})(2\times10^3 \text{ L/car}) = 4\times10^{11} \text{ L}$$

per year of gasoline, nationwide. Checking with reality, the U.S. Energy Information Administration claims that we consumed 142.86 billion gallons of gasoline in 2018. Ignoring their risible claim that we know this number to five significant figures, this is 6×10^{11} liters, so our estimate is pretty good (especially because we neglected non-automotive uses of gasoline).

We can estimate the energy contained in gasoline a few different ways. We might remember that gasoline contains 4×10^7 J/L; we might remember that energy costs about the same for gasoline (at \$4 per gallon) and electricity (at \$0.1 per kiloWatt-hour); we might treat gasoline as CH_2 which combusts to H_2O and CO_2, gaining 1.5 eV for each reaction (see *Guesstimation* for details); or we might just DuckDuckGo it. The energy cost parity method implies that one gallon contains 40 kW-hr so that one liter contains 10 kW-hr (or 4×10^7 J). Thus, our cars consume energy

$$E = (6\times10^{11}\text{L})(4\times10^7\text{J/L}) = 2\times10^{19} \text{ J}$$

every year. That is 20 ExaJoules. Sounds like a lot. Of course, it should be a lot, to fuel 200 million cars for an entire year.

Now let's compare to our actual electrical energy consumption. We can estimate our consumption a few ways. We might start from our own power bill (about \$100 per person per month at \$0.1/kW-hR gives 10^3 kW-hr per person per month, or 1.5 kW per person); we might remember that 100 1-GW nuclear power plants supply 20% of our electrical energy; we might have some other piece of otherwise useless, but suddenly applicable, knowledge. Either way, we get to 500 GW:

$$P = (100)(1 \text{ GW})/0.2 = 500 \text{ GW}$$

or

$$P = (1.5 \text{ kW/person})(3\times10^8 \text{ persons}) = 500 \text{ GW}.$$

Since there are about $\pi\times10^7$ seconds in a year [a useful number to remember, although of course the exponent (7) is far more important than the coefficient (π)], this gives a total yearly electrical energy consumption of

$$E_{elec} = (\pi\times10^7 \text{ s})(5\times10^{11}\text{W}) = 2\times10^{19}\text{J}.$$

This is ~~exactly~~ (nothing we do in this column is exact) about the same as the energy consumed in our cars.

However, we are comparing chemical energy in gasoline with the mechanical energy of electricity, so we need to include the efficiency of converting gasoline energy to mechanical energy. The efficiency of automobile engines is more than 10% and less than 100%, so we will take the geometric mean and estimate 30%. This means that our 20 ExaJoules of gasoline energy can be replaced by 6 ExaJoules of electrical energy.

Thus, if we replace all of our gasoline-fueled cars with electricity-fueled cars, we will need to generate about 30% more electrical energy. That's 150 more 1-GW power stations. That is a lot.

Question 2: Chicken poop

How much chicken excrement is produced in the United States every year?

Answer: To estimate this, we need to estimate the number of chickens produced annually and the excrement per chicken. We will only consider literal chicken #$%#^ and not figurative chicken #$%#^ (that is, excluding politicians, bureaucrats, managers, administrators, etc.).

We could estimate the number of times per week we eat chicken, the type of chicken consumed (wings, tenders, thighs, breasts, salad, …), and the amount of chicken per serving, or we just can consider the overall consumption. The average American consumes more than 1 and less than 10^3 pounds of chicken per year, giving a geometric mean of 30 pounds (15 kg) per person per year.

Since the span of our bounds is three orders of magnitude, the uncertainty of our estimate is correspondingly large. If our bounds are a 95% confidence interval, then that corresponds to four standard deviations ($\pm 2\sigma$). This means that our uncertainty, σ, is ¾ of an order of magnitude, or about a factor of five, and our estimate is thus between six and 150 pounds per year. That is rather imprecise, even for this column.

Let's try again to refine the estimate. There are 21 meals in a week, so we can estimate that we eat chicken more than once and fewer than 21 times per week, giving a geometric mean of five times per week. We eat more than ¼ pound and less than a pound, giving an estimate of ½ pound per meal (that's the volume of one cup, so it is not unreasonable). At 50 weeks per year, we then consume

$$m = (5 \text{ meals/wk})(0.5 \text{ lb/meal})(50 \text{ wk/yr}) = 10^2 \text{ lb/yr.}$$

Reality, according to the National Chicken Council (I didn't even know we have a National Chicken Council), was 93.8 pounds per year in 2018.

So how much, um, excrement does a chicken produce? How can we possibly estimate that? I have no idea how to estimate chicken "output," but I can estimate chicken "input" and apply conservation of mass. The standard conversion factor from one "trophic level" to another is 10. In other words, at each level of the food chain, 10 pounds of food gives one pound of animal. However, chicken is far more productive than most animals, which is why chicken meat is much less expensive than pork or beef. Since chicken is about three times cheaper than beef (cheaper, but not 10 times cheaper), we will estimate that it takes three times less food to make a pound of chicken than a pound of beef. Therefore, the 100 pounds of chicken we ate last year consumed 300 pounds of feed and excreted 200 pounds of excrement.

Now we can estimate the total amount of chicken poop produced:

$$M_{\text{poop}} = (2 \text{ lbs/lbs-chick})(10^2 \text{lbs-chick/person})(3\times10^8 \text{people}) = 6\times10^{10} \text{ lbs} = 3\times10^{10} \text{ kg.}$$

That is 30 million tons of chicken poop. Every year.

But that's only the chickens we eat, not the chickens whose eggs we eat. There are about 10 eggs per pound. If we also eat two pounds of eggs per week, then we would consume 20 eggs, which seems high. Therefore, we'll estimate that we consume 5 to 10 eggs per week, or about 1/3 of our chicken consumption. Assuming the same conversion factor for feed to eggs as for feed to meat, we will get 1/3 as much more waste.

Thus, our total chicken excrement production is 40 million tons per year. That seems like a LOT! It is a lot. Imagine having to dispose of our share of 100 kg of chicken excrement every year. The guest room would fill up very quickly.

Phheeew!