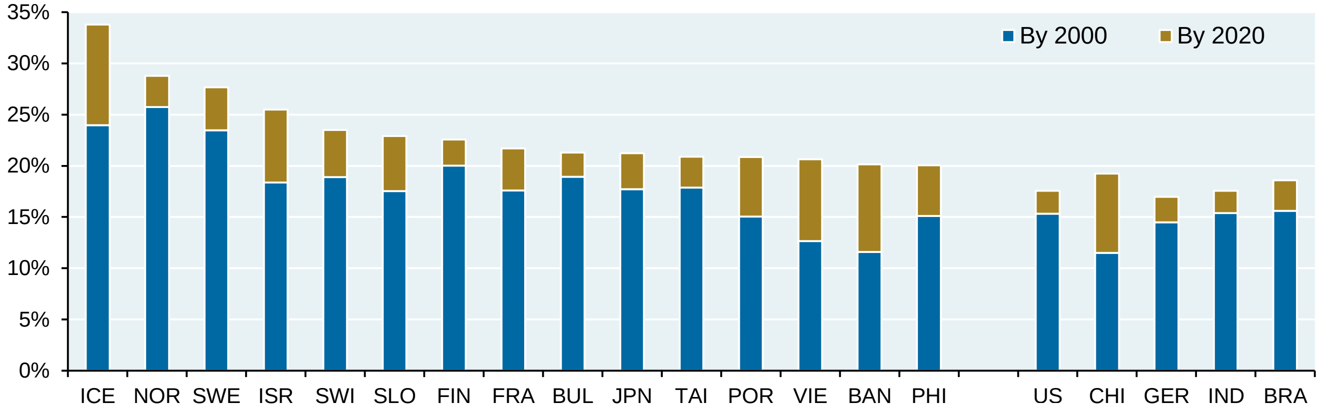
## Introductory comments on the electrification of everything

Electrification of energy use is at the center of many deep decarbonization plans. Is it possible to electrify large parts of a modern economy? The jury is out. Over the last 20 years, electricity as a share of energy use rose by just 2%-3% in most countries, a *very* slow rate of change. A few countries have reached 25%-30% electrification, but they are typically very small countries with abundant hydro- or geothermal power, and/or they are highly reliant on the outside world. Larger countries still rely on electricity for less than 20% of energy use with small gains since the new millennia began. Remember: a lot of what you read from energy futurists is a blueprint for a world that does not have proof of concept yet.

**The slow advance of electrification, 2000 to 2020**

Electricity share of primary energy consumption



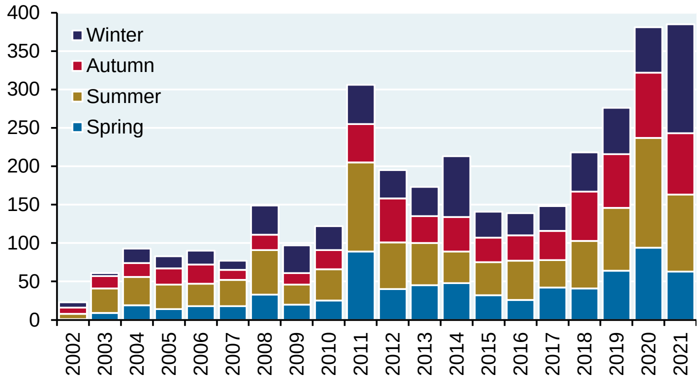
Source: BP Statistical Review of World Energy, JPMAM. 2021.

**The next three sections all relate to electrification**: the headwinds policymakers face when trying to expand transmission grids to facilitate greater electrification in the first place, and efforts to increase electrification of transportation and residential/commercial heating.

Quick overview of the grid status quo: the US electricity grid has been called the “largest machine in the world”, comprising 7,700 power plants, 3,300 utilities and 2.7 million miles of power lines. In the process of electrifying everything, policymakers will need to ensure the stability of this machine. Some US utilities are struggling already with rising grid outages in recent years. Each utility reports average outage minutes per customer per year; some experienced long outages in 2020, although they tended to be the smaller ones.

**US reported electric disturbances by season**

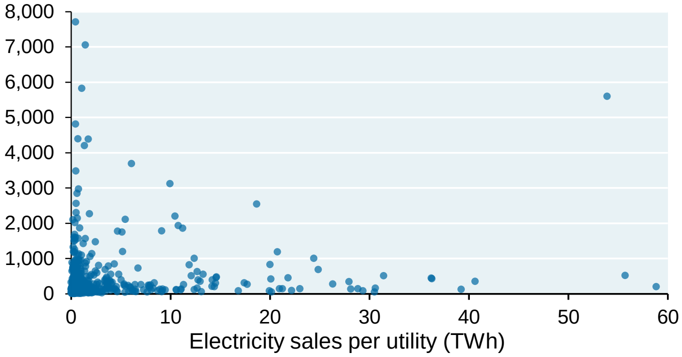
Number of disturbances



Source: Department of Energy, JPMAM. 2021.

**System average interruption duration index (SAIDI)**

Outage minutes, annual average per customer, 2020

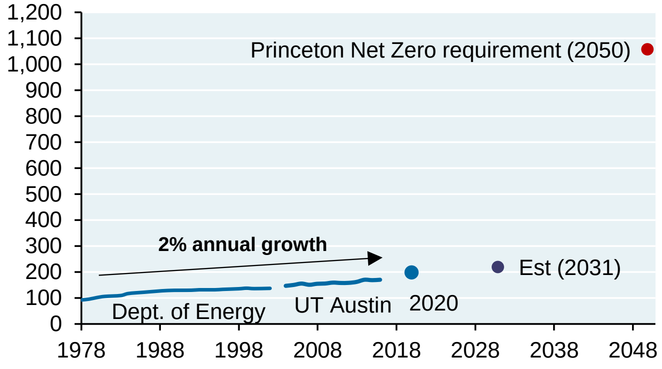


Source: EIA, JPMAM. 2020. Dots represent a given utility's operations within a specific state.

## [1] The US transmission quagmire shows little sign of changing

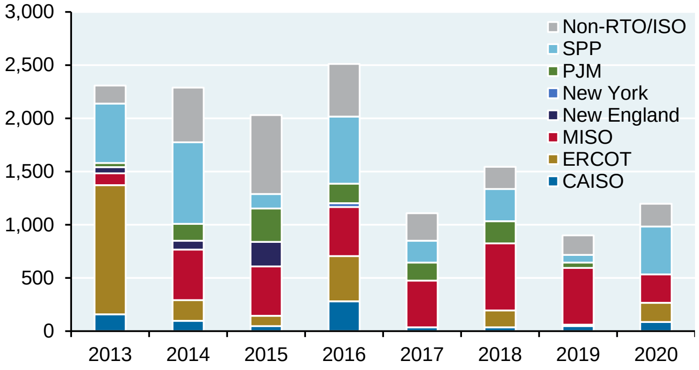
The US plans to electrify a lot of household and commercial energy use over the next ten years. Unfortunately, the US grid is a slowly-changing morass that's already struggling to incorporate more renewables as traditional generation capacity is retired[6]. US transmission infrastructure has been growing at just 2% per year since the late 1970's. More recently, despite the need for more transmission, the grid has been growing even more slowly (second chart). Some projections now estimate just 1% transmission growth to the year 2030. Compare that with the grid expansion required for many Net Zero plans, one example of which is shown in the first chart.

**US transmission grid growing at just 2% per year since 1978,** Thousands of gigawatt-miles



Source: DOE, UT Austin, *"Net Zero America"*, Larson et al., Princeton. 2020.

**Most recent growth has been just 1% per year**
Miles of transmission lines added by year and region



Source: S&P Global. 2020.

In last year's paper, we covered the saga of the now-defunct Northern Pass project designed to bring hydropower from Quebec to Massachusetts, blocked by some of the most progressive states in the country. When I speak with Net Zero advocates, if they stare off into space on this topic rather than confronting the NIMBY/state's rights issue head on, it tells me that they are not that serious about addressing real-world obstacles to deeper decarbonization.

Northern Pass is not the exception. **Transmission projects are being blocked across the country by landowners and by conservation groups objecting to the very electrification that they intensely lobby for on paper**. If you want to see people contort themselves into pretzels, read how lawyers at the Illinois Environmental Law and Policy Center explain their litigation to block wind transmission projects in the Midwest[7].

- After New Hampshire blocked Northern Pass, Maine voters blocked the New England Clean Energy Connect project which was also designed to bring Canadian hydropower to Massachusetts. Maine voters approved a referendum by 59% to 41% to block power lines in the Upper Kennebec region, and to require Maine's legislature to approve by a 2/3 majority all large transmission projects on public lands. Conservation efforts to block the project were reportedly financed by NextEra and other utilities in the region. Avangrid, a subsidiary of Iberdrola, had already spent $350 million on the project
- Iowa passed a law preventing the use of state eminent domain for transmission lines. Iowa has one of the highest wind capacity factors in the country at ~40%, but this move effectively shelved a project designed to bring wind power from Iowa to Illinois, and another project to bring wind power to Wisconsin
- Arkansas blocked a wind project from Oklahoma to the Southeastern US
- Missouri blocked a wind project from Kansas to Indiana
- Colorado blocked a wind project from Wyoming to Nevada, Arizona and California
- In California, the state's environmental protection law is often used to delay or stop projects that would have significant benefit to the environment such as solar farms and mass transit
- In Florida, oddly enough, Gov. DeSantis and the state legislature passed laws *preventing* local entities from blocking solar projects and renewable natural gas projects

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[6] 39 GW of coal, gas and nuclear capacity have been retired since 2013; another 27 GW to be retired by 2028

[7] "*In aim to expand power grid, Biden faces pushback from conservation allies*", Houston Chronicle, Jan 2022

Some Republicans blame Democrats for the ease with which infrastructure projects are blocked. "*Now with Joe Biden's ambitious climate goals, Democrats are realizing that allowing activist groups to sue over every infrastructure project might not have been their smartest idea. You are lying in the bed you made. It did not have to be this way*" (Rep. Pete Stauber, R-Minn).

**Why is it so hard to get transmission projects approved and built?**

- **Federal eminent domain** was used over the last 100 years to build railroads, parks, natural gas pipelines, airports, naval stations, interstate highways and fiber optic cables. But eminent domain is *not* being used broadly today by the Federal government to accelerate transmission grid improvements
- **There is no mechanism at the Federal level** to enable national transmission grid planning involving regional integration of renewables across regions and interconnections. The Energy Policy Act of 2005 established a potential pathway to give the Federal government backstop siting authority. However, that authority was challenged in the courts and has been effectively neutralized (see box)
- Even when regional transmission authorities conclude that a given new multi-state line would produce economic benefits for the entire region, **regulators in a state crossed by that line can block it**, and multi-year challenges can be staged by consumer and environmental groups
- The **cost allocation process** for large interregional projects can take years, even when all parties involved agree to proceed with a given project
- **The US Federal Energy Regulatory Commission also does not have jurisdiction** over public power and municipal utilities which serve ~28% of all electricity customers in the US

**Then there's the issue of US interconnection queues**. Developers of generation capacity have to ensure in advance that their project will be connected to the grid, and how much it will cost since they usually have to pay for the interconnection. The process requires interconnection requests to be handled one at a time in the order they enter the queue. It all worked well when generators added large centralized nuclear and gas plants.

**But when hundreds of small renewable projects swarm the queue at the same time, it's an inefficient process that can take up to 4 years**. This is particularly true when a given project withdraws from the queue (usually when developers find out that interconnection costs are too high), which then requires the rest of the queue to be re-shuffled and re-evaluated. This is not just a US issue; last year in **Spain**, 40 GW of wind power and 40 GW of solar power had connection permits for the grid but risked losing access due to administrative delays.

**US Courts constrain eminent domain powers granted to FERC in the 2005 Energy Policy Act**

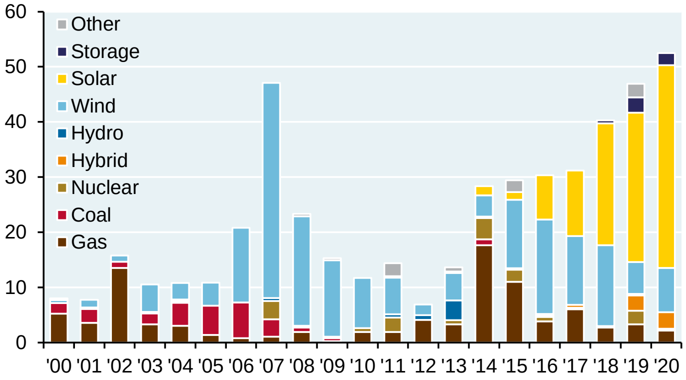
The Energy Policy Act of 2005 granted FERC siting and eminent domain authority on transmission line projects if, for example, a state is able to site the project but has not done anything after one year. FERC interpreted this clause as meaning that "a state *could* have sited the project but decided to deny it anyway", and tried to apply eminent domain. States, environmental groups and industry groups all challenged the rule in court. In 2010, the US Court of Appeals for the Fourth Circuit invalidated the rule as being beyond FERC's authority, ruling that FERC can only use its backstop siting authority when a state refuses to even *rule* on the project within a year, or if the state grants a permit but attaches "project killing conditions". See "*Interstate Transmission Challenges for Renewable Energy: A Federalism Mismatch*", Alexandra Klass and Elizabeth Wilson, Vanderbilt Law Review, 2019

The MISO region which spans 15 Midwestern and Southern states is a good example. The first chart below shows the requested GW of generation entering the interconnection queue each year by generation type. On the right, we show the amount that ended up ultimately getting connected: usually much less than 50%, with the remainder withdrawn. **The problem is not just in the MISO region: from 2010-2020, only 24% of projects in interconnection queues reached commercial operation in CAISO, ISO-NE, MISO, NYISO and PJM regions combined[8].** Completion rates were even lower for wind (19%) and solar (16%) projects. Time in the queue almost doubled from 2 years from 2000-2010 to 3.7 years from 2011-2021.

The third chart shows an aggregation of all projects that were in US interconnection queues at the end of 2021. These "in limbo" projects represent multiples of existing wind, solar and storage capacity, but a timetable for their completion is uncertain due to the factors discussed earlier. The last chart shows the growth in the queue on a national level since 2014, broken down by fuel type.

**The clogged MISO interconnection queue**

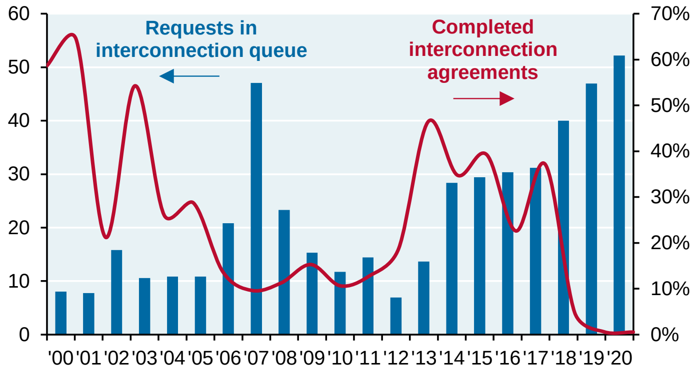
Requested gigawatts in interconnection queue



Source: MISO. June 2021.

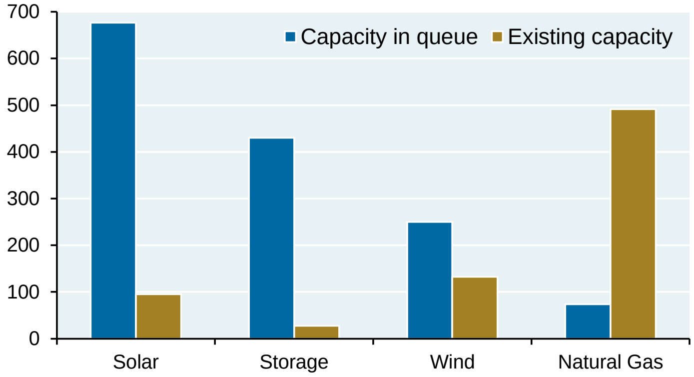
**Less than 50% of MISO queue projects are completed**

Gigawatts %, completed requests



Source: MISO. June 2021.

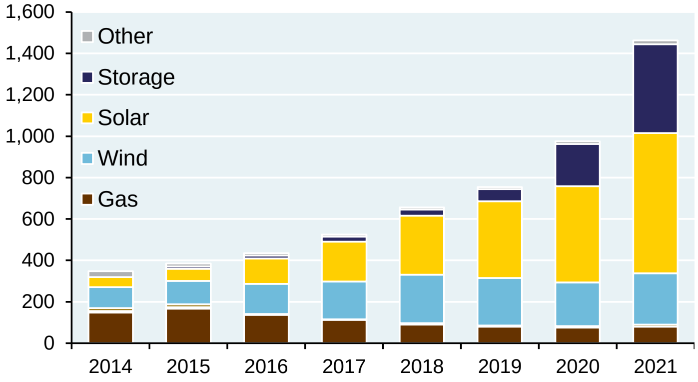
**Renewable capacity in interconnection queues dwarfs existing capacity,** Gigawatts (December 2021)



Source: LBNL, EIA, JPMAM. April 2022.

**US interconnection queue by fuel type**

Requested gigawatts in interconnection queue



Source: LBNL. 2021.

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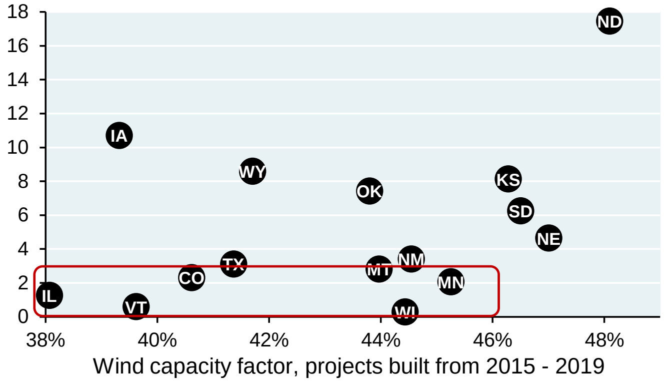
[8] "*Transmission in the United States: What Makes Developing Electric Transmission So Hard?*", Scott Madden Management Consultants, July 2021

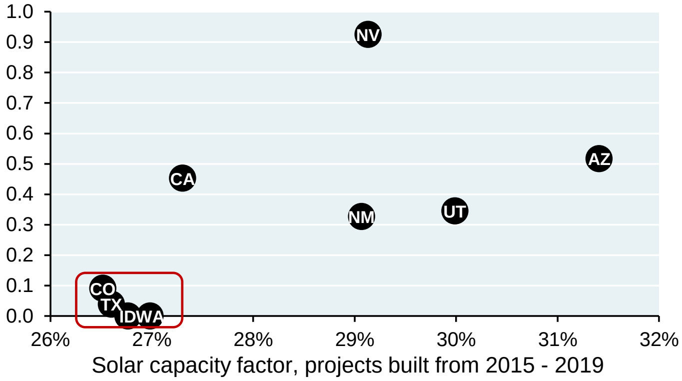
**Where might local objections and interconnection queue delays have the largest impacts?** One way to think about it: which states are underutilizing their wind and solar natural resources? We measure wind or solar resource potential by looking at capacity factors on recently built facilities, and compare this resource potential to actual generation per capita. Illinois, Colorado, Vermont, Wisconsin and Minnesota have wind capacity factors over 38% but low in-state wind generation per capita. Similarly, Idaho, Texas, Colorado and Washington have underdeveloped solar resources given solar capacity factors on recent projects that exceed 26%.

**Wind resource vs generation**
Wind MWh per capita, 2020



Source: EIA, JPMAM. 2020.

**Solar resource vs generation**
Solar MWh per capita, 2020

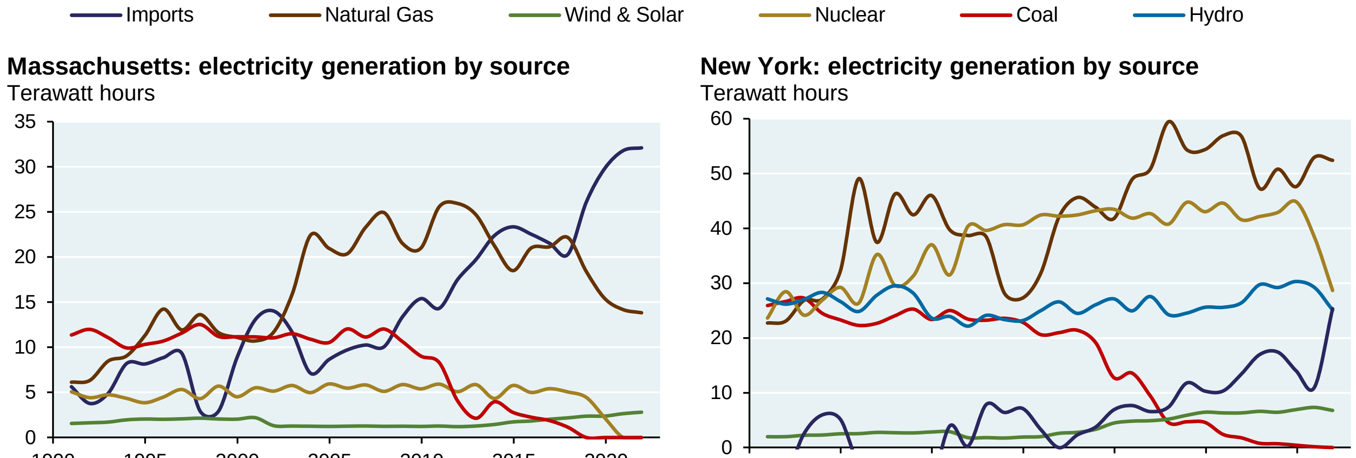


Source: EIA, JPMAM. 2020.

**So, where does that leave Massachusetts now that Maine and New Hampshire killed their access to low-cost, clean Canadian hydropower?** As shown in the next chart, Massachusetts is increasingly reliant on electricity imports from neighboring states, much of which is not very "green". **Over the long run, many states have given up on Canada and plan to rely on offshore wind instead**. It's not cheap: procurement prices for offshore wind in Massachusetts range from $70 to $100 per MWh for projects expected completed by 2025. That compares to average wholesale electricity prices in Massachusetts of $50 per MWh last year. Massachusetts long term policy commitments for offshore wind add up to almost 50% of the state's electricity consumption**. If so, there may eventually be sticker shock as offshore wind project costs are passed through to residential and industrial electricity consumers.** Around 10 GW of offshore wind are in the advanced permitting stage across the Eastern Seaboard; we will continue to monitor where PPAs and electricity prices end up.

**New York is notable as well**. Since the shutdown of the Indian Point Nuclear Plant, coal- and gas- powered electricity imports from PJM have closed most of the gap. This fall, construction is set to begin on a 339-mile high voltage transmission line transporting Canadian hydropower. It has taken 17 years to get to this point, and the power line may not be completed until 2025.

**To conclude: the disconnect between transmission grid assumptions in Net Zero plans and what's happening on the ground is almost as wide as the chasm between expectations and reality on carbon sequestration.**



**Massachusetts: electricity generation by source**
Terawatt hours

Source: EIA, JPMAM. November 2021.

**New York: electricity generation by source**
Terawatt hours

Source: EIA, JPMAM. November 2021.

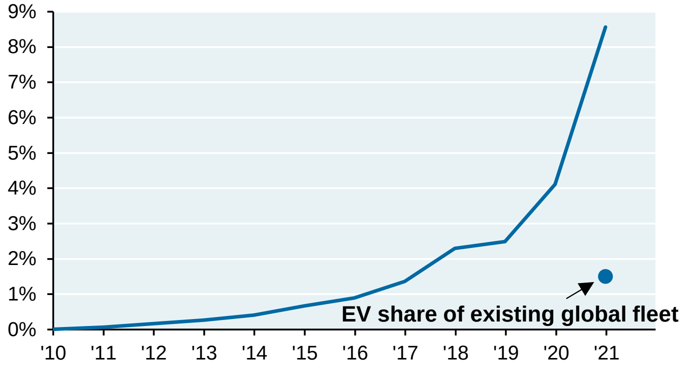
## [2] How should the US deal with gasoline super-users? And what about rising metals prices and battery costs?

Global EV sales gathered steam in 2021, growing to almost 9% of total vehicle sales. That's a meaningful jump from the prior year, although to be clear, EVs are still just 1.5% of the global fleet of vehicles on the road. As discussed last year, the longer useful life of today's automobiles limits the pace of EV adoption absent aggressive subsidies and incentives to switch. The charts on page 21 show projections for EVs as a % of sales for passenger cars and trucks, and how quickly EV sales translate into fleet share gains.

US EV sales trailed many countries in 2021, coming in at just 4.5% of total vehicle sales[9]. Furthermore, lower mpg light trucks and SUVs are still the most popular vehicles in the US market (see third and fourth charts). EVs face a steeper climb in the US, which has the highest share of global transport energy consumption, the highest vehicle share of transport energy, the highest number of vehicles per capita, the longest distances driven per capita, the lowest public transit usage and the lowest gasoline prices as well[10].

**Global electric vehicle market share**

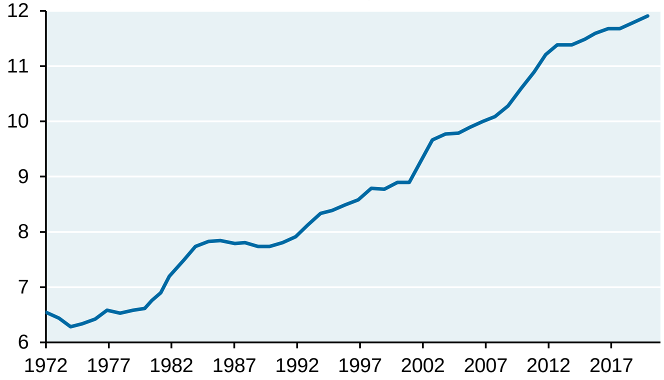
EV share of annual global vehicle sales



Source: IEA. 2021.

**Cars last a lot longer than they used to**

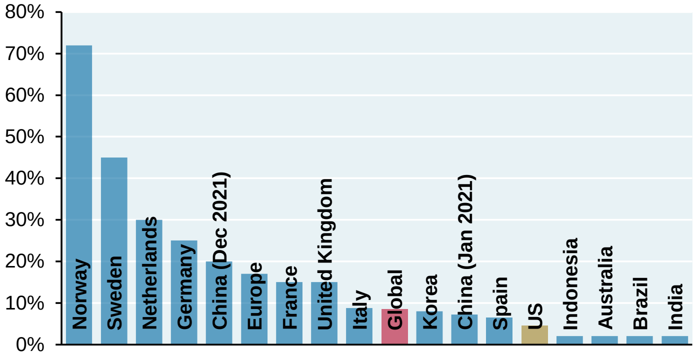
Average age of US light vehicles in operation, years



Source: US Bureau of Transportation Statistics, IHS Markit. 2020.

**Electric vehicle market shares in 2021**

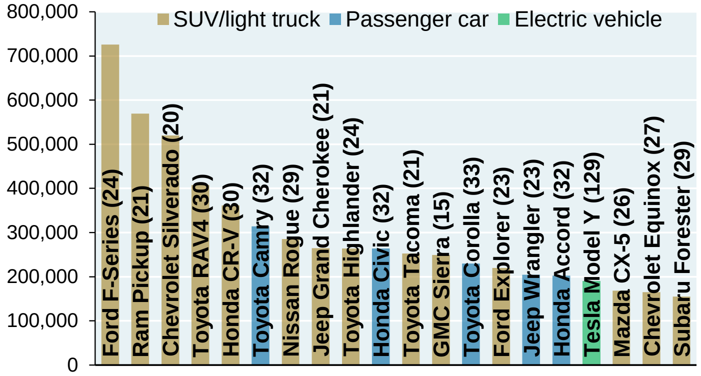
EV share of annual vehicle sales



Source: IEA. 2021.

**US: top 20 vehicles sold in 2021**

Number of vehicles sold (with miles per gallon or mpge)



Source: Forbes, fueleconomy.gov. 2021. Mileage = combined city / highway.

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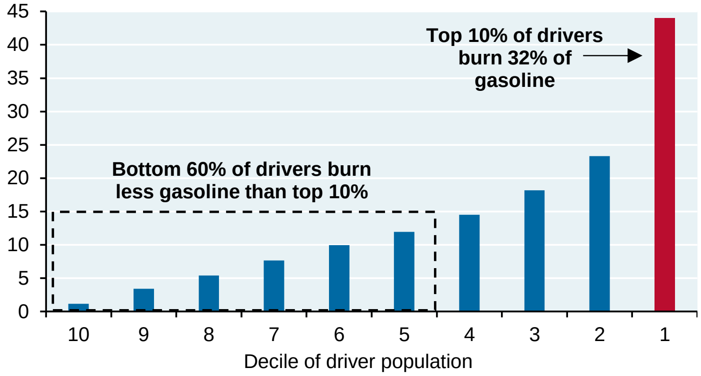
[9] I bought my first electric vehicle this year. It's a 4-door 2022 Jeep Wrangler hybrid. It has a 17 kWh lithium ion battery that allows for 21 miles of continuous EV driving. I use it mostly for local kayak fishing. Since I only drive it around 2,000 miles per year, my payback period is 13 years, even with the Federal subsidy.

[10] California State University, EV Volumes; see exhibit in last year's paper on page 14

**The prior chart on US vehicle preferences gets at a major issue: what to do about US gasoline "super-users"?** As shown below, the top 10% of gasoline consumers in the US account for almost one third of all gasoline consumption, more than the bottom 60% of gasoline consumers combined[11].

**The US gasoline super-users**
Gasoline consumption, billions of gallons



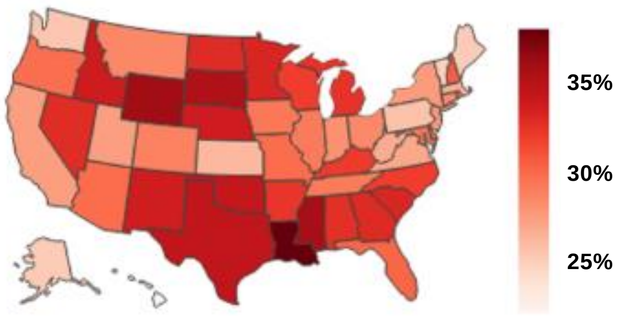
Source: Coltura. July 2021.

### Who are these gasoline super-users?

- They drive 3x more miles than the average driver
- They are more likely to drive pickups and SUVs
- They are more likely to live in rural areas
- They have similar income and education levels as the general population
- They spend 8%-13% of their income on gasoline, which is over 2x as much as the average driver

The maps illustrate the challenge. The map on the right shows where the highest concentrations of **EV purchases** are taking place. The shading on this map is almost the inverse of the map on the left, showing where gasoline super-users make up the largest share of gasoline consumption.

**Superusers' share of state gasoline consumption**



Source: Coltura. July 2021.

**EV registrations by state**

Source: Coltura. July 2021.

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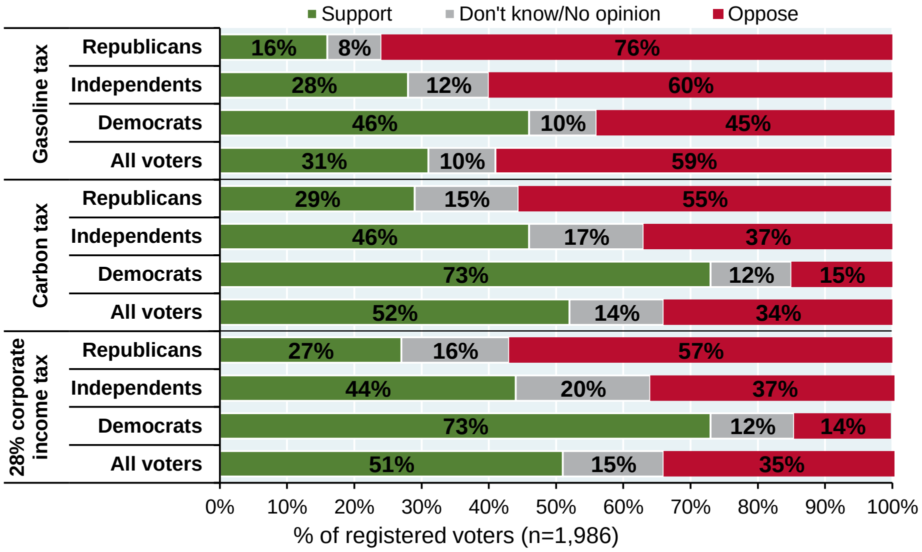
[11] "*Gasoline Super-users*", Metz, London and Rosler (Coltura), July 2021

**How might gasoline super-users be incentivized to adopt EVs more quickly?** Many will say "higher gasoline taxes!!", but that is unlikely for political reasons. Even before the Build Back Better bill ran into trouble with resistance in the Senate, polling showed that US voters are less in favor of gasoline taxes than other revenue raising means when paying for infrastructure. A "carbon tax" might sound like it achieves similar objectives as a gasoline tax, but in practice they are different. In Europe for example, the Emissions Trading System carbon tax applies to power generation, manufacturing and aviation but *not* to road or maritime transport.

**Gasoline tax has lower support than other options**

Voter polling on how to pay for infrastructure, April 2021



Source: Morning Consult. April 2021.

The current US approach is a $7,500 Federal tax credit for eligible EV purchases[12]. **The problem: this incentive delivers a "windfall" to EV buyers who were already driving a fuel efficient internal combustion engine car that they didn't drive much anyway**. In other words, Congress is overpaying them for foregone emissions. On the other hand, Congress is paying gasoline super-users a much lower rate on *their* foregone emissions, and might not be offering them enough to switch. If the goal is emissions reduction, there is another way: **a subsidy per gallon of foregone gasoline consumption rather than a fixed amount per vehicle**.

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[12] The $7,500 Federal tax credit is available only for EVs whose battery capacity is beyond a standard minimum size, and for cars whose manufacturer EV unit sales are still below 200,000 vehicle sold to date (Teslas, the GMC Hummer EV and the Chevy Bolt are no longer eligible).

**How would a gasoline usage-based incentive work?** Here's one option using an incentive of $10 for every gallon of displaced gasoline:

- Driver takes existing gasoline car to dealer
- Dealer obtains car registration history
- Dealer computes average annual miles driven based on initial and current odometer readings
- Dealer obtains EPA mileage rating for that specific vehicle
- Incentive amount = $10 * annual average gallons consumed (miles driven / miles per gallon)
- Driver eligible for incentive if new EV purchased within 30 days of trade-in

The following table uses three examples from lowest to highest gasoline consumption. Driver gallons displaced (C) are 8x higher for the Tacoma driver than for the Accord driver. A usage-based incentive offers the Tacoma driver a powerful incentive to switch: after assumed trade-in values (G), fuel savings (E) and maintenance savings (F), the Tacoma driver ends up *being paid* to swap for an EV (L). Compare that to the current policy which pays the Tacoma driver $6 per gallon of displaced gasoline while paying the Accord driver $73 per gallon.

Bottom line: if the goal is to accelerate the EV transition, the per-gallon incentive might work better given larger incentives for gasoline super-users, and given lower payouts to drivers with less switching benefits. For everyone who believes that a gasoline *tax* per gallon is the right answer, a gasoline *incentive* per gallon might be the second best option given the political realities in the US in 2022 and beyond.

**EV incentives: fixed amount per GALLON vs fixed amount per VEHICLE**

| | | 2015 Honda Accord 29 mpg | 2015 Toyota Highlander 21 mpg | 2015 Toyota Tacoma 19 mpg |
|---|---|---|---|---|
| | **Incentive: $10 per gallon** | | | |
| A | **Location** | New York Metro | Milwaukee Metro | Atlanta Metro |
| B | **Annual mileage** | 3,000 | 8,000 | 25,000 |
| C | **Annual gallons displaced** | 103 | 381 | 1,316 |
| D | **EV incentive @ $10/gallon displaced** | $1,034 | $3,810 | $13,158 |
| E | **Monthly fuel savings w/ EV** | $26 | $105 | $327 |
| F | **Monthly maintenance savings w/ EV** | $8 | $20 | $63 |
| G | **Trade-in value** | $15,848 | $18,927 | $10,315 |
| H | **EV alternative** | Hyundai Kona EV<br>3.7 miles/kWh | Tesla Model Y<br>3.6 miles/kWh | Ford F-150E<br>2.3 miles/kWh |
| I | **Price of EV** | $42,500 | $65,000 | $44,000 |
| J | **Net EV cost after incentive and trade-in** | $25,618 | $42,263 | $20,527 |
| K | **Monthly car payment on EV (6 years @ 5%)** | $421 | $694 | $337 |
| L | **Monthly cost to switch to EV** | $387 | $569 | -$53 |
| | **Incentive: $7,500 per vehicle** | | | |
| M | **Monthly cost to switch to EV** | $281 | $508 | $40 |
| N | **Taxpayer cost per gallon displaced under existing $7,500 per car tax incentive** | $73 | $20 | $6 |

Source: Coltura, Department of Energy, Autoblog, Edmunds, Forbes, JPMAM. April 2022. Assumes: Gasoline = $4.11/gallon; Electricity = 14 cents/kWh. EV cost = lowest available sticker price plus 10%. Assumes existing car is fully paid for.

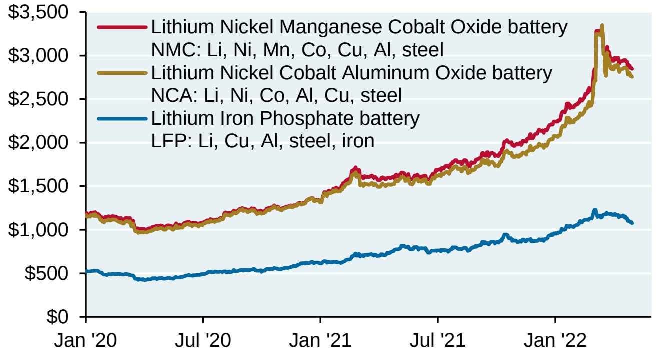
### EV special topic: what about rising metals prices and EV battery costs?

Since 2019, cobalt, nickel and aluminum inventory levels relative to demand have reached their lowest levels in many years and their prices surged. What might be the impact on EV battery costs? Using metals composition of EV batteries, we analyzed a hypothetical 60 kWh battery across three chemistry types: Lithium Nickel Manganese Cobalt (NMC), Lithium Nickel Cobalt Aluminum (NCA) and Lithium Iron Phosphate (LFP). The table shows battery chemistry by auto manufacturer; LFP batteries are used by Tesla and Chinese EV makers, while the rest mostly use NMC at least for now. LFP batteries are typically cheaper but have lower energy densities. China manufactures most LFP batteries while Samsung and LG Chem produce most NMC batteries.

Estimated LFP battery costs have risen by ~$500 since Jan 2020, mostly due to rising copper prices; this increase seems manageable as a % of vehicle cost. In contrast, estimated NMC and NCA battery costs increased by ~$1,500 since Jan 2020 with a large part of that increase occurring this year due to rising nickel and cobalt prices. For all EVs, there could be another $500 cost increase due to copper and aluminum for non-battery purposes in excess of amounts needed in gasoline cars. **Bottom line: there may be some sticker shock for EVs reliant on nickel and cobalt**. EV buyers can expect to offset part of this price increase via lower fuel costs if the current gap between gasoline and electricity costs per mile is sustained[13].

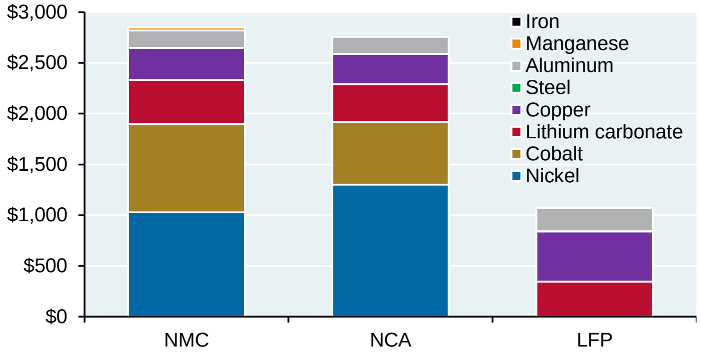
According to Rivian's CEO, EV battery supply chain pressures could surpass the current semiconductor shortage: "All the world's cell production combined represents well under 10% of what we will need in 10 years…**meaning, 90% to 95% of the battery supply chain does not exist**" [WSJ, 4/18/2022]. I doubt that many EV forecasts incorporate these kind of supply chain pressures. The path to higher EV shares may not be that easy.

**Estimated metals cost per EV battery type**
US$ per 60 kWh battery



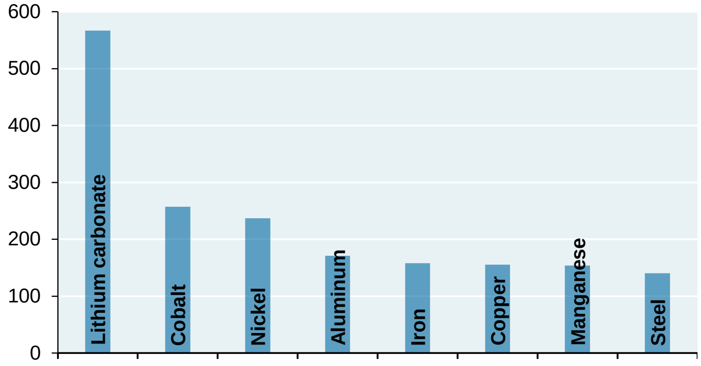
Source: Univ. of Birmingham (UK), Argonne National Lab, Bloomberg, JPMAM. May 2, 2022.

**EV battery cost breakdown using current metals prices**
US$ per 60 kWh battery



Source: Univ. of Birmingham (UK), Argonne National Lab, Bloomberg, JPMAM. May 2, 2022. Iron and steel values are plotted but are too small to see.

**EV metals prices have risen by 50% or more since 2020**
Index value (100 = Dec 2019)



Source: Bloomberg, JPMAM. May 2, 2022.

| Manufacturer | Vehicle type | Battery type |
|---|---|---|
| Audi | Passenger EV | NMC |
| BMW | Passenger EV | NMC |
| GM | Passenger EV | NMC |
| Hyundai | Passenger EV | NMC |
| Kia | Passenger EV | NMC |
| Mercedes-Benz | Passenger EV | NMC |
| Porsche | Passenger EV | NMC |
| BYD (China) | Passenger EV | LFP |
| Hongguang | Passenger EV | LFP |
| Ford | F-150 EV | NMC |
| Tesla | Short range passenger EV | LFP |
| Tesla | Long range passenger EV | NCA |
| Volkswagen (2023) | Entry level passenger EV | LFP |
| Volkswagen (2023) | High end passenger EV | NMC |
| Rivian | Electric trucks and SUVs | LFP |
| Rivian | Delivery vans | LFP |
| Chinese OEMs | Class 8 truck | NMC |

Source: S&P Global, Fitch Solutions, EV manufacturers, JPMAM. March 2022.

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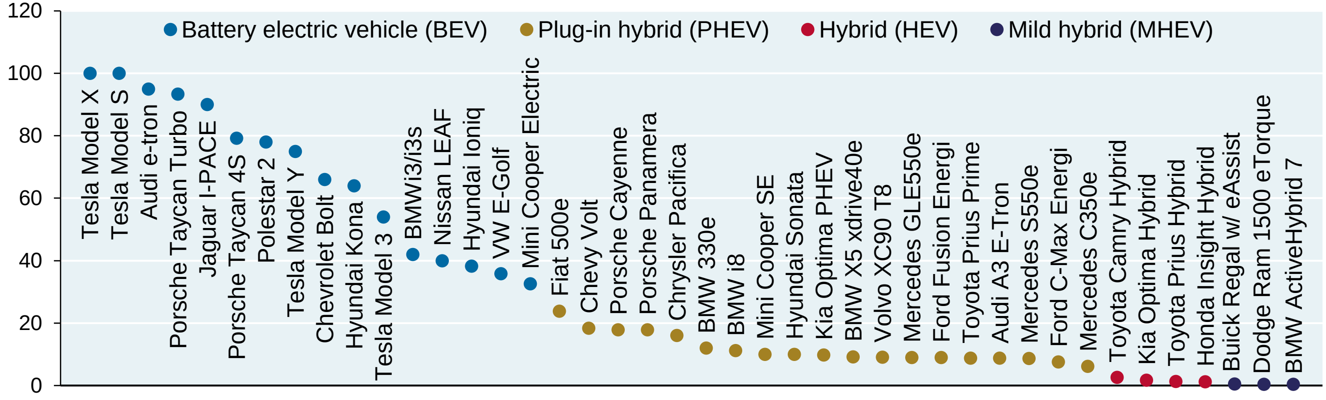
[13] Assuming 25 mpg for a gasoline car, 3 miles per kWh for an EV, $4 gasoline, 14 cents per kWh for electricity and 11,000 miles driven per year, EV owners would save ~$1,250 per year in fuel expenses. Comparing this annual amount to the incremental upfront cost of an EV over a gasoline car yields the payback period.

**EV exhibits: penetration as a share of sales and as a share of fleet size**

Most EV analyses include battery electric vehicles (BEV) and plug-in hybrid electric vehicles (BHEV) since the prime mover in both cases is the electric motor, even though some PHEVs have large backup fuel tanks. Most do not include hybrid electric vehicles (HEV) since its primary mover is usually an internal combustion engine, although this depends on the length of average trips and other driving behaviors. The first chart shows battery capacity by EV type. The subsequent four charts show BNEF forecasts of how quickly EVs as a % of sales translate into EVs as a % cars on the road. I'm not endorsing their forecasts since BNEF is often overly optimistic on a lot of things; but their modeling is a good illustration of the relationship between the two variables.

**Electric vehicle battery capacity by type**

Kilowatt hours, sorted in descending order by capacity

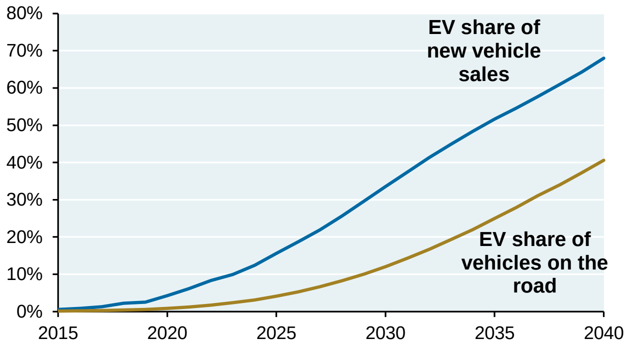


Source: Car and Driver, Automotive World, vehicle manufacturers. February 2021.

*Note: light duty vehicles are < 3.5 tons; medium duty 3.5 tons to 15 tons; heavy duty > 15 tons.*

**Passenger vehicles**

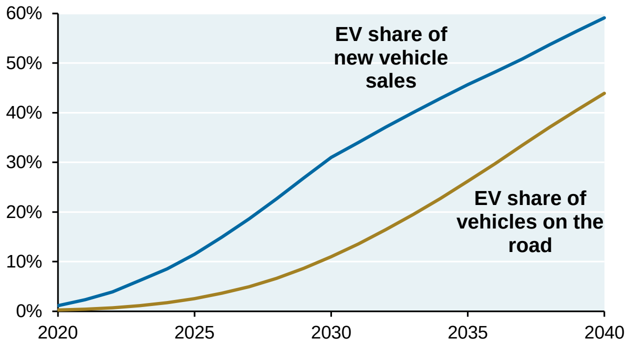
Percent, global



Source: BNEF. 2021.

**Light-duty vehicles**

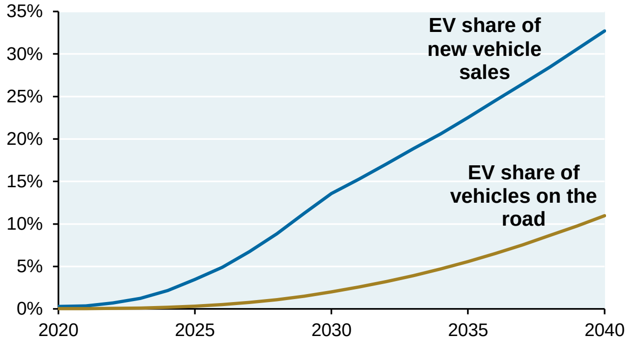
Percent, global



Source: BNEF. 2021.

**Medium-duty vehicles**

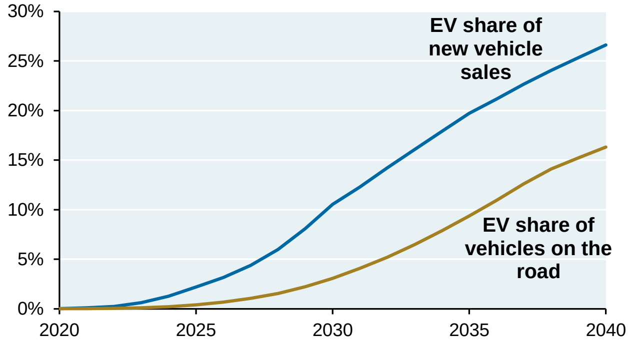
Percent, global



Source: BNEF. 2021.

**Heavy-duty vehicles**

Percent, global



Source: BNEF. 2021.

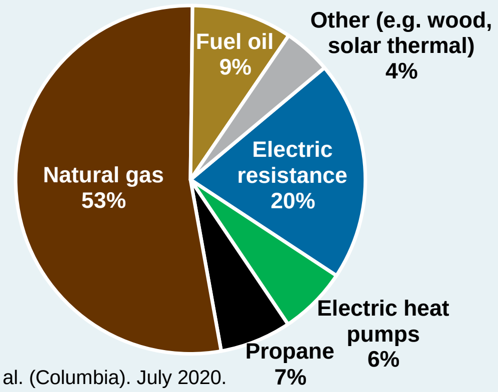
## [3] Residential heat pumps and fossil fuel combustion bans: more complicated than it looks

Residential heating in the US and Europe is dominated by on-site combustion of natural gas and other fossil fuels. Some European countries and US cities have banned combustion of fossil fuels in new residences; San Francisco, San Jose, Denver, Seattle and New York City[14] are recent examples and there are more bans on the way (see page 26 on European bans). The goal: require electrification of new residential heating instead, which can reduce $CO_2$ emissions as more wind/solar are added to the grid.

**First, let's review why electrification makes little sense using resistance (traditional baseboard) heating.** In areas where grids are reliant on coal and natural gas, emissions would sharply *increase* compared to combusting natural gas on-site. The reason: the energy efficiency of gas and coal-powered electricity generation (including transmission losses) is often less than half the efficiency of on-site gas combustion that can exceed 90%[15].

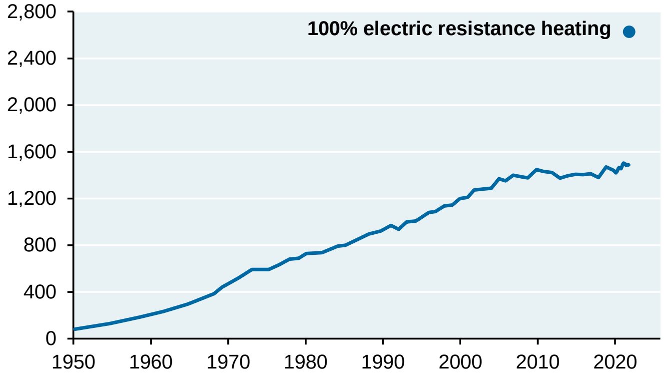
As a result, broad use of resistance heating could cause residential electricity demand to double, and that's not the only problem. As shown in the table, universal resistance heating could also increase peak loads in every Census tract in the US, each of whose peak loads would *more* than double[16]. The result: the need for more transmission and distribution which has to be built for *peak* loads rather than average ones. Given these outcomes, widespread electric resistance heating makes no sense, even in places with high renewable shares of electricity generation.

**Natural gas dominates US home heating**
% of total residential space heating energy



Source: Waite et al. (Columbia). July 2020.

**Universal resistance heating would cause electricity demand to soar,** Terawatt hours



Source: EIA, JPMAM. November 2021.

### Table 1: Universal resistance heating would also cause peak loads and infrastructure needs to skyrocket

| | Space heating shares | | | Residential emissions from all energy uses (mmt $CO_2$) | | | Electricity demand (TWh) | | Peak load increases | |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | Resistance heating | Heat pumps | Fossil fuels | Electricity | Fossil fuels | All | Space heating | All energy uses | Tracts w/ increased peak load | Average peak load increase in affected census tracts |
| **Current** | 20% | 6% | 69% | 250 | 339 | 589 | 368 | 1,382 | NA | NA |
| **All residences use resistance heating** | 96% | 0% | 0% | 1,084 | 0 | 1,084 | 1,613 | 2,626 | **100%** | **135%** |

Source: Waite et al. (Columbia). July 2020.

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[14] In December 2021, the **New York City Council** banned gas-powered heat and stove appliances in newly constructed buildings. The ban takes effect on December 31, 2023 for new buildings six stories and below. By July 1, 2027, it will include all new construction irrespective of size.

[15] "*Gas, oil and wood pellet fueled residential heating system emissions*", Brookhaven National Labs, Dec 2009

[16] Tables 1, 2 and 3 show output of a model of residential home heating and emissions built at the Census tract level by Michael Waite, Department of Mechanical Engineering at Columbia University. Michael worked with us on specific scenarios we designed after reading his February 2020 article in Joule Magazine, "*Electricity Load Implications of Space Heating: Decarbonization Pathways*" on air-to-air heat pumps in residences.

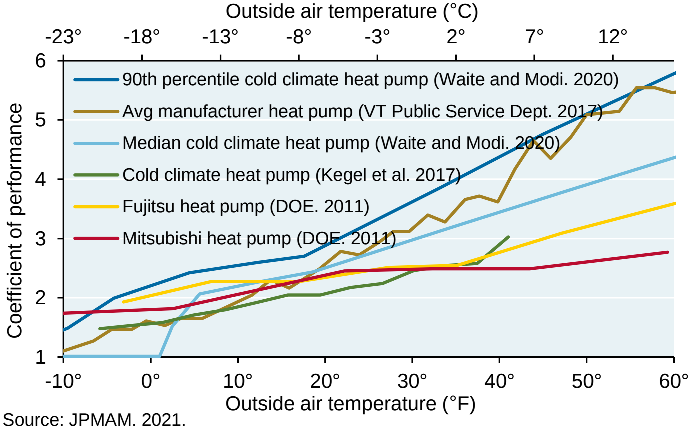
**Fortunately, there's a better way: air-to-air electric heat pumps[17] can provide heat much more efficiently than resistance heating.** A simplified heat pump explanation:

- Strange as it may seem, there's heat in the air even when the temperature outside is freezing. A heat pump extracts that heat using refrigerants as cold as -60°F (-51°C) that flow through the unit's outside coil. The refrigerant starts as a low temperature liquid, it absorbs heat and turns into a low temperature vapor
- The warmed refrigerant is then circulated to the interior via a compressor that increases its pressure and temperature, readying it to heat the interior air. The compressor is the main electricity-using component and since it's only driving heat transfer, it uses less energy than resistance heating
- The efficiency of a heat pump is defined by its "coefficient of performance" (COP), which refers to the amount of heat it provides per unit of electricity consumed. The higher the outside temperature, the greater the differential between the heat in the air and the unit's refrigerant, and the more efficient the heat pump will be. A COP of 1.0 would mean that the heat pump is only performing in line with resistance heating
- Estimates of heat pump efficiency vary (see below, left), but there's broad acceptance that they provide heat very efficiently at most ambient temperatures. As shown in the chart, heat pump COP might still be around 2.0x at temperatures as cold as 10°F (-12°C)

**Heat pumps may need a seasonal average COP of 2.0-2.5 to make sense from a climate perspective, and higher to make sense from an economic perspective.** Assume a home whose onsite combustion of natural gas is ~90% efficient, and that its regional utility is highly gas-reliant. Switching to gas-powered electricity would use roughly twice the energy at a COP of 1.0 given ~45% efficiency of modern combined cycle natural gas plants. So, a heat pump COP of 2.0 would be needed to match the energy/emissions of the original onsite natural gas burner.

More renewable energy reduces the COP required for heat pumps to make sense from a climate perspective. However, there's still the issue of homeowner economics. Per unit of energy, US electricity was 2x to 5x more expensive than natural gas in many states over the last three winters. **As a result, a heat pump would need a COP of 2x to 5x in these places for fuel cost expenses to break even**. In other words: a heat pump's COP needs to be roughly equal to the multiple of electricity to fuel costs for homeowner fuel costs to break even.

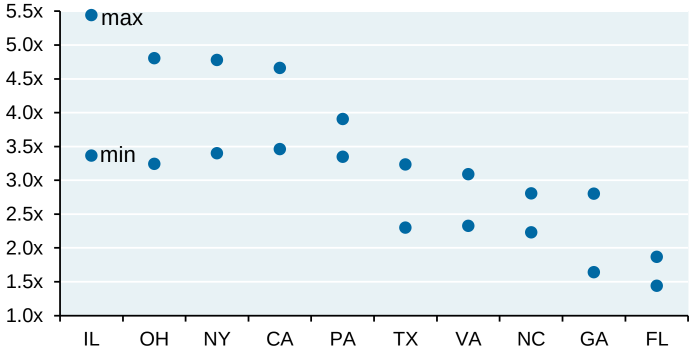
**Heat pump performance vs outside air temperature**



Source: JPMAM. 2021.

**US electricity costs 2x to 5x more than natural gas**

Residential electricity price per MJ divided by residential natural gas price per MJ, measured over last three winters



Source: EIA, JPMAM. January 2022. Top 10 states by electricity consumption.

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[17] **I recently installed several Bosch heat pump/air conditioning units in my home**. Assume the temperature outside is 35 degrees and the temperature in the house is 55 degrees since the system is turned off. Assume I then turn on the heating system and set the thermostat to 68 degrees. My particular Bosch system uses the fuel oil system in tandem with the heat pump until the temperature in the house is 3-5 degrees below the thermostat target, at which point the heat pump would work on its own.

**Broad heat pump adoption would entail large emissions declines, as shown in the third row in the table**. But what about electricity distribution capacity which has to be built for PEAK loads, not AVERAGE loads? Broad adoption of heat pumps without backup power could cause peak loads to surge in many parts of the country on very cold winter days, requiring massive grid upgrades. The red zone in the third row shows the results: 2/3 of all Census tracts would experience higher peak loads with average peak load increases of over 100%.

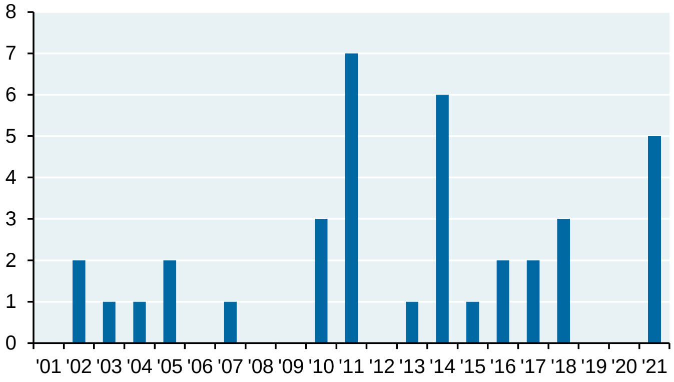
**Table 2: Universal heat pump adoption slashes emissions but increases peak loads and infrastructure needs**

| | Space heating shares | | | Residential emissions from all energy uses (mmt $CO_2$) | | | Electricity demand (TWh) | | Peak load increases | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Scenario** | Resistance heating | Heat pumps | Fossil fuels | Electricity | Fossil fuels | All | Space heating | All energy uses | Tracts w/ increased peak load | Average peak load increase in affected census tracts |
| **Current** | 20% | 6% | 69% | 250 | 339 | 589 | 368 | 1,382 | NA | NA |
| **All residences use resistance heating** | 96% | 0% | 0% | 1,084 | 0 | 1,084 | 1,613 | 2,626 | **100%** | **135%** |
| **All residences use heat pumps, no backup thermal power** | 0% | 96% | 0% | 282 | 0 | 282 | 415 | 1,429 | **63%** | **109%** |

Source: Waite et al. (Columbia). July 2020.

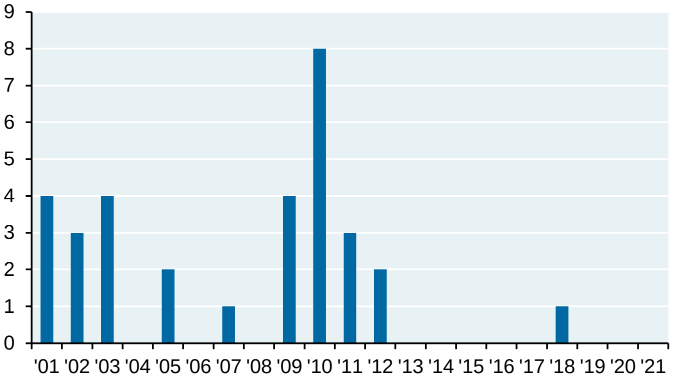
**Temperature histories for Dallas and Tallahassee illustrate the issue.** It doesn't get very cold that often, but there can be several days a year when minimum temperatures fall below 20°F (-7°C). As a result, any plan needs to account not just for average winter demand but for demand on the coldest days[18] when days demand could surge as illustrated in Table 2. If so, "smart" systems that switch to non-electric backup power on the coldest days could in theory reduce peak grid surges and reduce the need for transmission grid investment.

**Dallas: days with min. temperatures below 20 degrees F**



Source: NOAA, JPMAM. September 2021.

**Tallahassee: days with min. temps below 20 degrees F**



Source: NOAA, JPMAM. September 2021.

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[18] While grid outages would negatively affect homeowners with electrified heating systems, boilers powered by gas, heating oil and propane also do not work without electricity. The big policy question: **would greater electrification of residential heating increase the frequency or duration of grid outages by overloading the grid with incremental demand?**

**"Smart systems" could help…but what kind?** Backup non-electric power looks like the right answer: this would still result in large reductions in fossil fuel use and emissions, but does not result in peak load increases anywhere in the US. This seems like a great solution but…**is it economically viable for the natural gas industry to maintain residential infrastructure for backup purposes only?** If not, the last row may not really be a viable outcome. Perhaps residential fuel cells could be used as backup on cold days to reduce grid surges, but now we're talking about even more structural change and higher all-in costs.

**Table 3: Non-electric backup power on cold days eliminates peak load increases and grid buildout needs, but from what energy source?**

| | Space heating shares | | | Residential emissions from all energy uses (mmt $CO_2$) | | | Electricity demand (TWh) | | Peak load increases | |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | Resistance heating | Heat pumps | Fossil fuels | Electricity | Fossil fuels | All | Space heating | All energy uses | Tracts w/ increased peak load | Average peak load increase in affected census tracts |
| **Current** | 20% | 6% | 69% | 250 | 339 | 589 | 368 | 1,382 | NA | NA |
| **All residences use resistance heating** | 96% | 0% | 0% | 1,084 | 0 | 1,084 | 1,613 | 2,626 | 100% | 135% |
| **All residences use heat pumps, no backup thermal power** | 0% | 96% | 0% | 282 | 0 | 282 | 415 | 1,429 | 63% | 109% |
| **All residences use heat pumps, backup thermal power in place** | 0% | 93% | 3% | 268 | 13 | 281 | 405 | 1,419 | 0% | 0% |

Source: Waite et al. (Columbia). July 2020.

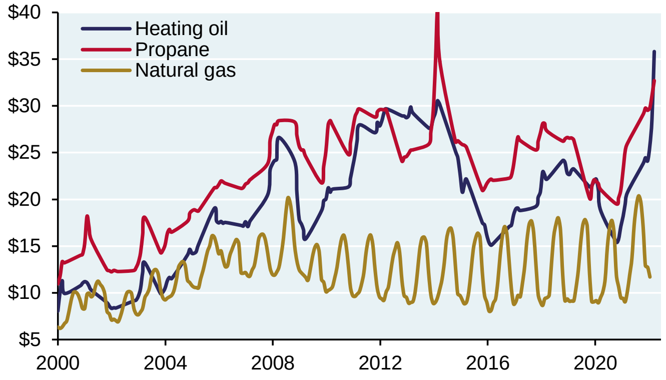
**Economic incentives to switch.** A separate analysis examined the economic consequences of residential heat pump adoption[19]. As shown in the next table, 40%-80% of homeowners using propane, fuel oil and electric resistance heating have economic incentives to switch to heat pumps. However, natural gas homes are by far the largest share of US residential housing stock, and the share of natural gas homeowners with incentive to switch to heat pumps is estimated at less than 10%. The primary reason for their lower incentives: **natural gas is usually much cheaper than propane and fuel oil**, as shown in the last chart.

**Economic incentives to switch to heat pumps are much lower for homes heated by natural gas**

| Fuel type | Share of housing stock | % with economic incentive to switch |
|---|---|---|
| Natural gas | 56% | 8% |
| Electric resistance | 20% | 48% |
| Fuel oil | 8% | 40% |
| Propane | 6% | 79% |

Source: Vaishnav et al (University of Michigan). 2021. Analysis assumes 2018 average fuel and electricity prices.

**Natural gas is a lot cheaper than propane or fuel oil**
US$ per million BTU, residential pricing



Source: EIA, JPMAM. March 2022.

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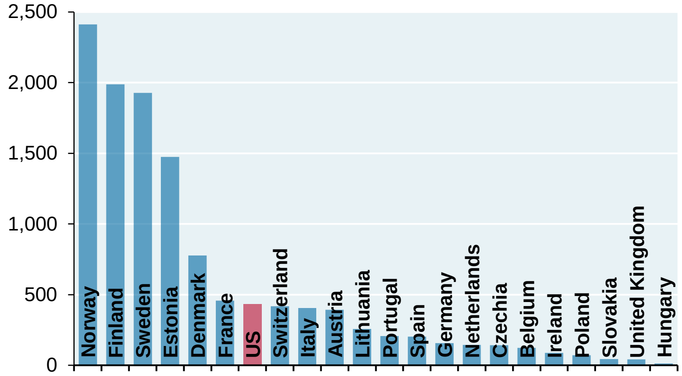
[19] See "*US residential heat pumps: the private economic potential and its emissions, health, and grid impacts*", Deetjen (UT Austin) and Vaishnav (University of Michigan), Environmental Research Letters, July 2021. Assumed heat pump costs: $3,300 (existing central air systems), $3,700 (without central air systems) or $4,800 (homes requiring removal of existing boilers); plus $143 * kW of capacity for purchase and installation; and up to $6,000 depending on need for ductwork

**Heat pump adoption without backup thermal power can be done in cold climates**. Heat pumps are popular in Scandinavia where they compete favorably with resistance heating, biomass and "district" heating (centralized heating from biomass and waste timber, and from data center excess heat). In addition to air-to-air heat pumps, other heat pump types extract heat from the ground or from groundwater. These heat pumps are often more efficient and have higher capacity since they're drawing from heat sources which are warmer than the ambient air (they also cost more due to installation and materials). As for heat pumps without backup power, homes in Scandinavia are more energy efficient as indicated by their lower energy consumption per dwelling on a climate adjusted basis than the rest of Europe[20]. US homes use ~2x the energy as homes in Europe and even more vs Scandinavia, increasing the difficulty of heating US homes via heat pumps with no backup systems in place.

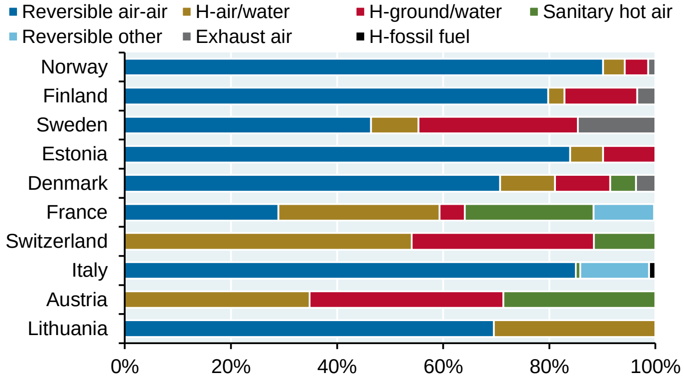
Norway, for example, provided subsidies to switch, applied high fossil fuel taxes (basic plus carbon taxes are ~$130 per metric ton for fuel oil compared to just $11 in the US), its electricity prices are low and oil boilers were first restricted and now banned. **However, Norway is not a great template for larger, denser countries**. Norway has 5 million people, its population density is 10% of European levels and 97% of its electricity comes from cheap hydropower. The rest of the continent has to deal with larger surges in peak loads: 4x as much electricity can be used on a very cold day compared to a normal one. That might explain why heat pumps are used at lower rates in the rest of Europe: only 6% of Europe's 240 million residences have heat pumps installed.

**Heat pump adoption highest in Scandinavia**
# of heat pumps per 10k people



Source: EHPA, European Statistical Office, Census. 2020.

**Europe heat pump types**
Percent of stock



Source: European Heat Pump Association. 2018. H = hybrid heat pump.

**Europe aims to phase out fossil fuels for residential heating by 2040, and the IEA's 10 point plan for reducing European reliance on Russian energy also calls for a faster pace of heat pump adoption**. To get there, 40% of residential and 65% of commercial buildings will need to be electrified by 2030 via 35 million new heat pumps[21]. As with green hydrogen, Europe will be a litmus test for the achievable pace of change in energy production and consumption. Combustion bans have expanded in Europe, which should increase heat pump momentum[22]:

- Denmark (2013) banned the installation of oil and gas boilers in new buildings
- Netherlands (2018) banned connection to the gas grid for new buildings
- Austria (2020) banned the installation of oil and coal boilers in new buildings
- Norway (2020) banned the use of oil for heating new and existing buildings
- France requires new construction after 2022 to meet maximum $CO_2$ emissions per square meter with different levels depending on the building type, effectively banning all mono-fuel fossil fuel systems
- Belgium's Flemish region introduced a ban on fuel oil boiler installation for new buildings and major energy renovations in residential and non-residential buildings starting in 2022
- Germany banned installation of mono-fuel oil and coal boilers starting in 2026

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[20] "*International comparisons of household energy efficiency*", Odyssee-Mure Project, EU Commission

[21] *"How Norway Popularized an Ultra-Sustainable Heating Method"*, Peter Yeung, January 17, 2022

[22] "*Phase out regulations for fossil fuel boilers at EU and national level*", Institute for Applied Ecology, Oct 2021

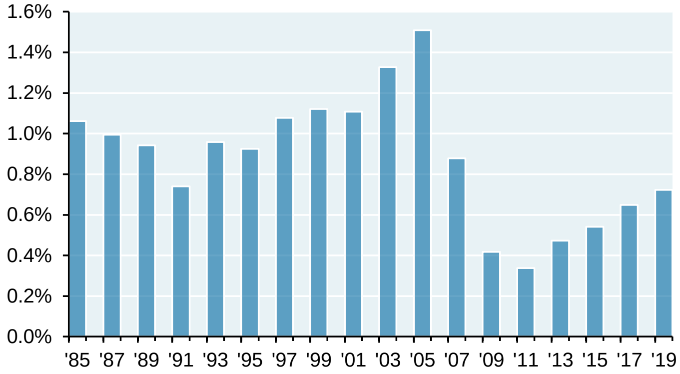
## Wrapping up: heat pump adoption will be slow if it relies mostly on new homes

Both studies we cited analyzed *existing* US homes and the costs and benefits of switching to a heat pump. For *new* homes, all-in costs for heat pumps can be lower given greater energy efficiency of a new home[23] and no need for retrofit ductwork. For new homes, heat pumps may even be cheaper than natural gas in more cases. In the US, heat pumps accounted for 40% of all new single family home heating units in 2020 and almost 50% for multi-family[24].

That's good news, but the transition to heat pumps will be slow if it relies mostly on new homes due to changing public policy: **new homes sales in the US and Europe average just 1% or less of the housing stock each year**. Think about it this way: a car can last 10-15 years before having to be replaced, while a house can last 40-50 years or more. Of course, burners and furnaces don't last as long as a house does. But they last a lot longer than cars do: the average life of a natural gas furnace is 15-20 years, and the average life of a fuel oil furnace is 20-25 years. Replacing them with new furnaces when they expire is also simpler than shifting to a new form of home heating. As a result, electrification of residential heating may be a slower process than electrification of transport, unless generous subsidies are provided to promote switching.

**US single family home turnover per year**

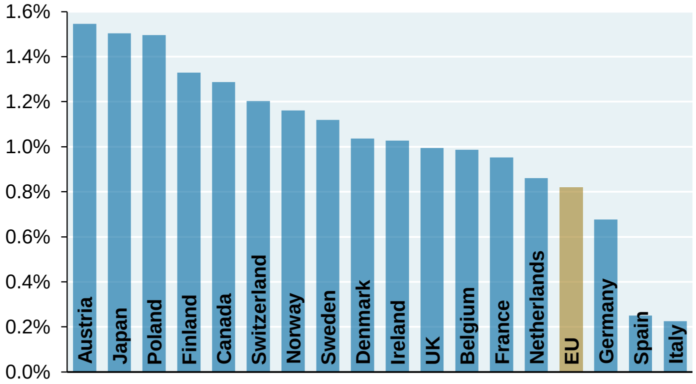
Percent, new single family home sales / single family housing stock



Source: Census, JPMAM. 2019.

**European new home turnover per year**

Percent, completed new homes as % of existing housing stock



Source: OECD, JPMAM. 2020 or latest year available.

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[23] According to Harvard's Joint Center for Housing Studies, the average home built before 1960 consumes 42.5 thousand btu per square foot compared to 27.2 btu per square foot for a home built from 2010 to 2015.

[24] "*Heat Pumps: More Efforts Needed*", IEA, November 2021

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