Estimating the Cost of Decarbonizing the Transportation Sector

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Emissions from the US Transportation Sector

US GHG Emissions by Sector, 2019

Sources: EPA Greenhouse Gas Inventory, EIA AEO 2021

AEO 2021 reference scenario: energy for transport

US Transport CO2 Emissions by Mode, 2019

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:
  o GHG externality
  o Innovation externality
  o 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
  o total system costs = EVs – ICEs + O&M differential + charging stations + power system upgrades (all gross of federal support)
  o *not* welfare

LDV model elements

• Discrete choice model of EV demand (by cars, SUVs+), logistic, depends on:
  o Full user cost (with myopia)
  o Charging stations (Level 2, 3)
  o Non-price attributes/tastes

• Private charging station buildout
  o Early adopters largely charge at home
  o Insufficient Level 3 (DC fast chargers)
  o 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
  o **Key references:** Zhou & Li (2017, 2018), Springel (2020), Archsmith, Muehlegger, & Rapson (2021)
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): 0.91; Leard, Linn, and Zho (2019): 0.54 and <0.30. We use higher value because of salience at point of making ICE/EV decision.
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

A: Charging station 25%/50% cost-share
Note: Histogram shows distribution across Monte Carlo simulation draws

B: $5k EV instant rebate
Note: Histogram shows distribution across Monte Carlo simulation draws

C: eRIN (quarterly check to EV owners)
Note: Histogram shows distribution across Monte Carlo simulation draws

D: 25%/50% charging stations + $5k instant rebate + eRIN
Note: Histogram shows distribution across Monte Carlo simulation draws

E: Enhanced GAA standards
Note: Histogram shows distribution across Monte Carlo simulation draws

F: $40 carbon tax
Note: Histogram shows distribution across Monte Carlo simulation draws
LDVs: New EV sales share, various policies (means)

A: Charging station 25%/50% cost-share
B: $5k EV instant rebate
C: eRIN (quarterly check to EV owners)

D: 25%/50% charging stations + $5k instant rebate + eRIN
E: Enhanced CAA standards
F: $40 carbon tax
LDVs: Fiscal costs of policies with fiscal components

Fiscal costs (NPV)
A. Charging station 25%/50% cost-share

Fiscal costs (NPV)
B. $5k EV instant rebate

Fiscal costs (NPV)
D. 25%/50% charging stations + $5k instant rebate + eRIN

Note: Histogram shows distribution across Monte Carlo simulation draws.
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 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
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

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
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:
  o low-carbon renewable diesel, low-carbon renewable natural gas
  o Both have competing uses: renewable jet, eRIN
• Scalable technologies:
  o Batteries
  o Green hydrogen
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
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 electrolyzers 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.
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
Decarbonizing Transportation

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

\[
s_{i}^{\text{car}} = \text{Logistic}\left(\alpha_{\text{car}} + \beta_{P} \ln P_{i}^{\text{car,EV}} + \beta_{N_{2}} \ln \left(\frac{N_{t-1}^{L_{2}}}{Q_{t-1}}\right) + \beta_{N_{3}} \ln N_{t-1}^{L_{3}} + \phi_{t}\right)
\]
\[
s_{i}^{\text{SUV}} = \text{Logistic}\left(\alpha_{\text{SUV}} + \beta_{P} \ln P_{i}^{\text{SUV}} + \beta_{N_{2}} \ln \left(\frac{N_{t-1}^{L_{2}}}{Q_{t-1}}\right) + \beta_{N_{3}} \ln N_{t-1}^{L_{3}} + \phi_{t}\right)
\]

where

- \(s_{i}^{\text{car}}\) = EV share of cars
- \(P_{i}^{\text{car,EV}} = \frac{P_{i}^{\text{car,ICE}}}{P_{i}^{\text{car,ICE}}}\) = full perceived user cost relative price for cars
- \(Q_{i}\) = stock of EVs
- \(N_{t-1}^{L_{2}}\) = number of Level 2 chargers
- \(\phi_{t}\) = attribute drift
- \(\eta_{P}\) = price elasticity =\((1 - s_{i}^{\text{car}})\beta_{P}\) (and same for charger elasticity)
- \(s_{i} = \sigma_{\text{car}} s_{i}^{\text{car}} + \sigma_{\text{SUV}} s_{i}^{\text{SUV}}\) = 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) \(\times\) (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 \(\phi_{t}\) 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 \(t-1\).
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

\[
\tilde{C}_t^{L2} = C_t^{L2} - (1 + r)^{-1} C_{t+1}^{L2} \\
C_t^{L2} = \text{installed cost of a Level 2 charger}
\]

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

Stock/flow accounting
- LDV scrappage rate 10%/year
- Charging station scrappage rate 10%/year

Calibration
\[ \kappa_2 : \text{calibrate so full-penetration public Level 2/EV ratio} = 0.1 \text{ (US 2019: \sim 0.04; Norway: \sim 0.03)} \]
\[ \kappa_3 : \text{calibrate so full-penetration public Level 3 stations/EV = current gas stations/2 = 60k} \]
\[ C_t^{L2} = C_{2020}^{L2} \left( 0.5 + 0.5 e^{-0.02(y-2020)} \right) , C_{2020}^{L2} = \$2k \]
\[ C_t^{L3} = C_{2020}^{L3} \left( 0.5 + 0.5 e^{-0.02(y-2020)} \right) , C_{2020}^{L3} = \$500k \text{ (10 @ } \$50k) \]
**LDVs: Parameterization & MC**

**Model:**

\[
s_t^{\text{car}} = \exp\left(\alpha^{\text{car}} + \beta_P \ln P_t^{\text{car}} + \beta_{N2} \ln \left(\frac{N_t^{L2}}{Q_{t-1}}\right) + \beta_{N3} \ln N_t^{L3} + \psi_t\right)
\]

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

**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%

\[\psi_t = \mu + \psi_{t-1} + \zeta_t, \mu \sim N(0.02\beta_P, 0.005|\beta_P|), \zeta_t \sim N(0, 2\mu)\]

**References:**

- \(\eta_{N2}\): 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): 0.91; 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)
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
Projected total cost of ownership for class 8 trucks by fuel type

Source: National Renewable Energy Laboratory (2020)