Energy & personal transport
MIT 11.165/477, 11.286J

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MIT DUSP

September 22, 2022

Materials for today

- David JC MacKay. Sustainable Energy - Without the Hot Air. UIT Cambridge Ltd., 1 edition, February 2009. Chapters 3 & 20 (A, optional)
- Marco Miotti, Geoffrey J. Supran, Ella J. Kim, and Jessika E. Trancik. Personal Vehicles Evaluated against Climate Change Mitigation Targets. Environmental Science & Technology, 50(20):1079510804, October 2016. doi. URL. Publisher: American Chemical Society.
- Noah Kittner, Ioannis Tsiropoulos, Dalius Tarvydas, Oliver Schmidt, Iain Staffell, and Daniel M. Kammen. Electric vehicles. In Technological Learning in the Transition to a Low-Carbon Energy System, pages 145163. Elsevier, 2020. ISBN 978-0-12-818762-3. doi. URL.
- Victoria Penney. Electric Cars Are Better for the Planet and Often Your Budget, Too. New York Times, January 2021. URL.
- Andrew J. Hawkins. Yes, the new electric vehicle tax credits are really confusing, but we can help, The Verge, August 2022. URL.
- M.J. Bradley & Associates. Financial Incentives for Electric Vehicles, 2022. URL.

Personal transport

Main questions for today:

- Why is personal mobility important in terms of energy?
  - Are EVs more efficient than ICE cars?
  - How much? Is this the same in all places?
- What about other vehicles?
  - bicycles
  - electric bicycles, scooters
- What policies move the international vehicle market?
  - (One answer: Mary Nichols and the California Air Resources Board!)
- What does the Inflation Reduction Act do?
  - how do its policy incentives work?
- Next week: what about the larger infrastructure needed?
  - roads
  - fuel infrastructure (oil, grid)

Mobility is a superpower

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Mobility is the ability to access:

- jobs
- housing
- services
- leisure

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Enabling mobility in cities is particularly hard due to population density.

Carbon emissions from personal transport

Daniel Sperling at UC Davis has a nice way to think about this:

`Mobility (vehicle-miles-traveled)`

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×  Vehicle energy efficiency (energy use / vehicle mile)
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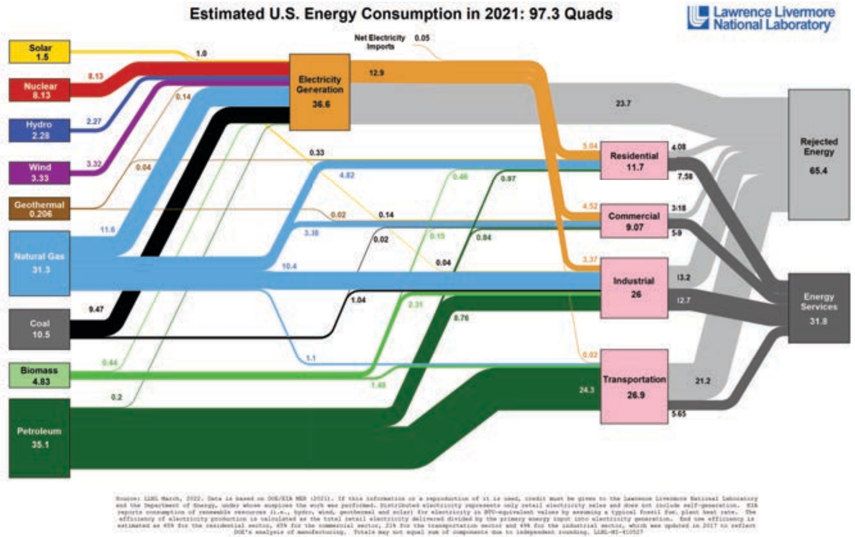
×  Vehicle energy efficiency (energy use / vehicle mile)
×  Carbon intensity of energy (GHG / unit of energy)
-------------------------------------------------------
=  GHG emissions
```

Energy for transport: see Sankey diagram!



Sankey diagrams for the US and every state at flowcharts.LLNL.gov

Public domain image courtesy of LLNL / US Department of Energy.

Energy for transport: see Sankey diagram!

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Energy services = 5.65 / 26.9 = 21% of energy input becomes services!

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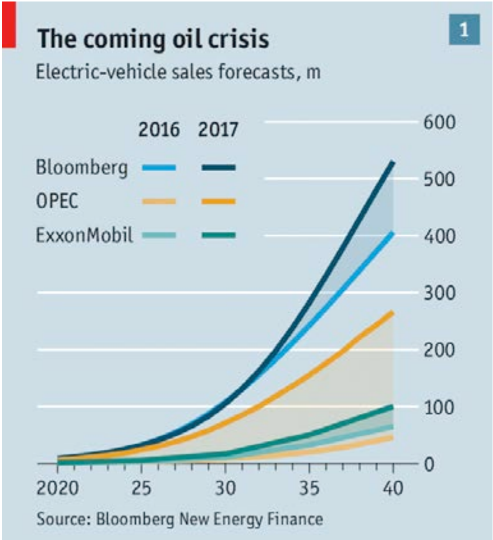
Energy services = 5.65 / 26.9 = 21% of energy input becomes services!

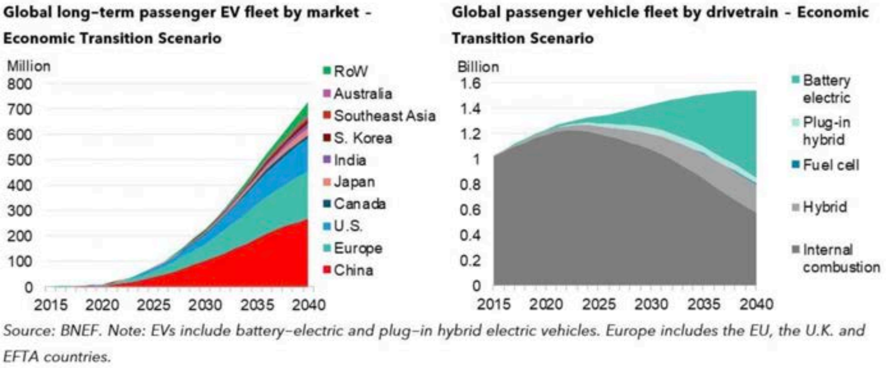
Rejected energy = 21.2 / 26.9 = 78% of energy input is wasted.

When I started teaching this class in 2017 . . .



From The Economist, August 12, 2017

More recently:



Bloomberg New Energy Finance Electric Vehicle Outlook 2022

EVs are still very new!

- Bolt EV introduced in 2016, Tesla Model 3 in 2017
- most automakers have yet to introduce EV models
- EV sales as share of new cars in the 1H 2021 $\rightarrow$ 1H 2022:
  - globally: 4-5% $\rightarrow$ 12%
  - Germany:

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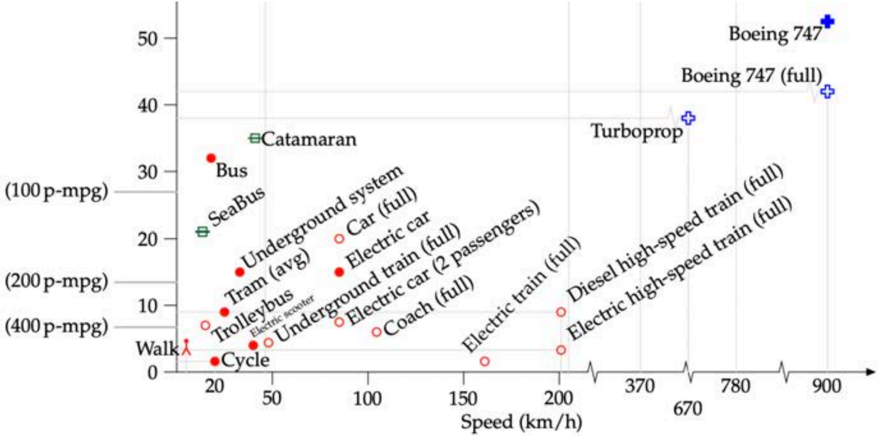
  - Germany: 12% → 13.6%
  - China: 12% → 20%
  - U.S.: 3.6% → 6.2% (despite declines in sales of other vehicles)

Start by analyzing private vehicles, i.e. personal transport

Vertical axis in terms of energy consumption (kWh / 100 p-km)



Mackay, Figure 20.23

Vehicle efficiency

Policy question: which vehicles should we focus on making more efficient?

- making SUVs slightly less gross: 11 MPG to 13 MPG?
- making passenger cars super-efficient: 29 MPG to 49 MPG?

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$$\text{gallons}/11\text{miles} = 0.091$$
$$\text{gallons}/13\text{miles} = 0.077$$

$$\text{gallons}/29\text{miles} = 0.034$$
$$\text{gallons}/49\text{miles} = 0.020$$

The difference between both pairs of vehicles is the same: 0.14 gallons per mile!

American Economic Review: Papers & Proceedings 2011, 101:3, 98–104
http://www.aeaweb.org/articles.php?doi=10.1257/aer.101.3.98

Consumers' Perceptions and Misperceptions of Energy Costs

By HUNT ALLCOTT*

Economic decisions depend on preferences over outcomes and beliefs about how each possible choice maps into these outcomes. While economists often estimate preferences, we typically assume beliefs, often under some combination of rational expectations, perfect information, and unbounded computational capacity. In some domains, however, there is evidence that these assumptions are not realistic (Charles F. Manski 2004). For example, people have systematically biased beliefs about food calorie content (Bryan Bollinger, Phillip Leslie, 2007) and that beliefs may have particular systematic biases (Shahzeen Z. Attari et al. 2010).

Perhaps the most noted perceptual error in this domain is "MPG Illusion," under which people intuitively think that automobile fuel costs scale linearly in miles per gallon (MPG), whereas they in fact scale linearly in gallons per mile (Richard P. Larrick and Jack B. Soll 2008). As an example, consider two pairs of vehicles. The first pair is two vans, one rated at 11 MPG and the other at 13 MPG, and the second pair is two cars rated at 29 and 49 MPG. Many people

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4. Electric vehicle (EV)
   - battery (e-) moves car (200-400 miles)
   - drastically less maintenance (1/2)
   - less mechanically complex
   - depends largely on battery costs

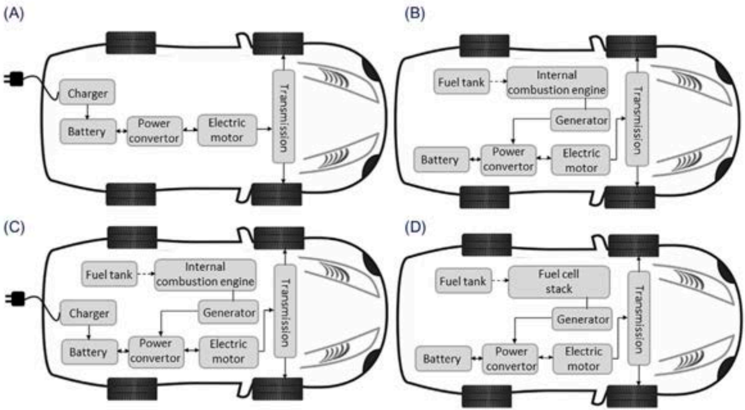

Figure 9.1

Overview of typical power train configurations for personal (A) BEV, (B) series HEV, (C) series PHEV, and (D) series FCEV. *BEV*, Battery electric vehicle; *FCEV*, fuel cell electric vehicle; *HEV*, hybrid electric vehicle; *PHEV*, plug-in hybrid electric vehicle. Source: *Based on Yong et al. (2015); Das et al. (2017)*

Figure 9.1 of powertrains from Kittner et al

Internal combustion engine SUV, 22 mpg:

$$\frac{10\text{kWH}}{\text{l}} \times \frac{\text{gal}}{22\text{ miles}} \times \frac{\text{l}}{0.26\text{ gal}} \times \frac{\text{mile}}{1.6\text{ km}} \times \frac{100}{100} \quad = \quad \frac{109\text{ kWH}}{100\text{ km}}$$

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Multiple between these vehicle types: SUV/EV = 5-7x, Hybrid/EV = 2-3x

Have EVs changed since Mackay's 2009 book?

Car model, ('year)	Energy [kWH]	Range [miles]	Range [km]	E./dist. $[\frac{kWH}{100\mathrm{km}}]$	Cost [$]	E./d.$. $[\frac{kWH \times cost}{100\mathrm{km}}]$
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Tesla X	90	325	500	18	$82.5	1485
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Tesla 3 std. ('17)	50	220	339	15	$45	675
Tesla 3 LR ('17)	75	315	485	16	$60	960

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Kia Niro ('18)	64	243	375	17	$40	680
Kia Soul ('18)	64	293	451	14	$40	560
Hyundai Kona ('19)	64	259	400	16	$40	640

What about the carbon of the electricity for EVs? (Mackay 2009)

You've shown that electric cars are more energy-efficient than fossil cars. But are they better if our objective is to reduce CO_2 emissions, and the electricity is still generated by fossil power-stations?

This is quite an easy calculation to do. Assume the electric vehicle's energy cost is 20 kWh(e) per 100 km. (I think 15 kWh(e) per 100 km is perfectly possible, but let's play sceptical in this calculation.) If grid electricity has a carbon footprint of 500 g per kWh(e) then the effective emissions of this vehicle are **100 g CO_2 per km**, which is as good as the best fossil cars (figure 20.9). So I conclude that switching to electric cars is *already* a good idea, even before we green our electricity supply.

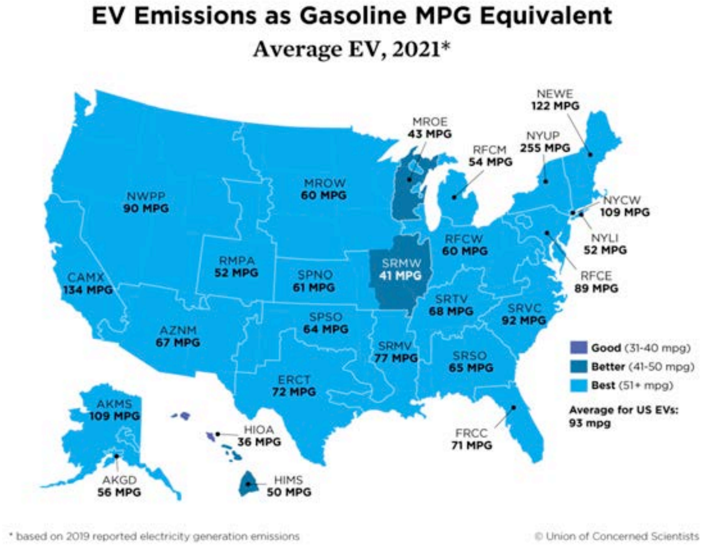

Figure: Union of Concerned Scientists

Lifecycle analysis

Consider the environmental impact from the complete lifecycle of the vehicle, including:

- manufacturing (also: construction)
- fuel use (also: subsequent users, time of use, occupancy, etc.)
- scrappage (also: waste, decomposition)

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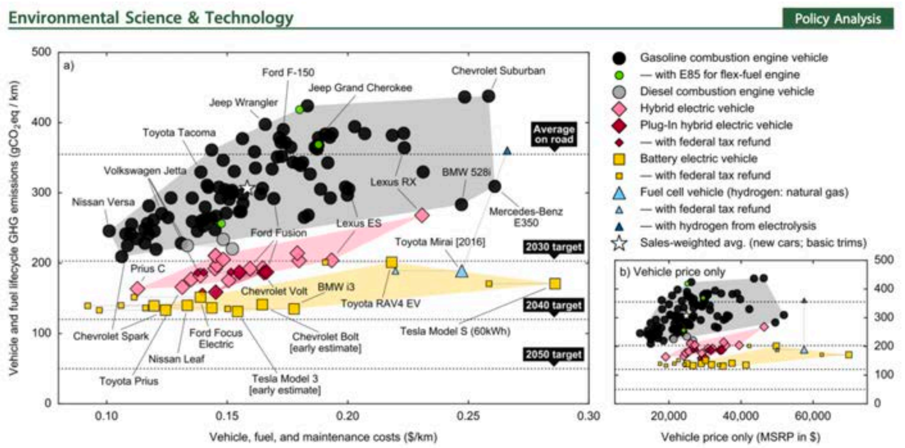
Depends heavily on accounting / attribution:

- what do we measure? costs, carbon emissions . . .
- how do we discount over time?
- boundaries around the object?

Miotti et al paper, methodology, page 10797

Estimating Vehicle GHG Emissions. Lifecycle GHG emission intensities are calculated using GREET 1 and 2.[35] GREET is a widely used, publicly available full-vehicle-lifecycle model developed by Argonne National Laboratory.[35] GREET 1 models the lifecycle emissions of fuels and of electricity, and GREET 2 models the lifecycle emissions of the vehicles themselves. For each powertrain technology and model, the vehicle class (car, SUV, or pickup), curb weight, fuel consumption, battery power (for HEVs), battery capacity (for PHEVs and BEVs), and fuel-cell power (for FCVs) are determined. These parameters are obtained from manufacturers' web sites and a car-information web portal.[40] The carbon intensity of electricity is modeled as the average U.S. mix, including emissions from infrastructure construction (623 gCO_2eq/kWh). We use a consistent lifetime of 169 400 miles (272 600 km) for all vehicle types, corresponding to the approximate averages for LDVs in the U.S.[41] Other GREET parameters are left at their defaults. Because consistent

Miotti et al paper, figure 1



Miotti et al paper, figure 4

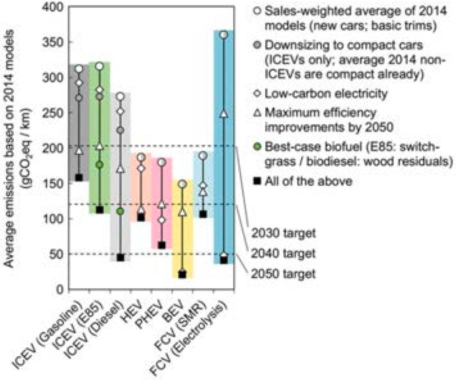


Figure 4. Average GHG emissions intensities of each powertrain technology in response to vehicle downsizing, a low-carbon (zero-fossil-fuel) electricity supply mix (24 gCO_2eq/kWh), efficiency improvements, the use of future biofuels (for ICEVs), and the combination of all factors. Efficiency improvements include a 15% weight reduction and reduced fuel consumptions of 40% (ICEVs), 45% (HEV and PHEVs in charge-sustaining mode), 30% (BEV and PHEVs in charge-depleting mode), and 35% (FCV).[50]

Outside Magazine, Sept. 8, 2022

Why You Should Buy an E-bike Instead of an Electric Vehicle

Whatever your reason for considering an EV–your wallet, the environment, or practicality–adding an e-bike is a far better choice than replacing your current car

Joe Lindsey

Sep 8, 2022

For Saving Money

One big aspect that attracts people to EVs is the prospect of saving money on things like fuel and maintenance. Fuel costs to drive an ICE vehicle 10,000 miles a year (about $700-$1600) are roughly two to four times the cost to charge an EV for the same amount of driving, according to AAA's 2021 Driving Costs study. Gas has gotten more expensive in 2022: $1,840 for the average vehicle studied, which widens the gap further. You can estimate your specific costs in AAA's new Ownership Costs calculator.

But for e-bikes, costs are dramatically lower than either ICE or electric vehicles, thanks in part to the relatively tiny batteries and the fact that e-bikes' hybrid power source (electric and human) makes them highly efficient. In the heaviest use-case scenario—riding so much that you fully drain the 500 watt-hour battery 365 days a year, and living in the priciest state in the US for electricity costs (Hawaii)—the cost to ride an e-bike would be a little over $50 per year. Half that use, at national average electricity costs, your *annual fueling cost* would be $10, or about 2.5 percent of the cost of EV charging.

What about other costs, like registration, insurance, and depreciation? Factor in those and you can expect an EV to cost you about $7,500 per year ($2,500 without estimated depreciation), says AAA. That's about mid-pack measured against various ICE vehicle styles. So unless you're stepping down from a full-size ICE pickup or SUV, you won't actually save much, if any, money switching to an EV.

There isn't a single great resource for ownership cost of bicycles; estimates range from as low as $100 to more than $800. Both are wrong, in my view; the lower estimate doesn't realistically cover maintenance costs, while the higher one attempts to account for fueling in terms of extra calories for the rider. But bikes are already among the most efficient means of transportation ever created, and a lightweight electric motor means you'll burn fewer calories to ride, not more (although the difference isn't as large as you'd think). In short, the extra calories burned by pedaling are a rounding error in the scheme of your normal diet.

Life Cycle Assessment (LCA) is usually expressed in terms of grams of carbon dioxide produced per mile driven, which spreads the carbon produced in making the product over its estimated lifespan. According to Tesla's 2020 Impact Report, a grid-charged Model 3 in the U.S. has an LCA of 180g/mile, assuming it lasts about 200,000 miles with only minor repairs (aka it doesn't need a new battery pack). It's worth noting that figure is for a sedan; an E-SUV or truck would have a higher per-mile cost. That figure jumps around depending on how it's charged. In Europe, says Tesla, the Model 3's LCA drops to around 120g/mile thanks to electricity production that relies more on renewables and nuclear than our domestic power supply, while in China's coal-and-gas-heavy grid it's over 300g/mile.

What about bikes, though? They have a carbon cost too, right? Last year, as part of its sustainability initiatives, bike brand Trek published a detailed look at the carbon footprint of its products. Trek's average bike requires 174kg of CO_2 to produce. The only e-bike included in the analysis—the full-suspension Rail mountain bike series—is a decent proxy for cargo bikes in its aluminum-framed versions, and requires 190 to 240kg of CO_2 to produce.

Factor in charging costs (it takes two to three percent of the energy needed to charge a standard EV), and an e-bike ridden 2,000 miles a year has an LCA of about 10-15g/mile if it lasts 10 years on the original battery, frame, and motor. That's 12 to 18 times more efficient than a Tesla on a per-mile basis, literally an order of magnitude smaller than for even an EV charged completely via renewable energy. Doubt my math? This new study shows very close results.

Two- and three-wheeled vehicles

Pigalle on Flickr, CC BY-NC-SA 2.0

Two- and three-wheeled vehicles

By Ubong-isaac - Own work, CC BY-SA 4.0

Two- and three-wheeled vehicles

Road transport segment progress toward Net Zero

Segment	Current share of road transport CO_2 emissions	Current estimated global fleet size	Zero-emission vehicle (ZEV) fleet share in 2050 - Economic Transition Scenario	Level of policy intervention needed to hit Net Zero Scenario (100% ZEV share) by 2050
Two- and three-wheeled vehicles	5%	1.1 billion	Two-wheelers: 74% Three-wheelers: 94%	Almost on track: minor additional measures needed
Municipal buses	1%	3.8 million	84%	Almost on track: minor additional measures needed
Passenger vehicles	53%	1.3 billion	69%	Positive trajectory: moderate additional measures needed
Light commercial vehicles	11%	160 million	75%	Positive trajectory: moderate additional measures needed
Medium + heavy commercial vehicles	30%	80 million	29%	Not on track: strong additional measures needed urgently

Source: BNEF, various government sources. Note: Fleet size represents vehicles of all drivetrain types and are estimates based on various sources and BNEF data. Some values rounded. Current emissions and fleet size data are for 2021.

Bloomberg NEF EVO 2022

NYT, 8/29/2022

What to Know About California's Ban on New Gasoline-Powered Cars

By 2035, California shoppers looking for new vehicles will have to buy electric.

Give this article

By Soumya Karlamangla

Aug. 29, 2022

Sign up for California Today The news and stories that matter to Californians (and anyone else interested in the state), delivered weekday

Mary Nichols & California Air Resources Board (CARB)

- State of CA intervenes in local air pollution issues, leads to Air Quality Management District (AQMD) and CARB before the U.S. Clean Air Act.
- As 28-year old Yale Law grad, successfully sues the EPA for not enforcing the Clean Air Act of 1970.
- Joins CARB in 1975; chairman in 1979.
- Clinton's EPA in 1993, works on sulfur dioxide and acid rain; first national limit on fine particulates; rejoins CARB in 2003 under Schwarzenegger and Brown

CARB standards / ZEV mandates

Question: How do you force large national and international automakers?

2025: goal is 22 percent zero-emission vehicles (ZEV)

- ZEV states (CA + 13 states) = 800,000 vehicles
- 23 states sue to stop EPA rollbacks in fall 2019

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- manufacturers must make enough vehicles = 15.4% of all sales in CA
- will add $1900 to cost of new vehicle, but paid back in 3 yrs.
- 47% reduction in GHG emissions compared to today
- 75% reduction in air pollution compared to today

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- will add $1900 to cost of new vehicle, but paid back in 3 yrs.
- 47% reduction in GHG emissions compared to today
- 75% reduction in air pollution compared to today

2035: goal is 100 percent of new vehicles sold will be ZEV

- also greater use of low-carbon fuels being promoted

2050: only ICE cars are being phased out

- current: 99.9% of all cars run on gas
- target: 52.6% fuel cell, 16.8% batt. elect., 9.7% plugin, 20.9% gas

What did the Inflation Reduction Act do?

Hawkins, M.J. Bradley articles:

- extended incentives for manufacturers over 200K vehicles
- point-of-sale tax rebates for EVs, to overcome higher upfront costs
- first time tax rebates for used EVs
- domestic manufacturing requirements for vehicles and batteries
- probably more . . .

See you in class or at the next lecture!