One Billion Machines

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1 Introduction

Achieving net-zero emissions in the U.S., in time to comply with the International Panel on Climate Change (IPCC) goal of keeping global warming under 1.5-2.0 degrees C above pre-industrial levels, requires understanding the machines we use, their energy needs, and how, and how quickly, we can transition those machines to ones that are fueled by renewable energy (predominantly wind and solar). With the high-level goal of identifying the industrial and economic opportunities associated with achieving net-zero emissions for the U.S., we find it useful to start with a list of the demand-side machines that drive our consumption of fossil fuels, and a list of the electrical infrastructure machines that will enable us to provide modern electric alternatives and substitutes. The accounting is based on published data sets, and is necessarily imperfect[1].

To decarbonize our economy, we must electrify approximately one billion machines. In this report, we have added up these machines to understand how many we must replace at the earliest opportunity — either failure, or retirement —(we can best achieve our climate goals with a 100 percent adoption rate, which means replacing every fossil-fuel burning machine at the end of its life-cycle). We count vehicles in section 2. Space heating machines are counted in section 3 and water heaters in section 4. We count cooking machines in section 5, and clothes drying machines in section 6. In section 7 we tabulate home breaker box upgrades, and in section 8 we add residential solar and battery installations.

The tally ends up at 1,063,000,000 which is just a little more than a billion machines. That means that 1 billion machines, or 50 million machines a year for the next 20-25 years, is a first-pass approximation at the task to be completed.

This may sound like a lot, but we already have an extraordinary rate of annual machine sales and production. The U.S. manufactures around 12 million automobiles a year and with imports included purchases around 17 million. That's 340 million vehicles in 20 years. Similarly we purchase around 9 million water heaters a year already. The challenge isn't about making new machines as much as it is about making sure our /textbfnext machines are electric and powered by renewables or nuclear.

2 Road Vehicles

Not every road vehicle will be electrified, but under any full decarbonization scenario the great majority will be. The remainder will be able to operate on biofuels, (renewable) synthetic fuels, and (renewable) hydrogen. There are approximately 17 million automobiles (cars and light trucks) sold in the U.S. each year, of which around 12 million are domestically manufactured. The average age of these vehicles is 11-12 years and These vehicles last around 20-25 years implying we have one lifecycle to replace them all. We tally these in Table 1.

3 Space Heating

There is a large variety of space heating machinery in circulation in the US. These machines include, for example, central furnaces, boilers and gas heaters. We tally these in Table 2.

[1]For instance, we do not yet include counts of lawn equipment, such as lawn mowers and leaf blowers and chainsaws; nor do we include counts of recreational vehicles, such as ATV's and offroad vehicles, including unregistered motorcycles; nor do we include boats.

Type	Machines (M)
Cars	108.5
Light Trucks	144.0
Motorcycles	8.6
Heavy and Freight Trucks	14.4
Buses	0.95
Total vehicles	**276.5**
Currently Electric	1.6
Total fossil vehicles	**275**

Table 1: Transport machine count (2019). Data from Transportation Energy Data Book, Edition 39. Stacy C. Davis and Robert G. Boundy. Oak Ridge National Laboratory., Table 3.5., Argonne National Laboratory (2020-09-28). "FOTW 1153, September 28, 2020: Cumulative Plug-In Vehicle Sales in the United States Reach 1.6 Million Units". Vehicle Technologies Office, EERE, USDoE. Retrieved 2020-10-06.. Light Trucks includes pickups, vans, sport-utility vehicles and other light trucks. Heavy and Freight Trucks includes medium and heavy trucks over 10,000 lb. gross vehicle weight rating.

Fuel	Machines (M)
Natural gas	57.7
Propane	5
Fuel oil/kerosene	5.8
Total Fossil	**68.5**
Electric resistance	29.1
Total Fossil + Elect. Resist.	**97.6**

Table 2: Space heating machine count. Data from EIA RECS Table 8.5

4 Water heating

Most homes have a tank-type water heater that heats a large volume of water and stores it ready for use. These are most typically heated by electric resistance or natural gas. There are very viable electric heat-pump driven alternatives now that reduce the energy required by approximately 1/3. We tally these in Table 3.

5 Cooking Machines

Cooking is vital to practically all households in the U.S. and is often powered by fossil fuels. Cooking is a cultural touchpoint, and we have been told that high-heat, high-BTU natural gas is the 'best'. Excellent electric induction cooking alternatives now exist in every category as do new cooking appliances such as electric 'air-fryers'. These electric machines improve the air quality (and health) in the house, give greater control over temperature and offer many other advantages for our future kitchens. We tally these in Table 4.

Fuel	Machines (M)
Natural gas	56.3
Propane	4.2
Fuel oil/kerosene	2.8
Total Fossil	**63.3**
Electric resistance	54.3
Total Fossil + Elect. Resist.	**117.63**

Table 3: Water heating machine count. Data from EIA RECS Table 6.5

Fuel	Machines (M)
Natural gas range	35.2
Propane range	5.5
Total Fossil range	**40.7**
Natural gas cooktop	6.5
Natural gas wall oven	1.8
Outdoor grill (propane)	42
Outdoor grill (natural gas)	4
Total Fossil cooking	**95**

Table 4: Cooking machine count. Data from EIA RECS Table 3.5 and EIA RECS Table 3.1

Fuel	Machines (M)
Natural gas	17.9
Propane	1.3
Total Fossil	**19.2**

Table 5: Clothes drying machine count. Data from EIA RECS Table 3.5

6 Laundry Machines

Washing machines are already all electric, and advances in detergents have enabled much more energy efficient cold water cycles that have substantially reduced US energy use. The only machines using fossil fuels in our laundries are the gas and propane clothes dryers. The most efficient alternatives to these machines are heat-pump electric dryers that use approximately 1/3 of the energy of their resistance electric counterparts. We tally these in Table 5.

7 Breaker Boxes

Residential electrification will require upgrading breaker boxes in the majority of houses to supply a greater amount of electricity. The portion of houses that may not require such an upgrade are those already using electricity for major loads like space heating. According to the U.S. Census Bureau, 53 of the 140 million housing units currently use electricity as main space heating fuel[2]. We estimate that 75% of these units will not need a breaker box upgrade. This leaves approximately 100 million breaker boxes that will need to be upgraded.

8 Rooftop solar and home batteries

Using NREL's estimate of rooftop solar technical potential[3], we estimate that roughly 83% of residential housing unit rooftops are suitable for a solar installation. While residential rooftop solar stands to be the cheapest source of electricity where suitable, we estimate conservatively that half of households take advantage. Further, there are already approximately two million existing rooftop solar installations in place today[4]. Given the roughly 140 million housing units in the U.S. today, this means we add approximately 58 million new rooftop solar installations.

Given the rapidly falling prices of lithium ion storage, residential battery installations are expected to play a critical role in balancing supply and demand of a renewable grid[5]. The exact amount remains up for debate, but major solar installers now install batteries standard, as these systems can bring

[2]Note that this number of physical housing structures (U.S. Census Bureau, 2019 National Housing Unit Characteristics) differs from the approximately 120 million households which are occupied (U.S. Census Bureau, 2019 General Housing Data, All Occupied Units). See U.S. Census Bureau Definitions for more details. Data on electric heat from U.S. Census Bureau, American Housing Survey, 2019.

[3]Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment. Pieter Gagnon, Robert Margolis, Jennifer Melius, Caleb Phillips, and Ryan Elmore, National Renewable Energy Laboratory.

[4]United States Surpasses 2 Million Solar Installations, SEIA, 2019.

[5]Projecting the Future Levelized Cost of Electricity Storage Technologies. Joule. Volume 3, Issue 1, 16 January 2019, Pages 81-100

down soft costs and decrease solar payback periods[6]. We conservatively assume 50% of rooftop solar installations will be accompanied by a home battery. This gives approximately 29 million home battery installations.

9 All of the machines

In Table 6, we show the totals across these machines types. To cut fossil fuels from the demand–side energy uses, we must replace very nearly one billion machines.

Technically this is not even all of the machines we'll need to replace. Roughly 83 million space and water heating machines are in use today that use electric resistance heating. These machines don't take advantage of the thermodynamic gains of heat pumps (roughly three times less electricity required per unit of heat delivered), and thus add to the challenge of supplying 100% clean electricity and add to the emissions produced as we transition the electricity supply. We include these machines in our tally, as they stand to cut emissions, ease the clean electricity transition, and save householders money on energy bills in the process. A host of other machines will also be replaced in natural end-of-life replacement, and a many other categories (including boats, chainsaws, lawnmowers, etc.) will also be replaced. We are not starting from zero and the market already has momentum and there are viable non-fossil-fuel machines now available in every category.

Type	**Machines (Millions)**
Fossil space heating	69
Fossil water heating	63
Clothes Drying	19
Cooking	95
Vehicles	275
Breaker boxes	100
Vehicle chargers	275
Rooftop solar	55
Home battery storage	29
Total Fossil	**980**
Elect. Resist. space heating	29
Elect. Resist. water heating	54
Total Fossil + Elect. Resist.	**1,063**

Table 6: Adding up all the machines.

[6] Tesla's Solar Panels to Be Sold Only With Powerwall. Bloomberg, Max Zimmerman April 2021.