Estimating the Cost of Decarbonizing the Transportation Sector

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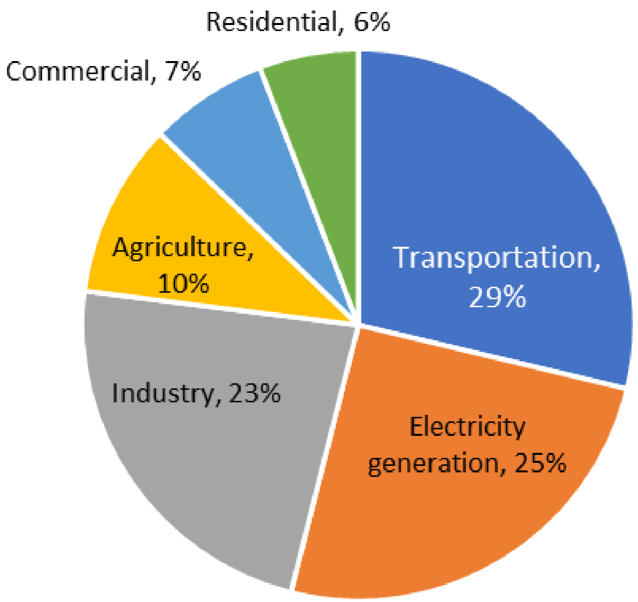
Thanks to Jim Archsmith, Sarah Armitage, Ken Gillingham, Chris Knittel, Shanjun Li, Erich Muehlegger,, and David Rapson for helpful conversations, and to Cassie Cole, Michelle Li, and Matej Cerman for research assistance.

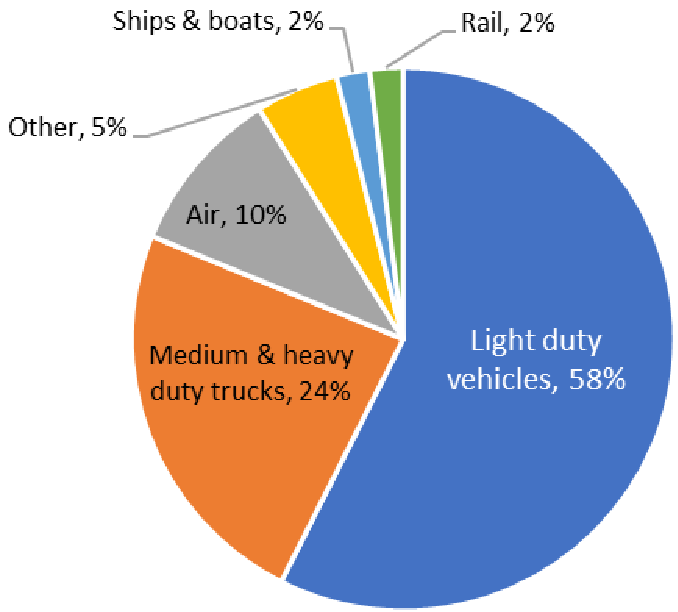
Emissions from the US Transportation Sector

US GHG Emissions by Sector, 2019

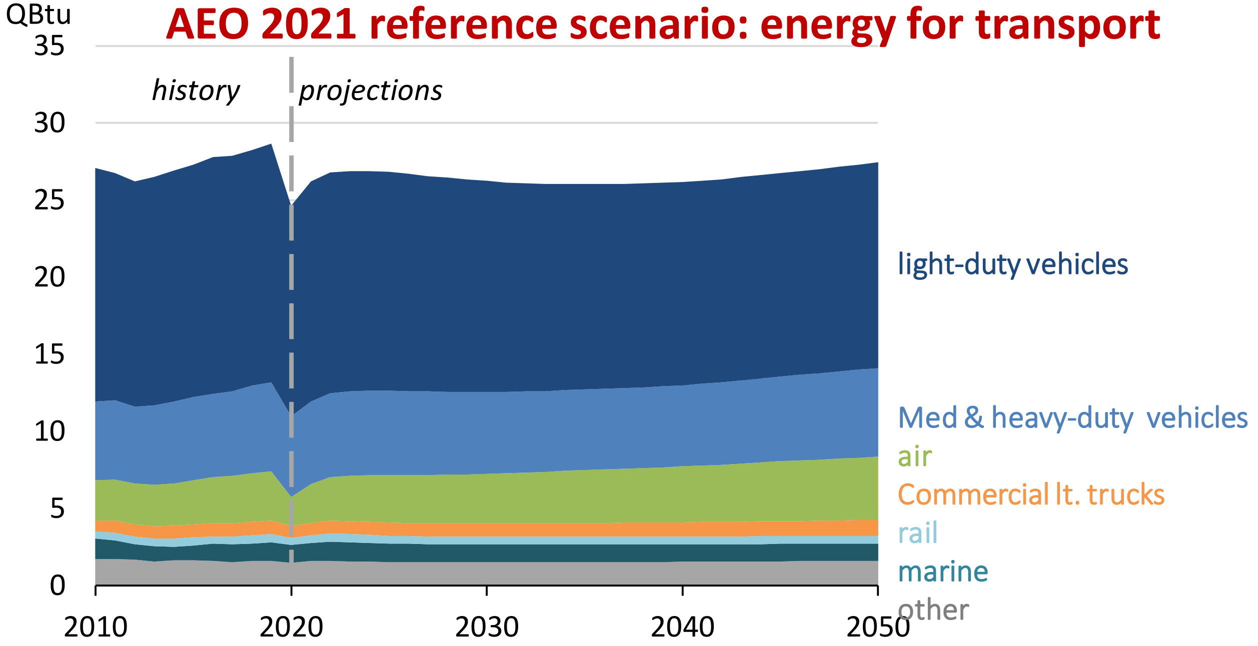


Sources: EPA Greenhouse Gas Inventory, EIA AEO 2021

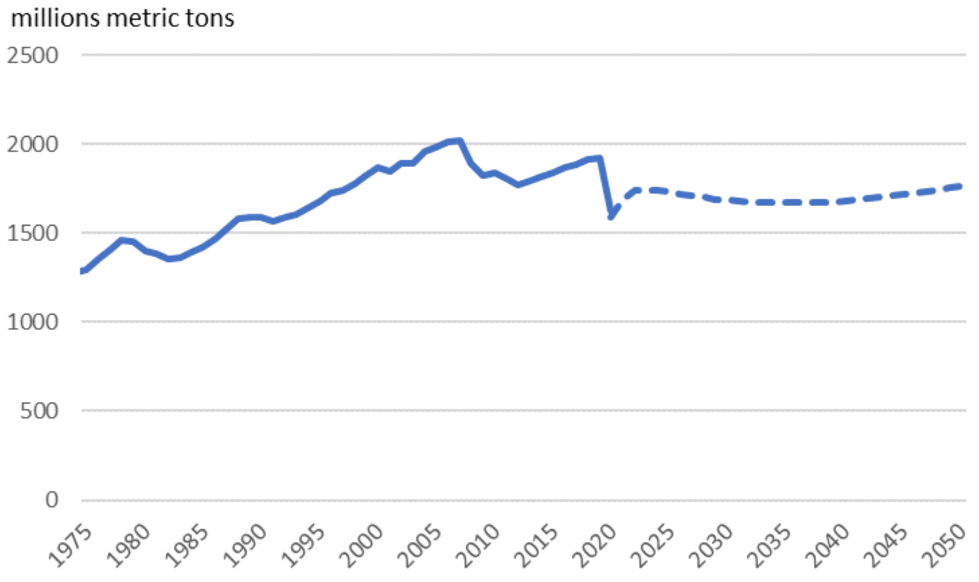
US Transport CO2 Emissions by Mode, 2019



AEO 2021 reference scenario: energy for transport



AEO 2021 reference scenario: Transport emissions



How much will it cost to decarbonize transportation?

What does "how much" mean?

- Gross investment not the right concept
- Technology cost vs. policy cost
- Marginal abatement curve: static vs. dynamic

Externalities and multiple equilibria

- Three externalities:
    - GHG externality
    - Innovation externality
    - Network (chicken & egg) externality
- + induced technical change, learning-by-doing,…

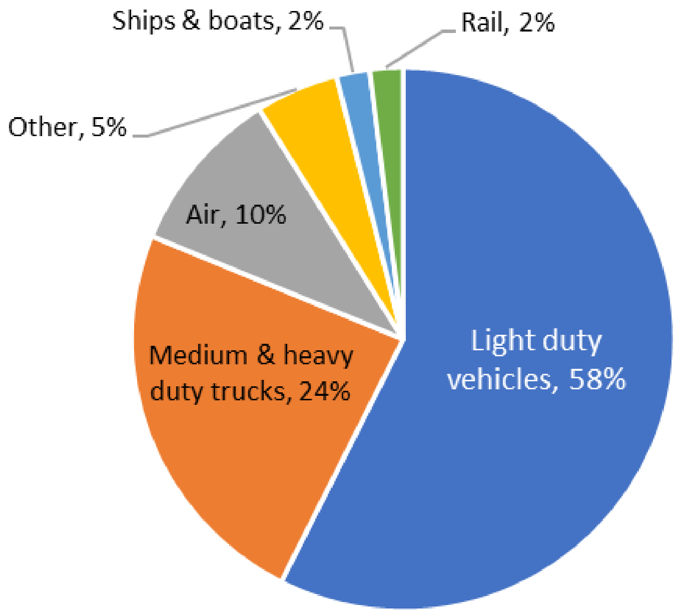
Cost-benefit analysis vs. Cost effectiveness analysis

- CBA uses the SCC
- CEA (here) takes a target date as given

Policy framing

- Transition to a cheaper, greener future or first step towards perpetual self-restraint?
- Existing policies:
    - RFS, CAFE/SAFE, BBTC, EVTC, [eRIN]; IDC, EOR,…; LCFS, TCI, ZEVs
    - ICAO/CORSIA, [RJFTC]
    - IMO MARPOL

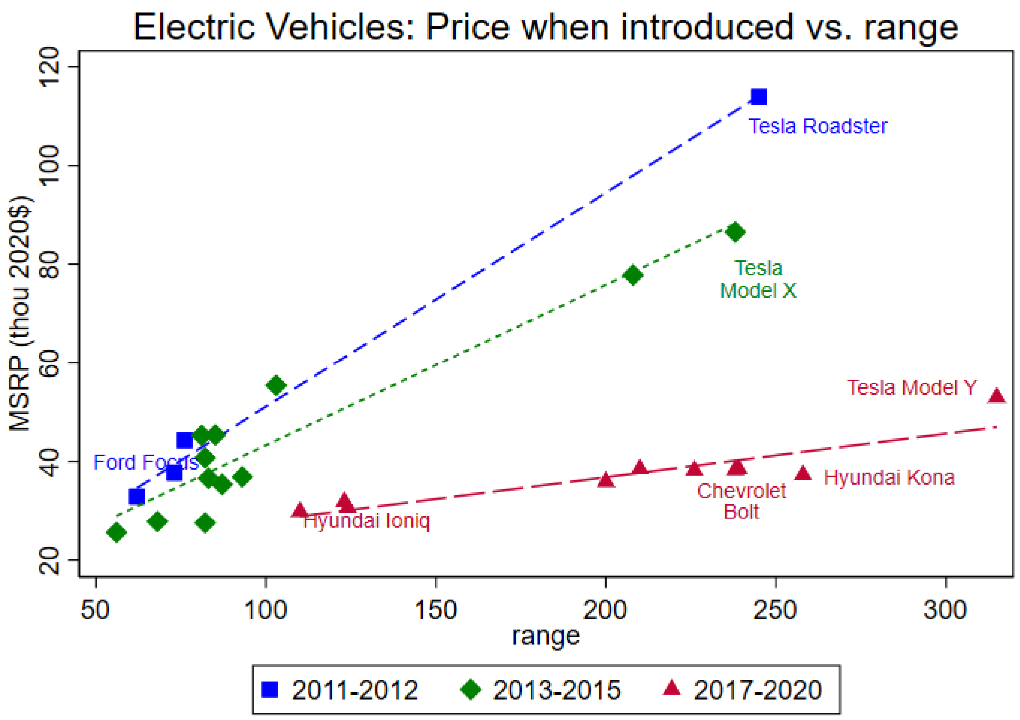
This is work in progress…



LDVs: Overview

The EV transition

- **Price**
  - Battery price declines
  - EV-ICE price parity 2024-2030?
- **Attributes**
  - + : performance, other battery uses
  - **-** : charging time & availability, range, cold weather
- **Penetration**
  - Norway: ~80% of new sales
  - US: 2% of new LDV sales
- **Industry**
  - GM, Ford announcements



For another day

- Hydrogen fuel cells, autonomous vehicles, flying cars,…

LDVs: Cost estimation strategy

Policy cost estimation

- Focus on $/ton of policies
  - total system costs = EVs – ICEs + O&M differential + charging stations + power system upgrades (all gross of federal support)
  - *not* welfare

LDV model elements

- Discrete choice model of EV demand (by cars, SUVs+), logistic, depends on:
  - Full user cost (with myopia)
  - Charging stations (Level 2, 3)
  - Non-price attributes/tastes
- Private charging station buildout
  - Early adopters largely charge at home
  - Insufficient Level 3 (DC fast chargers)
  - Level 2 chargers for those without home charging capability
- Ignore potential usage difference (Burlig et al. 2021)
- Exogenous technical change
- Multiple equilibria
- Model structure & parameters drawn from literature
  - **Key references:** Zhou & Li (2017, 2018), Springel (2020), Archsmith, Muehlegger, & Rapson (2021)

LDVs: Parameterization

Monte Carlo to handle parameter, technology, oil price uncertainty

Baseline & MC central values

- **Baseline**: Growing but incomplete EV penetration (even by 2050)
- **Demand**: price elasticity -2.5; charging station elasticity 0.37 (Springel 2020); consumer myopia parameter 0.75
- **Charger supply**: elasticity 0.67 (Springel 2020) (Norway)
  - steady state calibration = 0.1 L2/car & 60,000 L3 @ 10 plugs/facility (cf. 115,000 gas stations nationally)
  - Costs: L2 @ $2k/plug, L3 @ $50k/plug, declining 2%/yr
- **ICE, SUV prices**
  - Manufacturing & usage breakdowns in Lutsey & Nicholas (2019) and Clinton, Knittel, and Metaxoglu (2020)
  - Battery prices: -16% per year 2009-2019; project -9% with $50 floor
  - Cars: 3.4 kWh/mi; SUVs: 2.0 kWh/mi; ICEs: CAFE standard projections (ICE component)
  - Full user cost = Initial vehicle cost + valuation factor×O&M costs (after all taxes & incentives)
- **Oil price** path from AEO 2021 + random AR(1) departure estimated 1990-2021

Selected references

- *Demand elasticity*: Springel (2020): -1.5 to 2.0; Xing et al (2019): -2.7; Li (2019): -1.3; Muehlegger & Rapson (2018): -3.3; Archsmith, Muehlegger, & Rapson (2021) simulation values -1, -2 -3
- *Consumer myopia (all for ICEs)* : Gillingham, Houde, & van Bentham (forthcoming): 0.16-0.39; Allcott & Wozny (2014): 0.72; Grigolon, Raynaert, and Verboven (2018): 00.91; Leard, Linn, and Zho (2019): 0.54 and <0.30. We use higher value because of salience at point of making ICE/EV decision.

LDVs: Policies

Baseline

- CAFE standards: SAFE through 2026, increase @ Obama rates 2027-2031, increase @1% thereafter
- Power sector: TPS starting from status quo in 2022, 80% emissions reduction by 2030, 90% by 2035, 100% by 2050
  - Alternative: No power sector policy

A. Charging station subsidy

- 50% cost-share for Level 2, 75% cost-share for Level 3, 2022-2028

B. EV showroom rebate

- $5000 federal instant rebate, 2022-2026, $3500 in 2027, $2000 in 2028

C. eRIN

- Biogas -> electricity pathway, 2022-2032; EV owner gets quarterly check; gasoline prices rise slightly
- *Details*: third part aggregator with access to OEM vehicle data; D3 RIN @ D5 floor = $1.50; RFS energy value 10 kWh/RIN (based on ICCT 2017 methodology, updated, see EPA (2014) & ICCT (2017))

D. All in: A + B + C

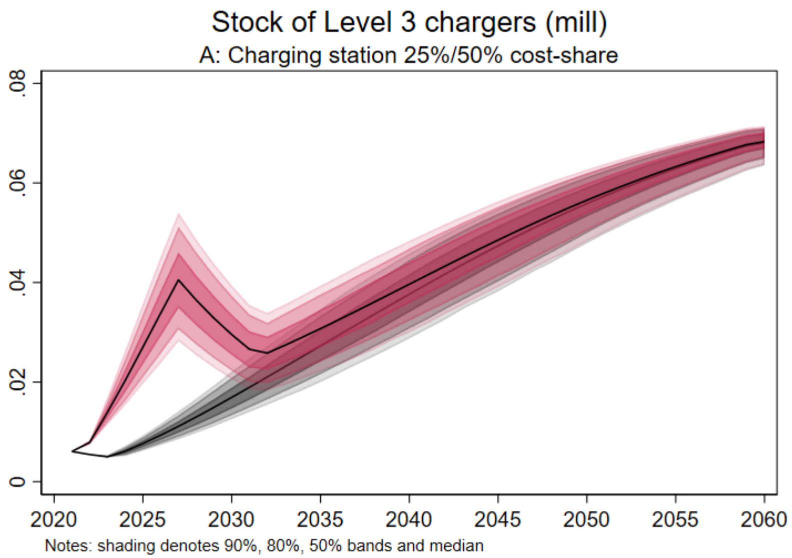
E. Enhanced Clean Air Act regulation

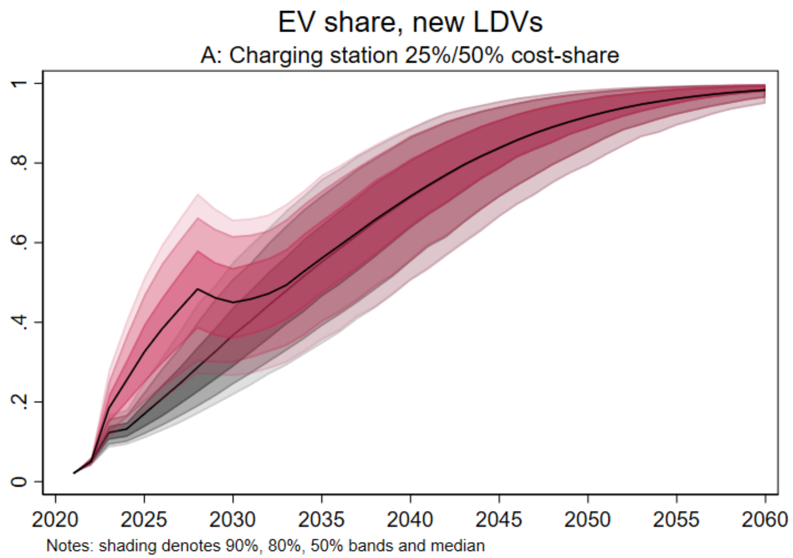
- Decouple EPA (CAA) & NHTSA (EPCA) rules.
- NHTSA sets (unchanged but binding) ICE mpg standard
- EPA implements CAA via clean vehicle standard (ZEV standard) with tradable allowance price cap

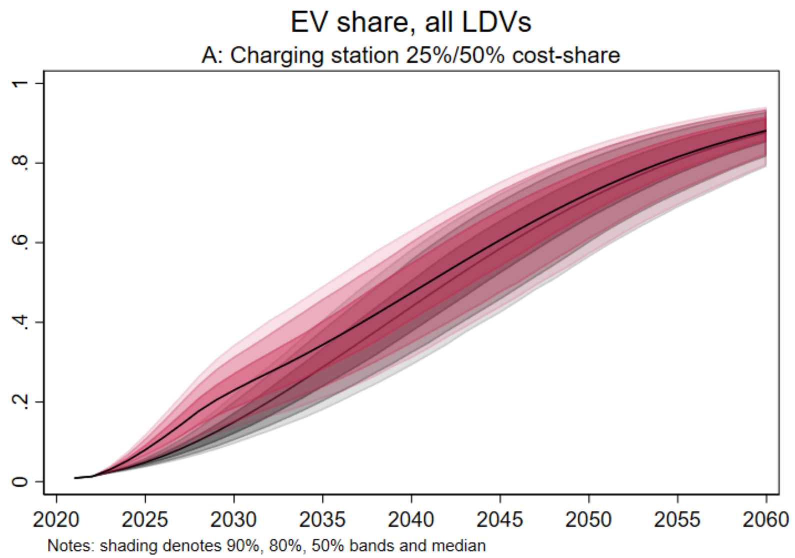
F. Carbon tax

- $40/ton starting in 2022 increasing 5%/year

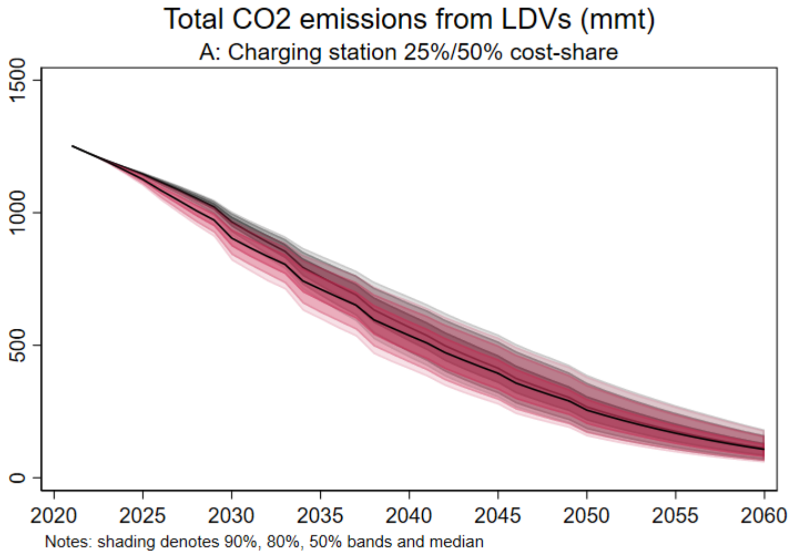
LDVs: Results for 50%/75% charging station cost-share

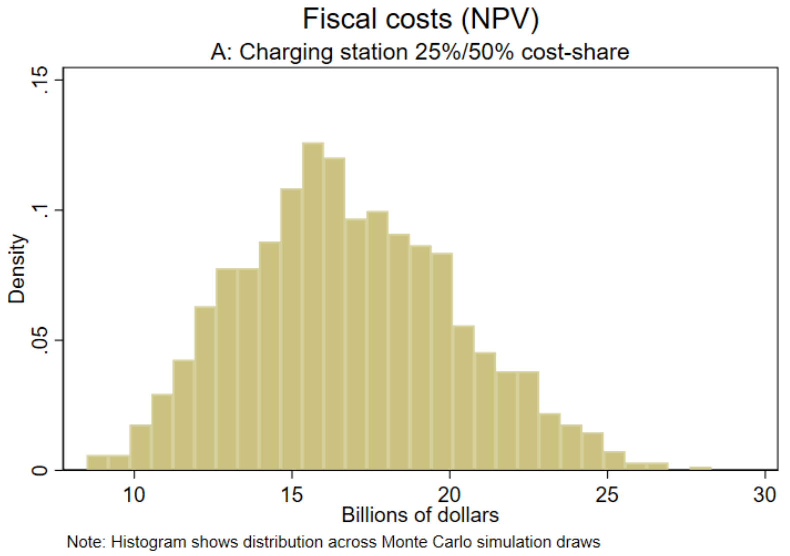


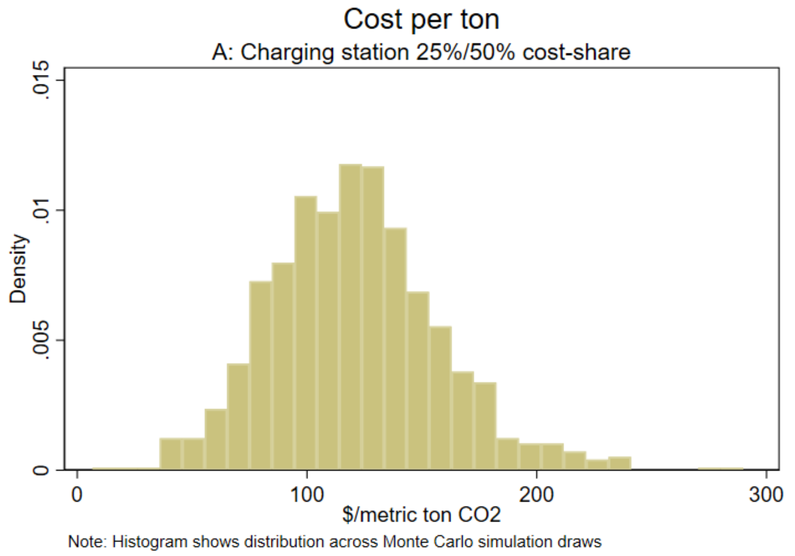




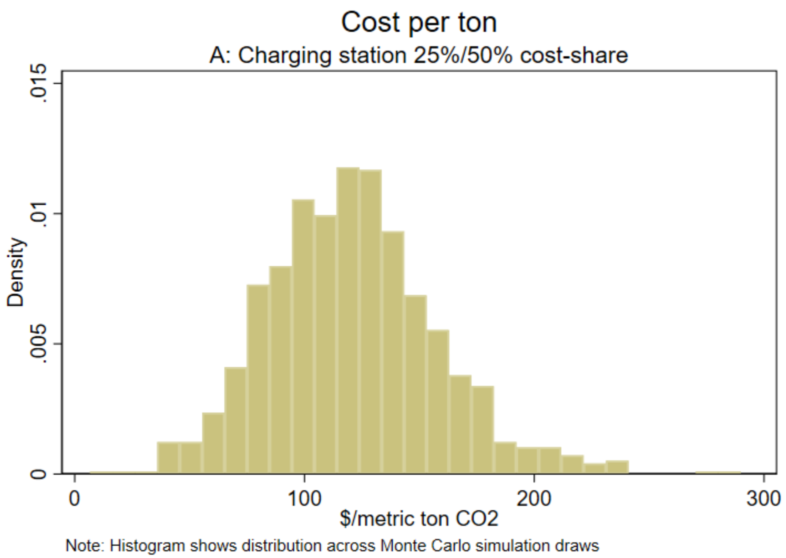
Notes: total new charging stations = 1.2m Level 2, 30k Level 3)

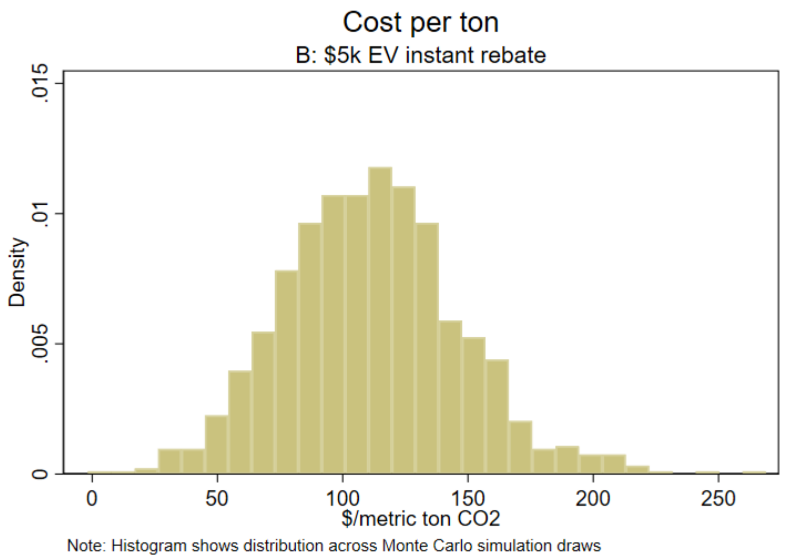


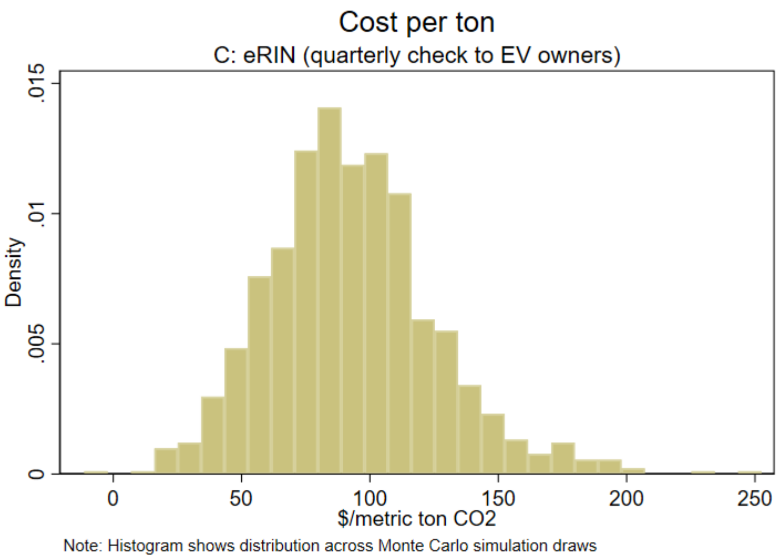


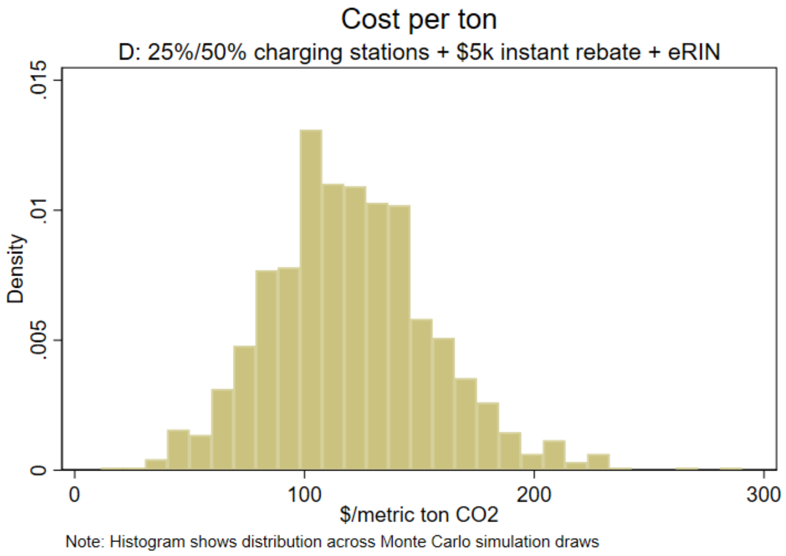


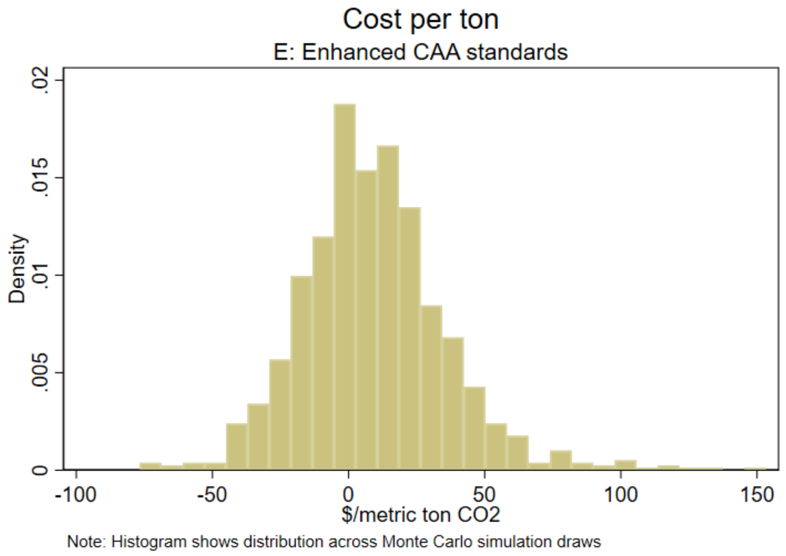
LDVs: Costs per ton, various policies

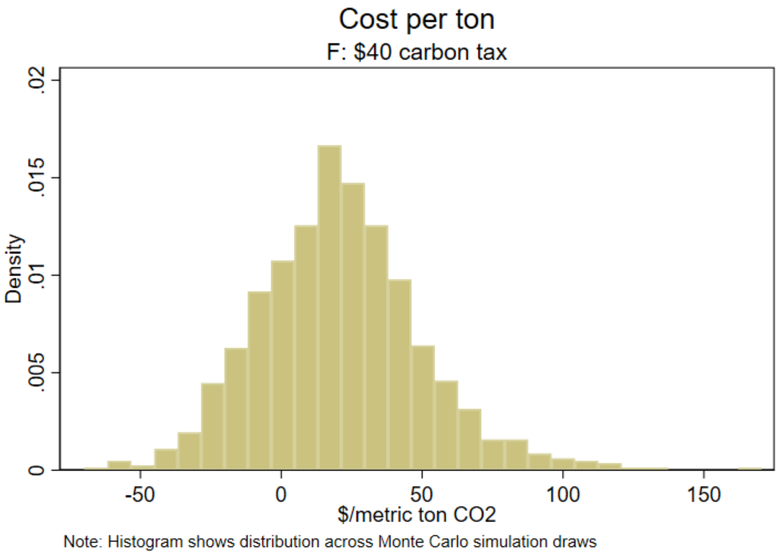






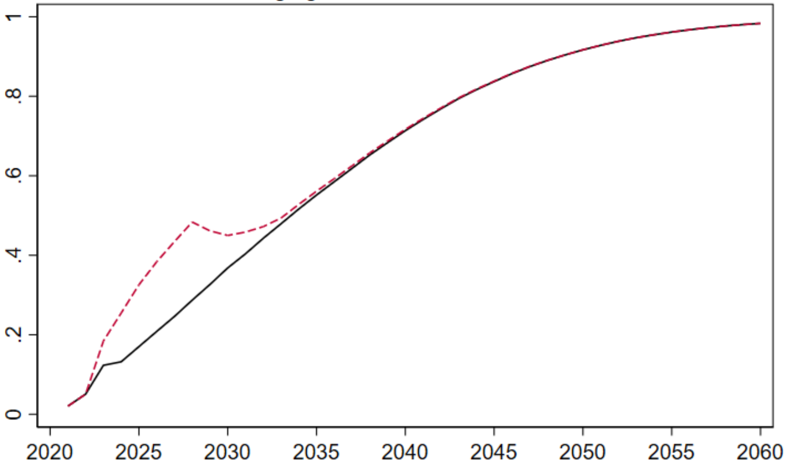






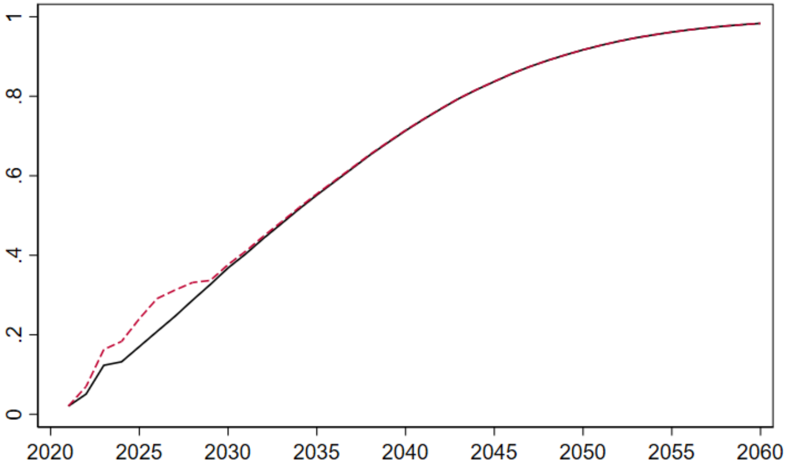
LDVs: New EV sales share, various policies (means)

EV share, new LDVs: Means
A: Charging station 25%/50% cost-share



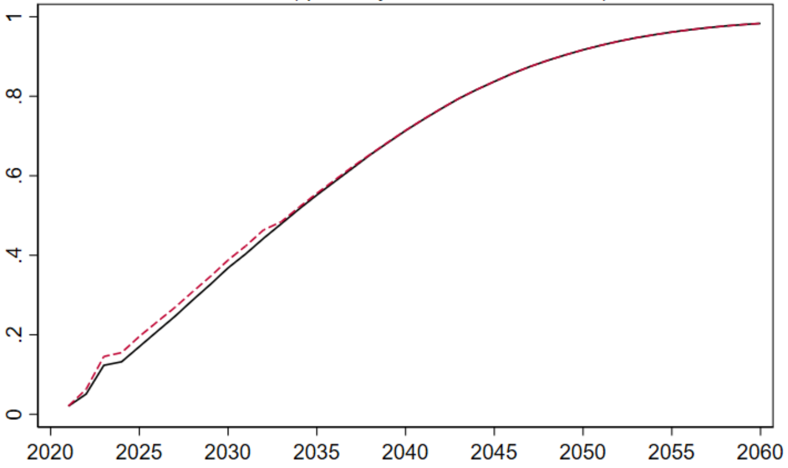
Notes: black line is baseline, red dash is policy scenario

EV share, new LDVs: Means
B: $5k EV instant rebate



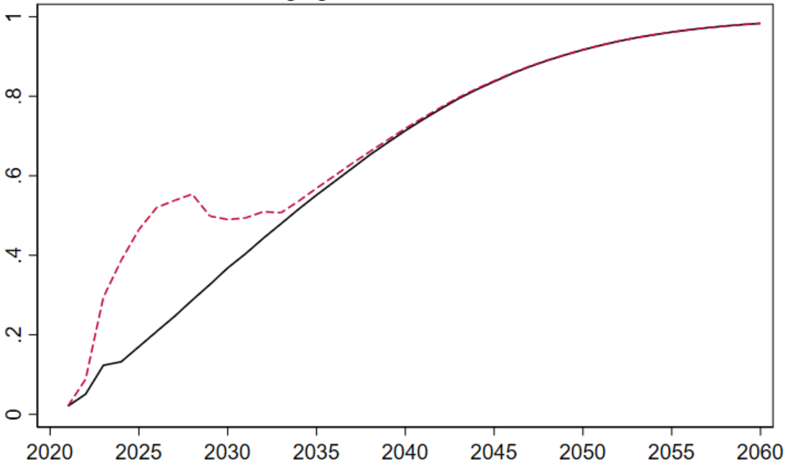
Notes: black line is baseline, red dash is policy scenario

EV share, new LDVs: Means
C: eRIN (quarterly check to EV owners)



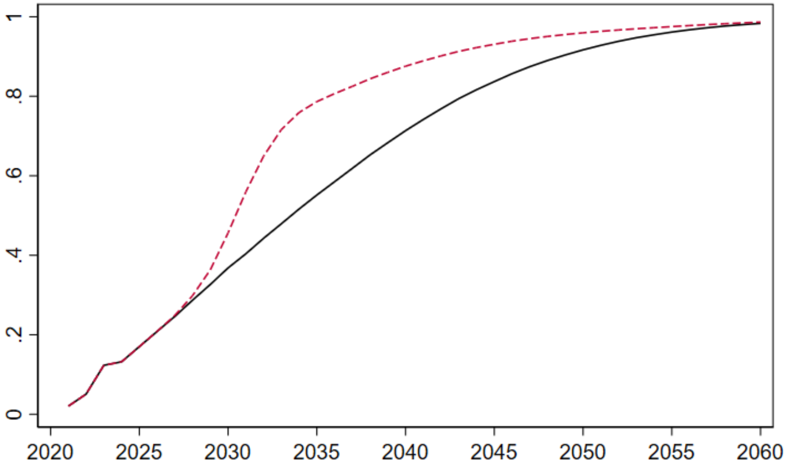
Notes: black line is baseline, red dash is policy scenario

EV share, new LDVs: Means
D: 25%/50% charging stations + $5k instant rebate + eRIN



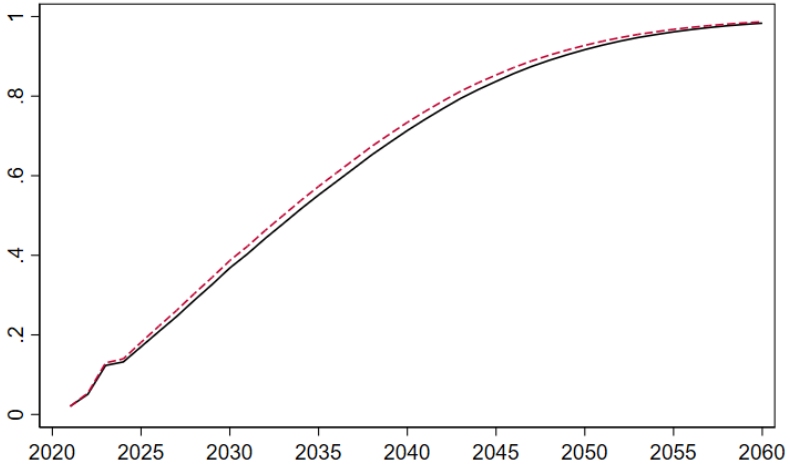
Notes: black line is baseline, red dash is policy scenario

EV share, new LDVs: Means
E: Enhanced CAA standards



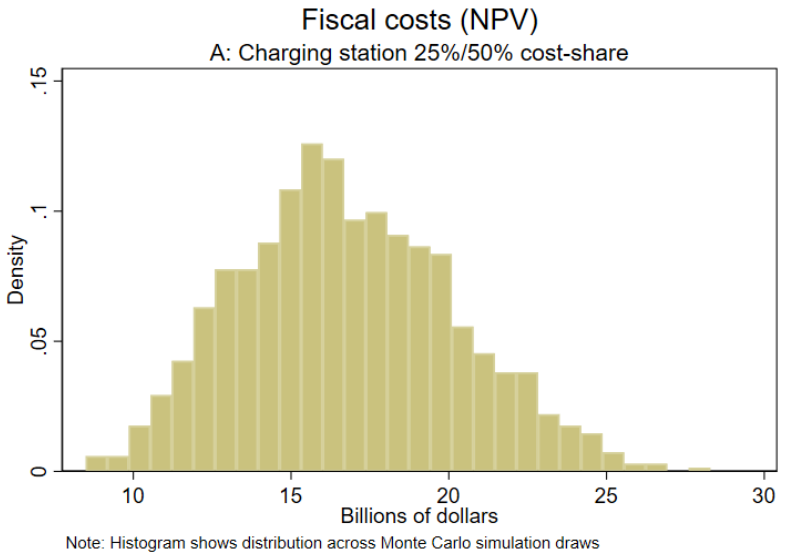
Notes: black line is baseline, red dash is policy scenario

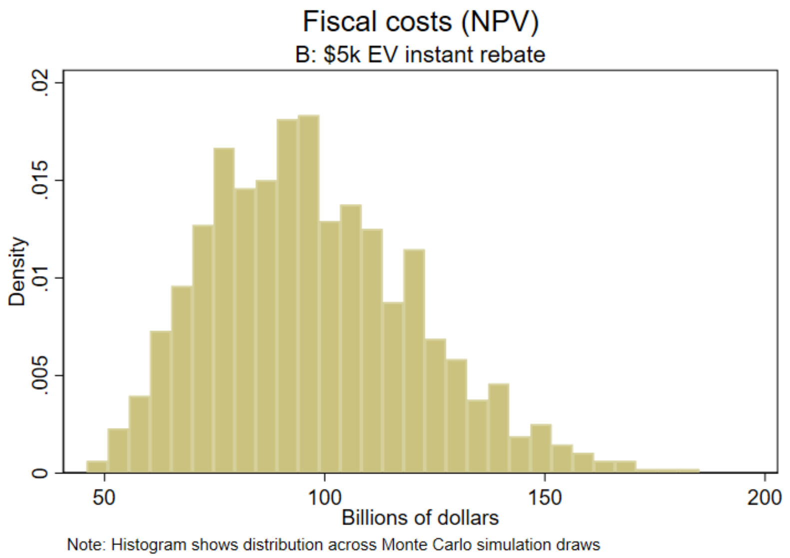
EV share, new LDVs: Means
F: $40 carbon tax

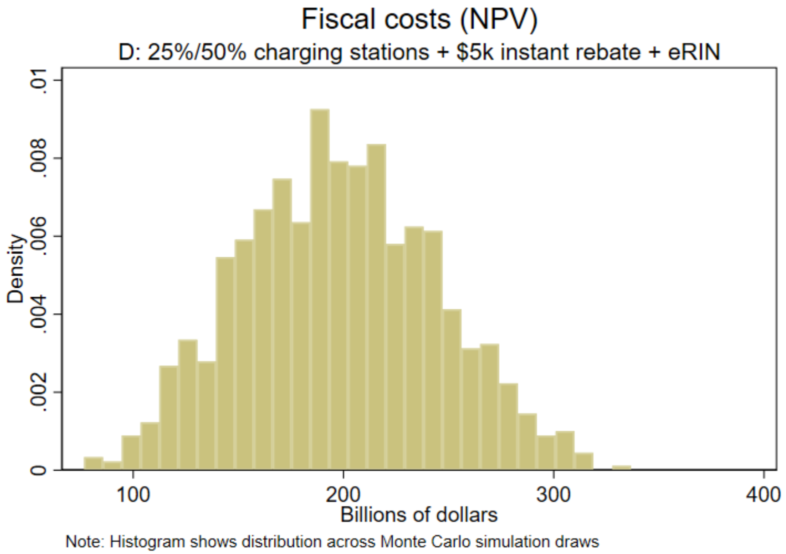


Notes: black line is baseline, red dash is policy scenario

LDVs: Fiscal costs of policies with fiscal components



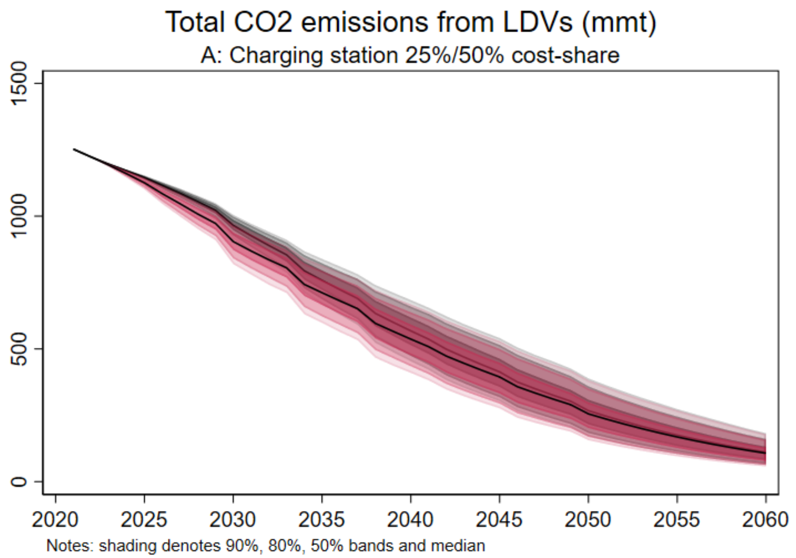


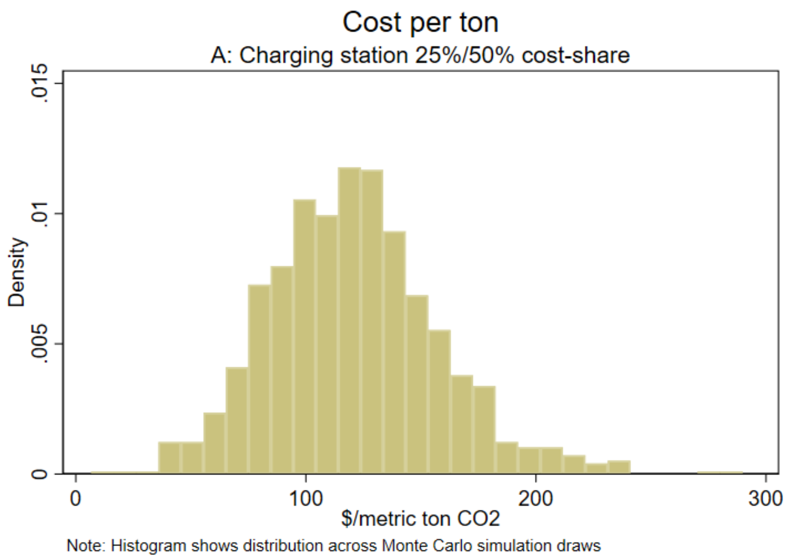


LDVs: Results – With and Without power sector policy

With power sector policy

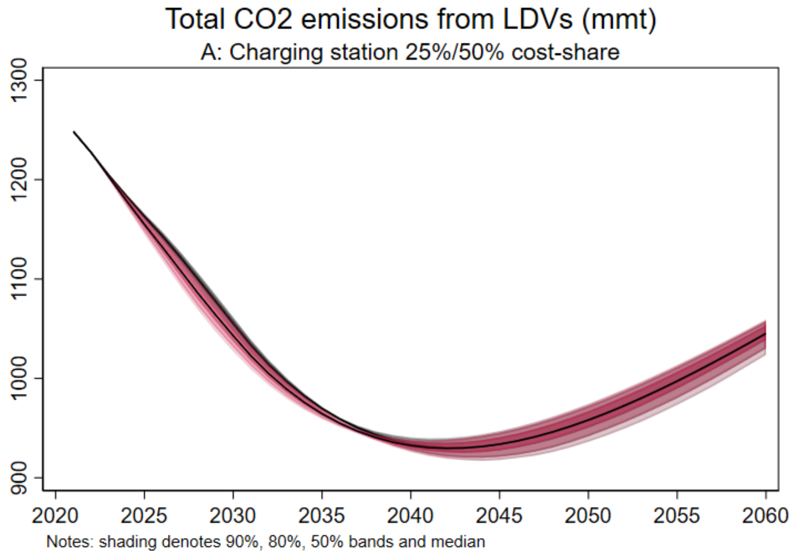
- Tradable performance standard (90% emission reduction by 2035), marginal emissions rates and costs from ReEDS (Stuart-Stock 2021)

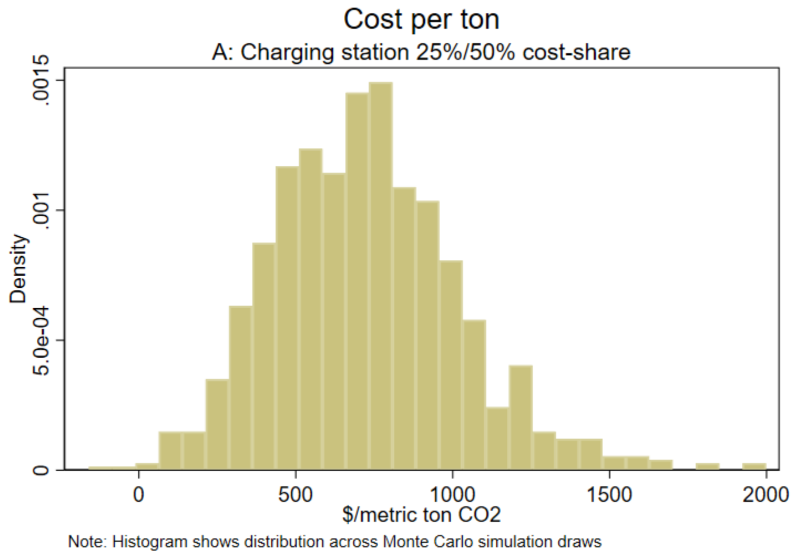




No new power sector policy

- Marginal power sector emissions from Holland et al (2021) (similar to AEO2021 NEMS)
- Marginal emissions are high because coal plants have become marginal (load-following), see NARUC (2020)

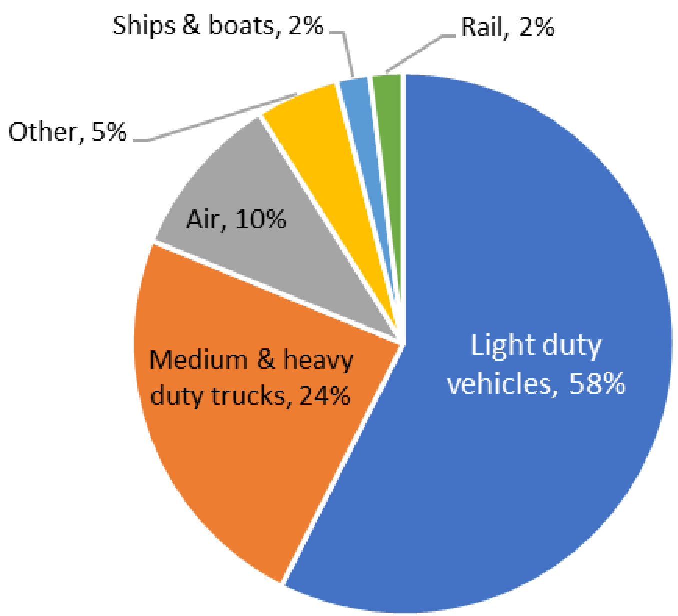


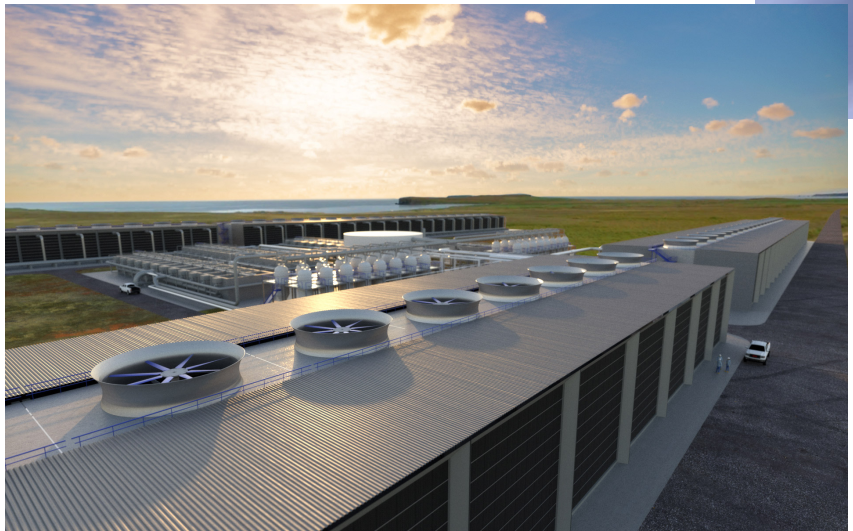


Air: Overview

Air poses major challenges

- Technologies largely don't exist
- Focus here on drop-ins:
  - Petroleum + firm offsets (e.g., direct air capture [DAC])
  - Sustainable aviation fuels (SAF) – "drop-ins"
- Other possibilities (not modeled):
  - Electric
  - Green hydrogen
  - Green ammonia





Air: Model

Too much uncertainty to conduct transitional policy cost assessment

- Transitional policies are largely technology policies

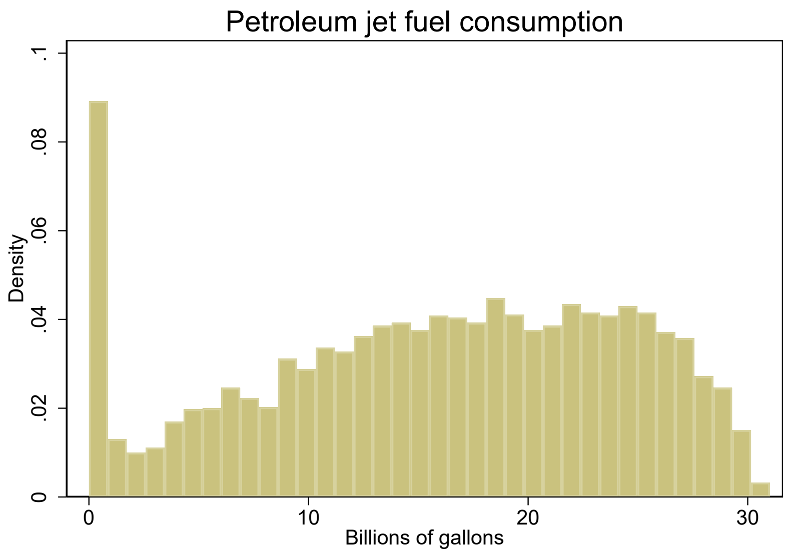
Still, some crude estimates are possible

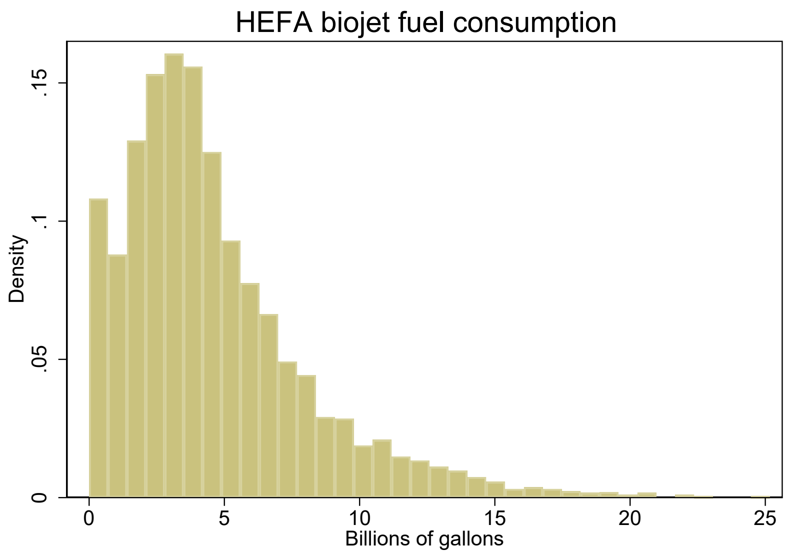
- Focus on 2050
  - Use projections in literature of mature technology costs
  - Suppose airlines required to fully offset emissions with firm offsets (DAC)
- Airlines choose among drop-in fuels:
  1. Petroleum + 100% offset
  2. Vegetable or waste oil-based biojet (Hydroprocessed esters & fatty acids, HEFA)
     - 75% emission reduction + 25% offset
     - limited feedstock supply (e.g., biomass-based diesel (~2Bgal/yr 2019)
  3. Advanced biojet (e.g., alcohol-to-jet (ATJ))
     - 100% emission reduction
     - Less limited feedstock supply (e.g., corn ethanol ~14.5Bgal/yr 2019 + larger cellulosic capacity)
- Supply and demand parameters with uncertainty ranges from economics, science, & techno-economic literatures
- Baseline demand & jet fuel prices ($2.77/gal (!)) from AEO 2021 for 2050
- Monte Carlo simulation over realizations of supply curves

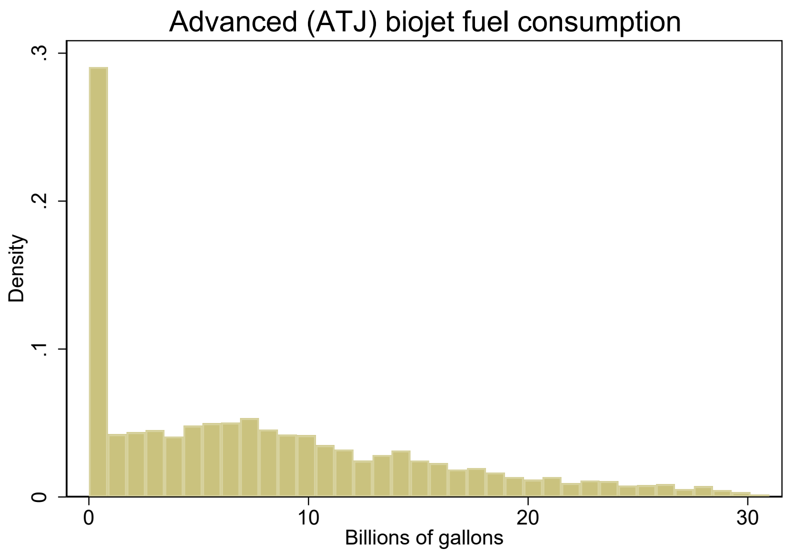
Selected references for supply & demand curves

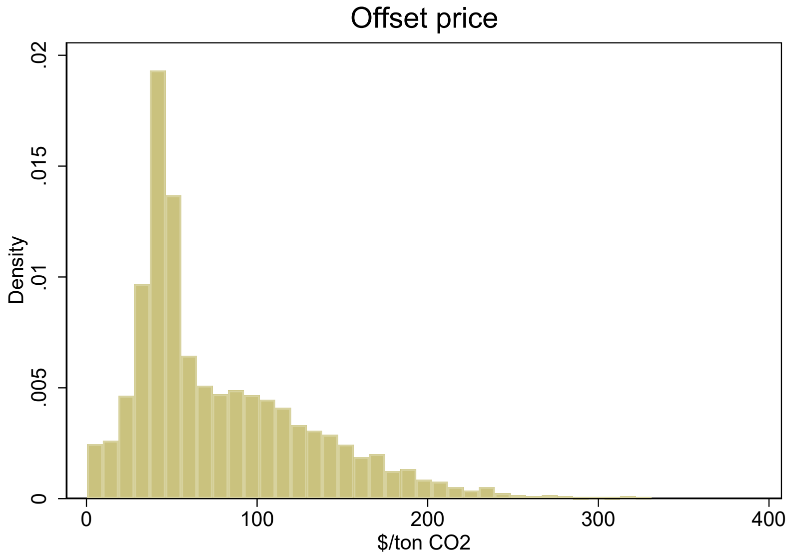
Prest (2020), Balke & Brown, 2018); World Economic Forum/McKinsey (2020), Irwin & Good (2017), Lade & Lin-Lawell (2020), Roberts & Schlenker (2013), Wang et al. (2016), Wei et al (2019) ; Fuss et al. (2018), Fasihi et al. (2019), Hepburn et al. (2019), Keith et al. (2018); Pavlenko et al. (2019), Capaz et al. (2021), Graver et al. (ICCT 2020); Visnawathan et al. (2019), Gray et al. (2021)

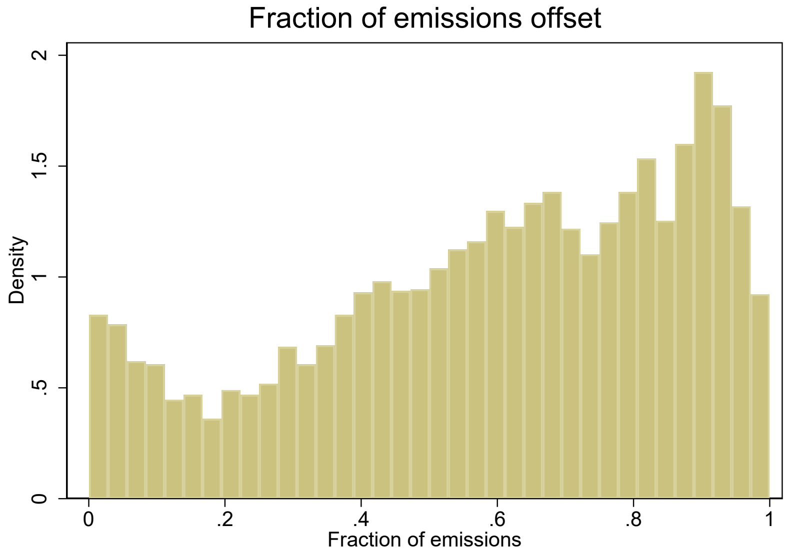
Air: Results











Key points

- Tough to beat petroleum jet fuel at $2.77/gal, even with offsets @ $100-200/ton
- HEFA scalability limits its use for SAF
- ATJ (and other advanced biojet) are scalable but existing cost projections do not give it a major role

HDVs: Overview

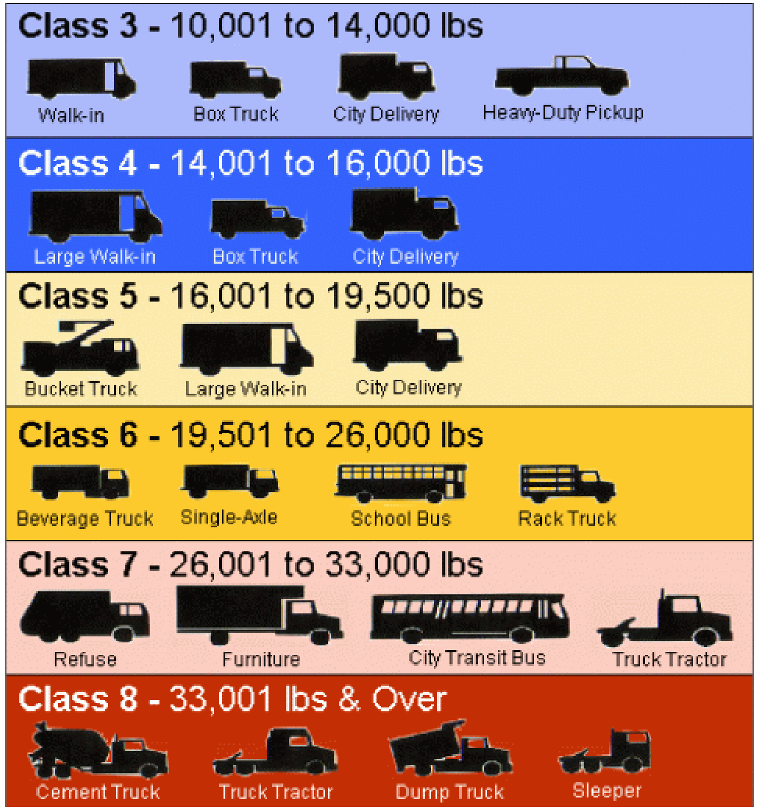
Medium-duty vehicles are amenable to electrification

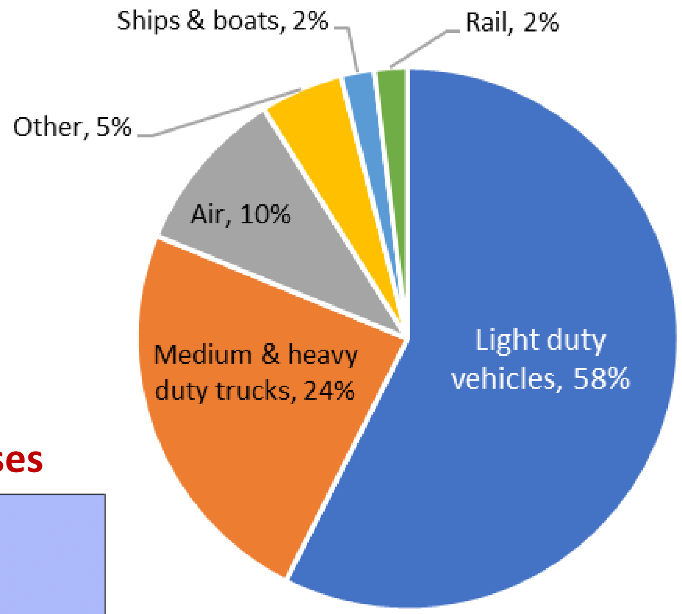
- Delivery vans, buses, heavy-duty pickups (many class 3-6 vehicles)

Class 7-8 distance haulage less clear

- Non-scalable technologies:
  - low-carbon renewable diesel, low-carbon renewable natural gas
  - Both have competing uses: renewable jet, eRIN
- Scalable technologies:
  - Batteries
  - Green hydrogen

Medium & heavy-duty truck classes



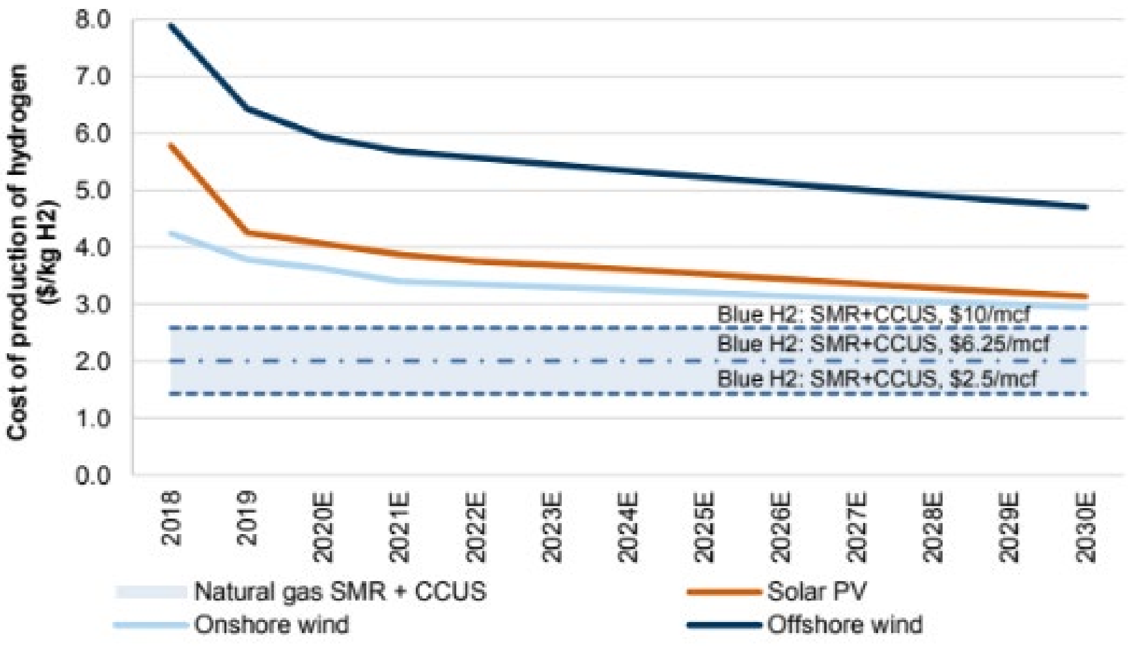


HDVs: Technologies for decarbonization

Hydrogen fuel cells

- 50 shades of hydrogen:
  - **Brown**: coal gasification + reformation
  - **Grey**: steam reformation of methane
  - **Blue**: Grey + carbon capture & storage
  - **Turquoise**: methane pyrolysis yielding solid carbon
  - **Green**: water electrolysis from renewables.
- Wave of enthusiasm:
  - cheap renewables (1-2 ¢/kWh?)
  - advances in electrolysis technology
  - expected scale economies is driving a wave of enthusiasm about green hydrogen.
  - $6-8 per kg considered to be cost parity with gasoline
- Challenges:
  - No fuel cell HDVs currently in production
  - Major challenges:
    - Power train redesign
    - Fuel storage redesign
    - New fueling infrastructure:
      - DOE (2020) estimates H2 fueling station costs at $1.9m each for CA 111-station pilot

LCOH ($/kg H2) implied in the cost of production for hydrogen



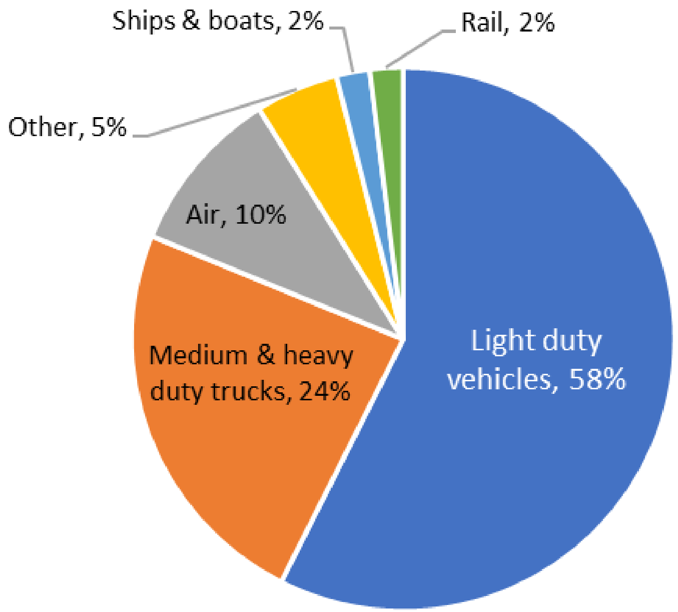
Source: IRENA, Goldman Sachs Global Investment Research

HDVs: EC Hydrogen Strategy

European Commission's hydrogen strategy

- Goals:
  - 6 GW renewable hydrogen electrolyzers and production up to 1 million metric tons renewable hydrogen by 2024
  - 40 GW renewable hydrogen electrolyzers and 10 million metric tons production by 2030
  - Large-scale deployment of mature renewable hydrogen electrolyzer technology especially in hard-to-decarbonize sectors between 2030 and 2050

- Required investments
  - €24-42 billion for electolyzers by 2030
  - €220-340 billion to provide wind and solar electricity for electrolyzers through 2030
  - €11 billion to retrofit existing plants with carbon capture
  - €65 billion for hydrogen transport, storage, and initial refueling stations
  - Estimate that construction of 400 additional refueling stations would require €850-1000 million
    - In line with $1.9m/station from DOE (2020)



Like air & HDVs, the scalable technologies remain unproven

- Non-scalable technologies:
  - low-carbon renewable diesel, low-carbon renewable natural gas
  - Both have competing uses: renewable jet, eRIN
- Scalable technologies:
  - Batteries for certain applications (tugs)
    - Provides significant health co-benefits
    - Gillingham & Huang (2020) estimate long-term NPV-positive electrification benefits in US waters currently requiring low-sulfur fuel
  - Green hydrogen
  - Ammonia
    - Can be burned in ICEs or used in fuel cells
    - Liquid at room temperature
    - But substantial safety & environmental (NOx) challenges
    - One estimate of full global transformation to green ammonia by 2050 is $1.2-1.6T (undiscounted, baseline unclear) (Getting to Zero/Global Maritime Forum/WEF (2020))
- Jury out on whether the clean equilibrium is cheaper.

Port of Auckland all-electric tug

Summary

LDVs

- Policy costs are comparable across policies
  - Near term policies are typically in the $100-$150 range
  - Later-implementation policies are
- Charging infrastructure plays critical role (as in Springel 2020)
- Non-policy path requires expensive oil, very significant attribute improvements, or a higher price elasticity than found in the literature so far.

Medium and some heavy-duty applications

- Local delivery van fleets, buses,… ripe for electrification – and plausibly cheaper on full user cost basis (plus local health benefits)

Air, Long-distance HDVs, Marine

- Based on current technology estimates, it is hard to be confident of a cheaper clean future
  - Critical role for firm offsets (direct air capture)
  - Critical role for RDD policy

More research needed

- To inform cost-effective policy to achieve decarbonization goals

Additional Slides

LDVs: Model

Consumer demand

- Two categories of vehicles: cars or SUVs (which includes light trucks & vans)
- Within category, choose EV vs. ICE
- Demand depends on relative price, charger availability (Level 2, Level 3), and other attributes/tastes

$$s_t^{car} = Logistic\left(\alpha^{car} + \beta_P \ln P_t^{car} + \beta_{N2} \ln\left(N_{t-1}^{L2} / Q_{t-1}\right) + \beta_{N3} \ln N_{t-1}^{L3} + \phi_t\right)$$

$$s_t^{SUV} = Logistic\left(\alpha^{SUV} + \beta_P \ln P_t^{SUV} + \beta_{N2} \ln\left(N_{t-1}^{L2} / Q_{t-1}\right) + \beta_{N3} \ln N_{t-1}^{L3} + \phi_t\right)$$

where $s_t^{car} = \text{EV share of cars}$

$P_t^{car} = P_t^{car,EV} / P_t^{car,ICE} = \text{ full perceived user cost relative price for cars}$

$Q_t = \text{stock of EVs}$

$N_t^{L2} = \text{ number of Level 2 chargers}$

$\phi_t = \text{ attribute drift}$

$\eta_P = \text{ price elasticity } = (1 - s^{car})\beta_P \text{ (and same for charger elasticity)}$

$s_t = \sigma^{car} s_t^{car} + \sigma^{SUV} s_t^{SUV} = \text{ EV share of LDVs}$

Notes: Based on Springel (2020), with the following modifications: (a) Springel uses price, I use log price. (b) Springel estimates demand at the vehicle model level, this aggregates to (EV, ICE) × (car, SUV); (c) Springel doesn't differentiate among charging station level; I differentiate between Level 2 &3. Here L2 is treated on a per-vehicle basis, L3 is treated on geographic density (or equivalently per road-mile) basis. Springel and Zhou-Li (2017) use ln(N) specifications. (d) I follow Archsmith et al (2021) and introduce the term φ_t to capture attribute and taste drift (modeled here as a random walk). (e) I model consumer choice in year *t* as depending on (observed) charging stations in year *t*-1.

LDVs: Model

Private-sector charging station provision

Separately model L2 and L3 chargers because of different costs and different saturation values

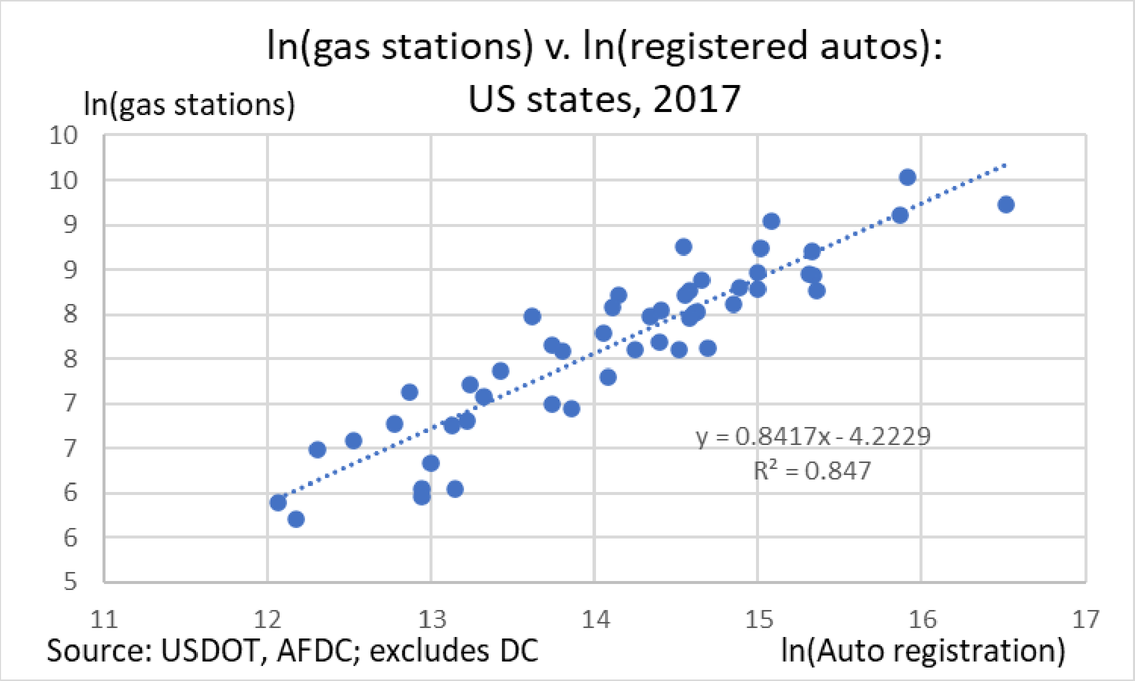
$$\ln N_t^{L2} = \kappa^{L2} + \gamma \ln Q_t^{EV} - \gamma \ln \tilde{C}_t^{L2}$$
$$\ln N_t^{L3} = \kappa^{L3} + \gamma \ln Q_t^{EV} - \gamma \ln \tilde{C}_t^{L3}$$

where

$$\tilde{C}_t^{L2} = C_t^{L2} - (1+r)^{-1} C_{t+1}^{L2}$$

C_t^{L2} = installed cost of a Level 2 charger

Source: Zhou & Li (2018-US), Springel (2020)



Stock/flow accounting

- LDV scrappage rate 10%/year
- Charging station scrappage rate 10%/year

Calibration

κ_2 : calibrate so full-penetration public Level 2/EV ratio = 0.1 (US 2019: ~0.04; Norway: ~0.03)

κ_3 : calibrate so full-penetration public Level 3 stations/EV = current gas stations/2 = 60k

$$C_t^{L2} = C_{2020}^{L2}\left(.5 + .5e^{-0.02(y-2020)}\right), C_{2020}^{L2} = \$2k$$

$$C_t^{L3} = C_{2020}^{L3}\left(.5 + .5e^{-0.02(y-2020)}\right), C_{2020}^{L3} = \$500k \ (10\ @\ \$50k)$$

LDVs: Parameterization & MC

Model:

$$s_t^{car} = \exp\left(\alpha^{car} + \beta_P \ln P_t^{car} + \beta_{N2} \ln\left(N_{t-1}^{L2} / Q_{t-1}\right) + \beta_{N3} \ln N_{t-1}^{L3} + \psi_t\right)$$

$$\ln N_t^{L2} = \kappa^{L2} + \gamma \ln Q_t^{EV} - \gamma \ln \tilde{C}_t^{L2}$$

Demand:

$\eta_P \sim N(-2, 0.5)$ at EV share 33% (Springel fn 38) (so $\beta_P = \eta_P / (1 - .33)$)

$\eta_{N2} = \eta_{N3} \sim N(0.37, 0.1)$ at EV share 33%

$\psi_t = \mu + \psi_{t-1} + \zeta_t$, $\mu \sim N\left(.02\beta_P, .005\left|\beta_P\right|\right)$, $\zeta_t \sim N(0, 2\mu)$

References:

η_P: Springel (2020): -1.5 to 2.0; Xing et al (2019): -2.7; Li (2019): -1.3; Muehlegger & Rapson (2018): -3.9; Archsmith, Muehlegger, & Rapson (2021) simulation values -1, -2 -3

η_P: Springel (2020): -0.418 (SE = 0.038) mean in random coefficients model @ ~12% market share (2014)

Technology: ICE, SUV price model follows Lutsey & Nicholas (ICCT (2019)), Clinton, Knittel, and Metaxoglu (2020).

- Full user cost = initial vehicle cost + valuation factor × O&M costs
- Manufacturing cost breakdown from Lutsey & Nicholas (2019).
- Valuation factor ~ U[0.5, 1].
    - References, all for ICEs: Gillingham, Houde, & van Bentham (forthcoming): 0.16-0.39; Allcott & Wozny (2014): 0.72; Grigolon, Raynaert, and Verboven (2018): 00.91; Leard, Linn, and Zho (2019): 0.54 and <0.30; Goldberg (1998): near 1. We use higher value because of salience at point of making ICE/EV decision
- Battery prices: -16% per year 2009-2019; project N(-.09,.02), with $50 floor
- *EV* (kWh/mi): 3.4 (cars – Chevy Bolt), 2.0 (SUVs & lt trucks – Car & Driver estimate for F150 Lightening)

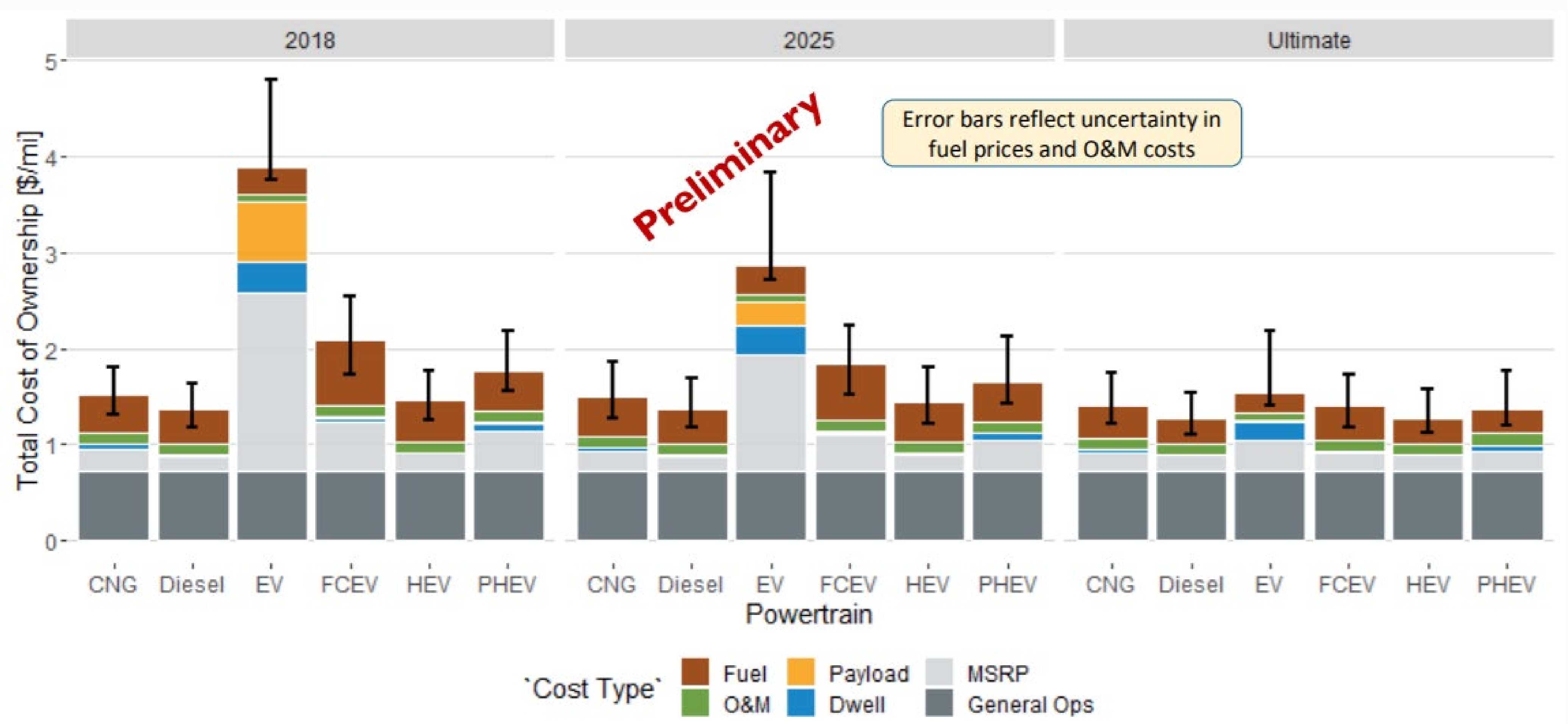
LDVs: Odds & ends

Odds & ends

- Discount rate: 3% real
- Prices & costs in 2020 $’s
- Power sector marginal emissions rate and incremental costs from added EV load under TPS from ReEDS (Stock-Stuart (2021))
- VMT growth from AEO 2021 reference case
- eRIN value flows upstream (marginal cost of biogas ≤ marginal cost of natural gas & competitive auto industry)
- System costs = additional power system costs, vehicle costs, & liquid fuel costs
- Total costs = system costs + federal share (set marginal cost of public funds = 1)
- Simulations span 2021-2060, 2021 fixed at (estimated) 2021 initial conditions
- No expectational channels

HDVs: Technologies for decarbonization

Projected total cost of ownership for class 8 trucks by fuel type



Source: National Renewable Energy Laboratory (2020)