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On the Road to Zero Emissions:

Potential of the IC Engine Based Powertrain

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Society of Automotive Engineers of Japan, Inc.

SAE INTERNATIONAL

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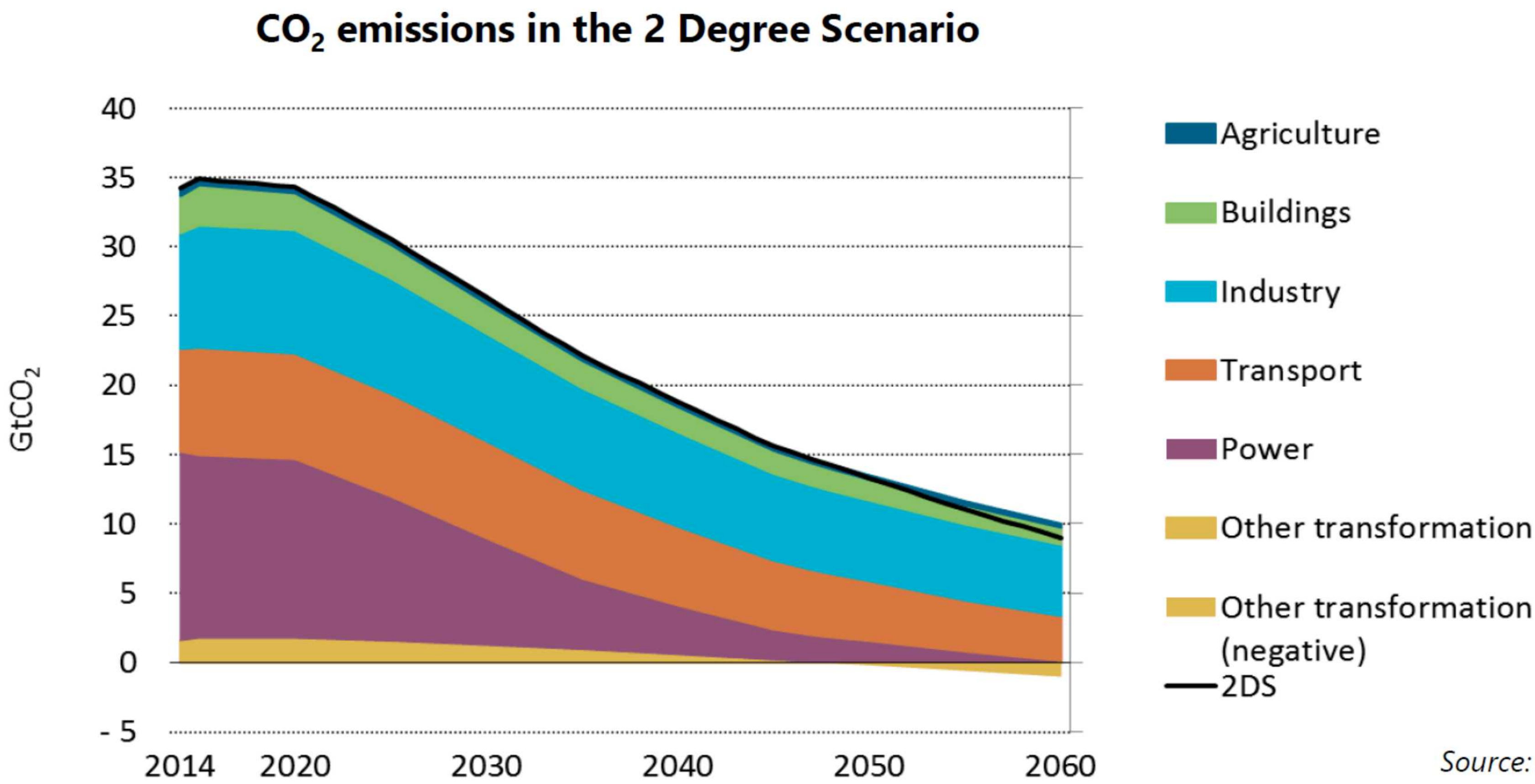
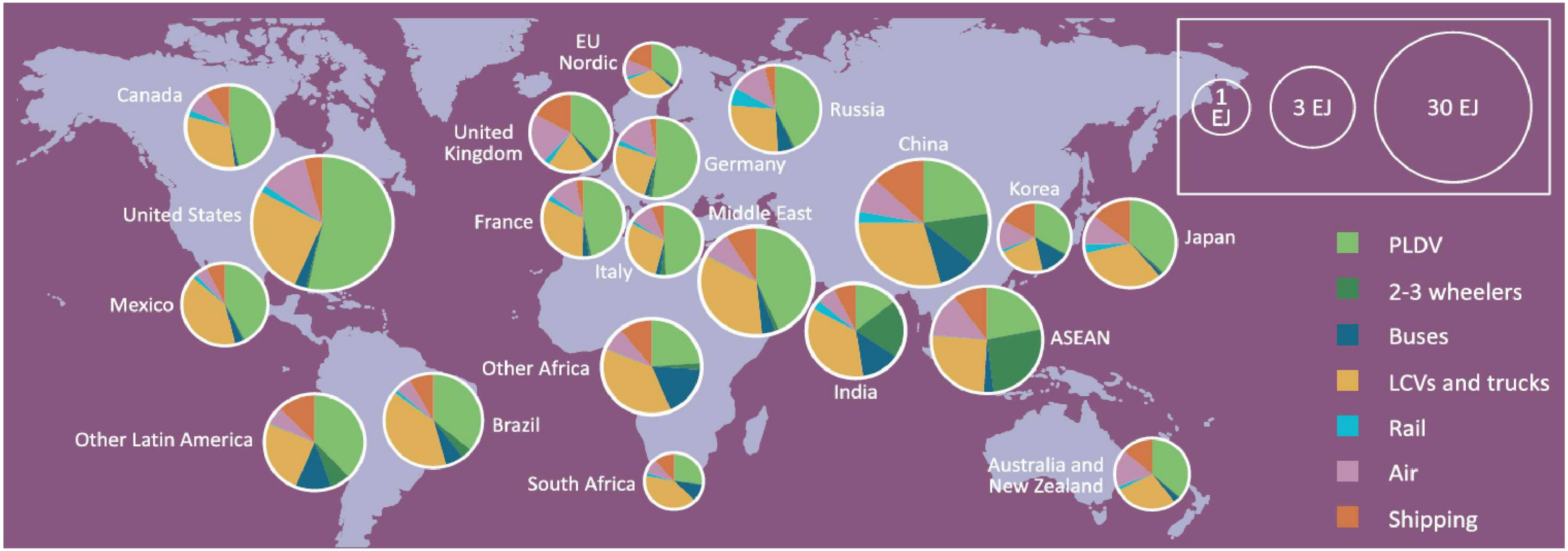
Transportation will be a major CO_2 emission source in 2050



Source: ETP 2017

Our focus will be on the US market and transportation energy scenario

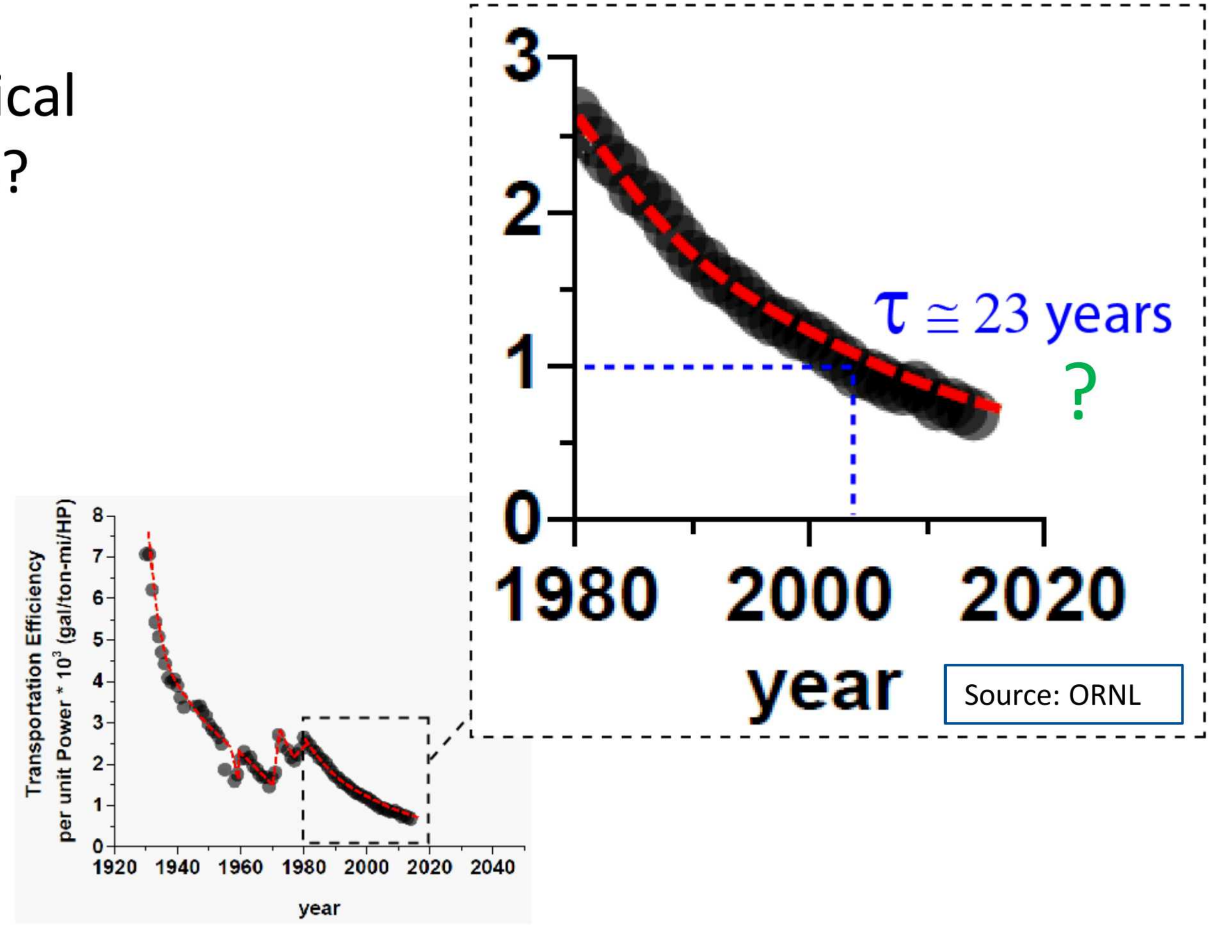


- The US transportation energy mix is similar to the world transportation energy mix
- Overall conclusions from this presentation should be broadly applicable

How much potential is left to improve ICEVs?

- Can we project historical trends into the future?

- What will the estimated impact on petroleum displacement or GHG emissions be?



Setting the baseline…

2017 fleet average fuel consumption

(EPA Real-World) 24.9 mpg
(Regulatory Test) 31.7 mpg

- Car 52.5%: **29.2 mpg**
  37.6 mpg = 6.26 L/100 km
  1610 kg, 145 kW, 8.4 s 0-60 mph
  (Malibu, Fusion, Camry)

- Truck 47.5%: **21.4 mpg**
  26.9 mpg = 8.74 L/100 km
  2130 kg, 210 kW, 7.9 s 0-60 mph
  (F150, Odyssey, Colorado)

What is the state-of-the-art?

EPA Benchmark Vehicles

- 2016 Mazda 6: **32.2 mpg (43.1 mpg)**
  (1470 kg, 140 kW, ~7.5 s 0-60)

  13% fuel consumption reduction from baseline fleet

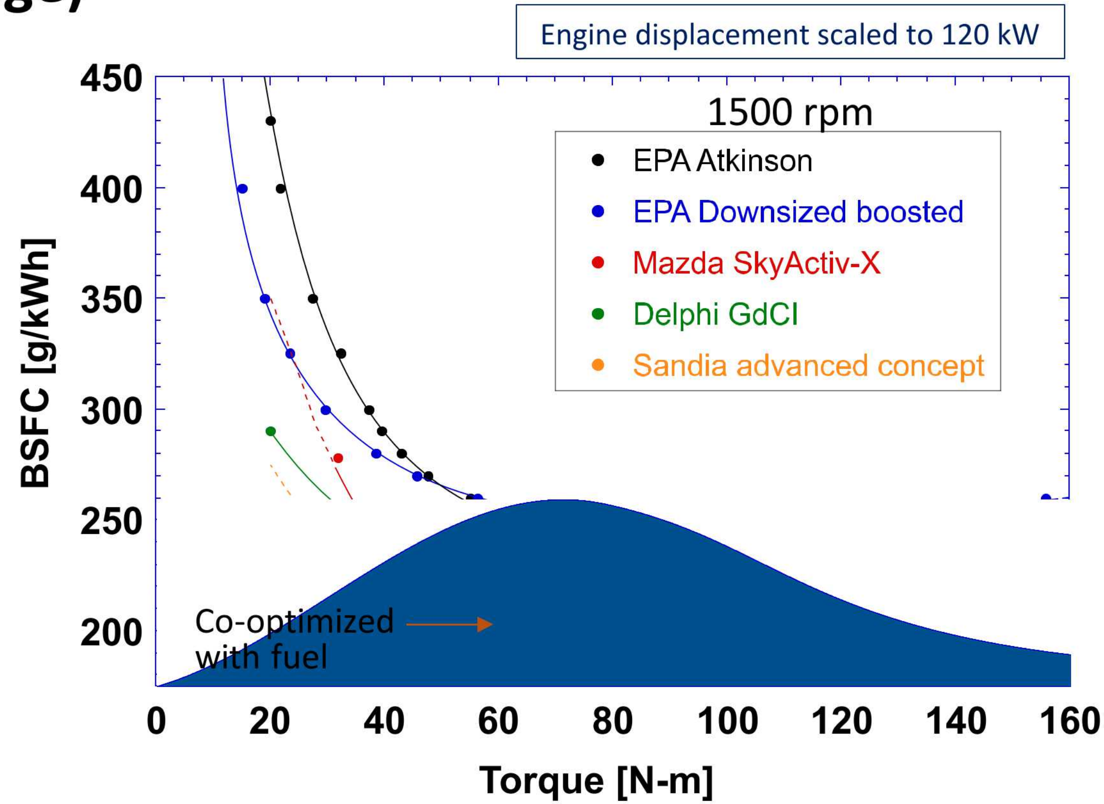
- 2015 Truck Ford F-150 : **21.8 mpg (28.5 mpg)**
  (2060 kg, 242 kW, <7.5 s 0-60)

  3% fuel consumption reduction from baseline fleet

What is the potential of advanced technologies?

2-Cycle Fuel Economy Improvement (relative to 2017 fleet average)

- EPA benchmark car **13%**
  EPA benchmark truck **6%**
- Adv. comb. car **24%**
  Adv. comb. truck **20%**
- Lab Car **28%**
  Lab Truck **24%**
- Lab Car w/fuel **32%**
  Lab Truck w/fuel **28%**



Fleet fuel economy improvements of **~ 30%** above the 2017 fleet average are possible with combustion improvement alone

Is this approximate analysis methodology credible?

Mazda SkyActiv-X

- Our analysis estimates a FE improvement for the SkyActiv-X, on the US 2-cycle test, of **12.9%**

↓

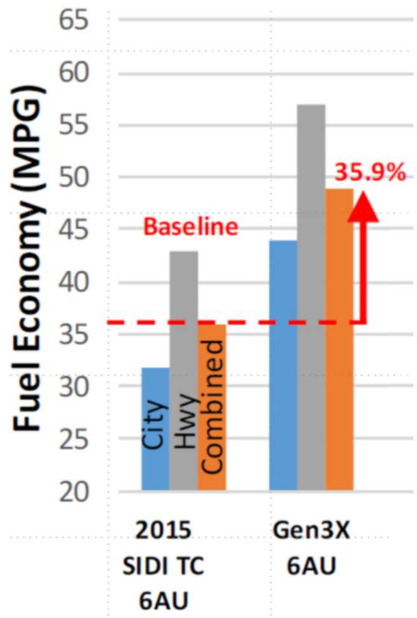
- US EPA estimate is 12.5 % [Dan Barba, 2018]
- Automotive press ~13-14%
- June 2019 Mazda press release:
  - ~10% WLTP fuel consumption reduction
  - ~15% NEDC fuel consumption reduction

Delphi GdCI

- We found a potential FC reduction of 24%, scaling by best BSFC (Gen2X/Gen3X), we estimate **28%**

↓

- Accounting for different baselines, and translating to %FC reduction, Delphi estimates **23%** FC reduction



Source: SAE 2019-01-1154

Several additional technologies can be brought to bear…

- Friction reduction
  (lubricants and mechanical design)
- Cylinder deactivation
- Accessory electrification
- Transmissions
- Low friction brakes
- Hybridization ~ 30% additional FC reduction

2018 Camry 32 mpg → 52 mpg

A 39% reduction

Gasoline midsize vehicles consume from **23%** to **49%** less fuel by 2050 compared with a 2015 reference

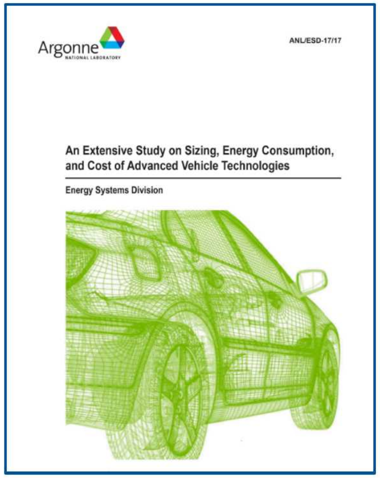
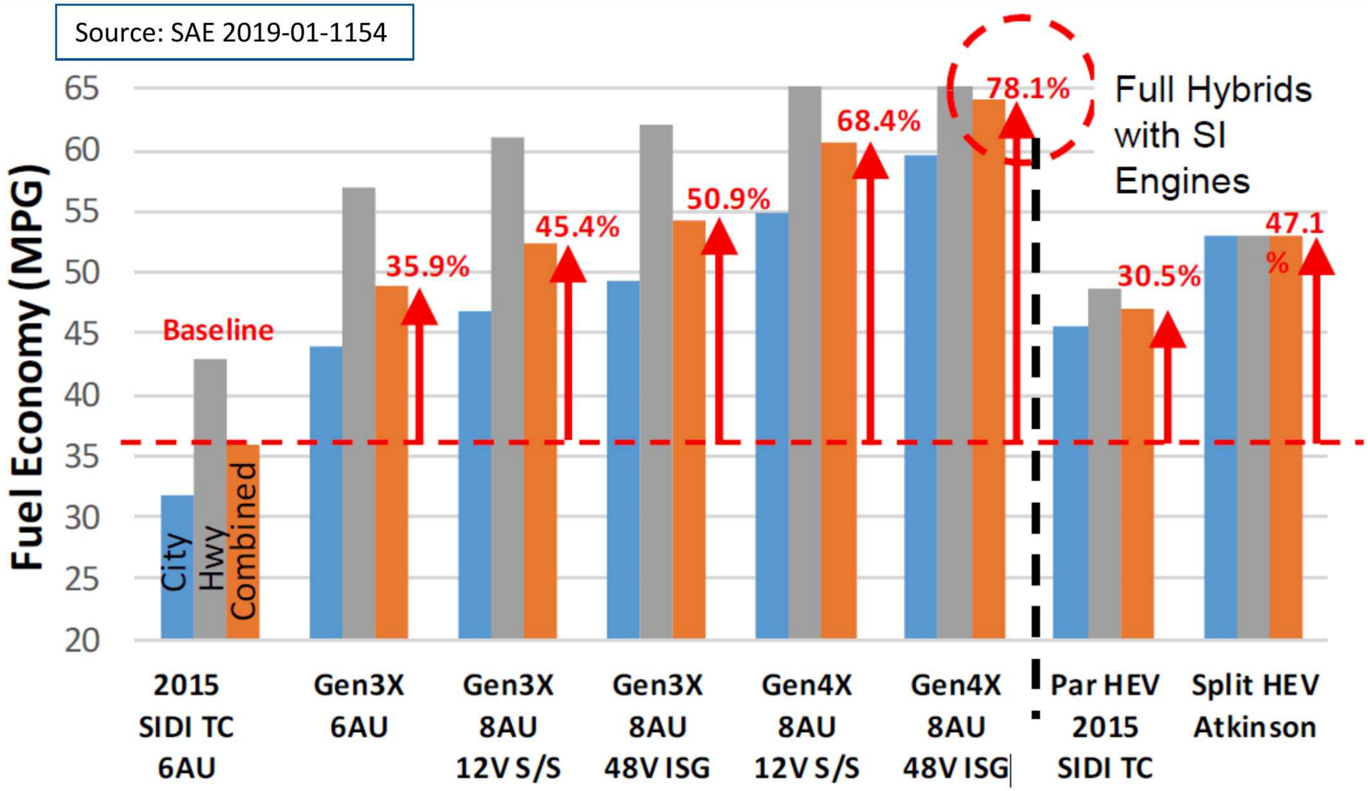


TABLE ES.1 Percentage gasoline-gallon equivalent fuel consumption reduction of each powertrain by 2045, compared with reference 2010 gasoline conventional powertrain

Fuel/ Powertrain	Conventional	HEV	PHEV25	PHEV40	PHEV50
Gasoline	23–49	50–73	78–89	84–92	87–94
Diesel	23–51	43–68	73–85	82–91	86–92
Fuel Cell		68–81	86–92	91–95	93–96

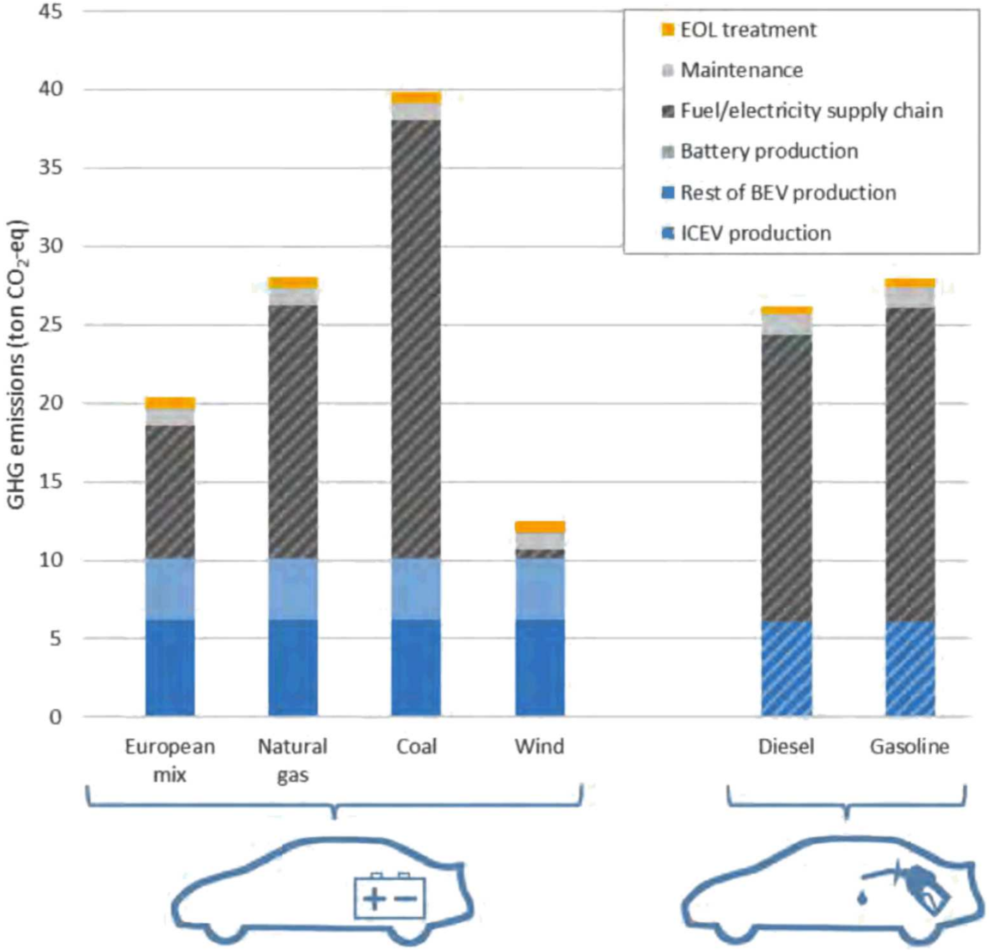
- Hybrids can provide an additional 35–47% reduction in FC

The Delphi work shows an additional 23% reduction in FC with mild-hybridization



- Autonomie modeling estimates GdCI with mild hybridization gives **64 mpg**, a 41% reduction in fuel consumption from fleet avg., 23% due to hybridization
- Allowing for full power-split hybridization, and additional combustion advances, a **75 mpg** HEV is readily achievable, <u>double the car fleet average</u>

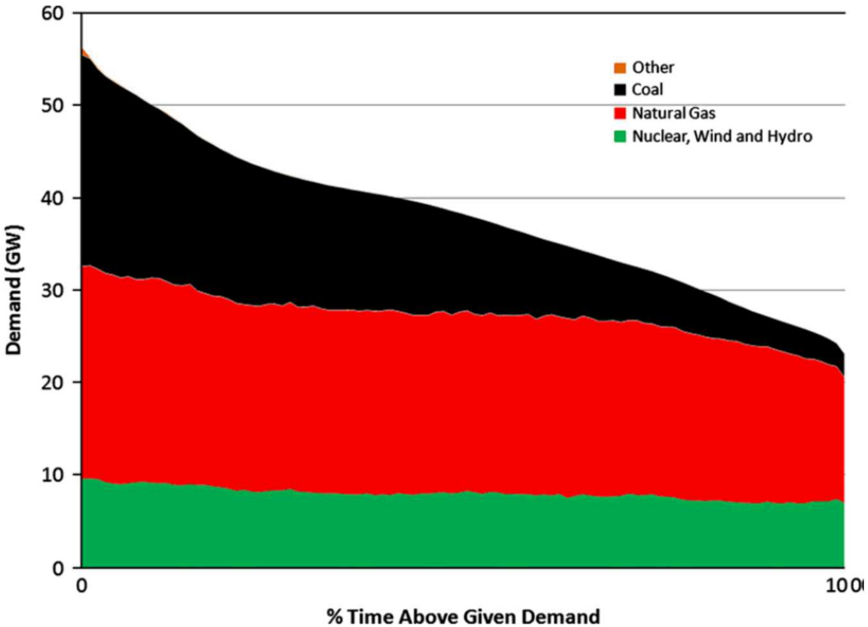
How do the carbon emissions of high-efficiency ICEs compare with BEVs?

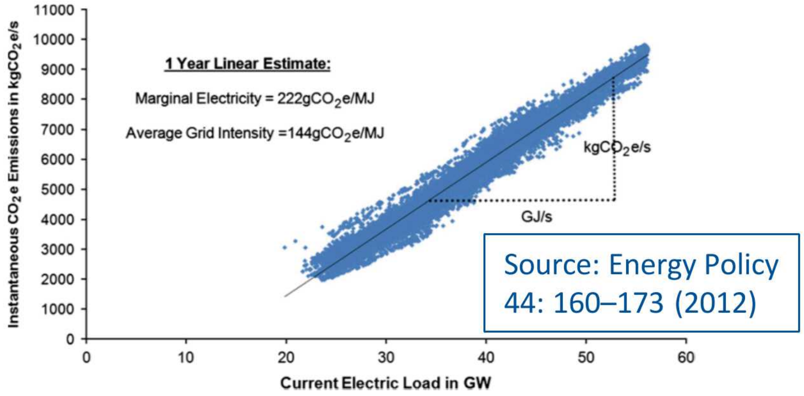


- CO_2 emissions due to vehicle manufacturing (excluding the battery) maintenance, and end-of-life (EOL) processing are similar between ICEVs and BEVs and independent of the CO_2 intensity of the electricity
- We need only consider in-use CO2 emissions and emissions associated with battery manufacturing in comparing ICEVs and BEVs

Source: Ellingsen 2018. Also see AD Little 2016, UCLA 2012

Marginal carbon accounting for added load to the grid





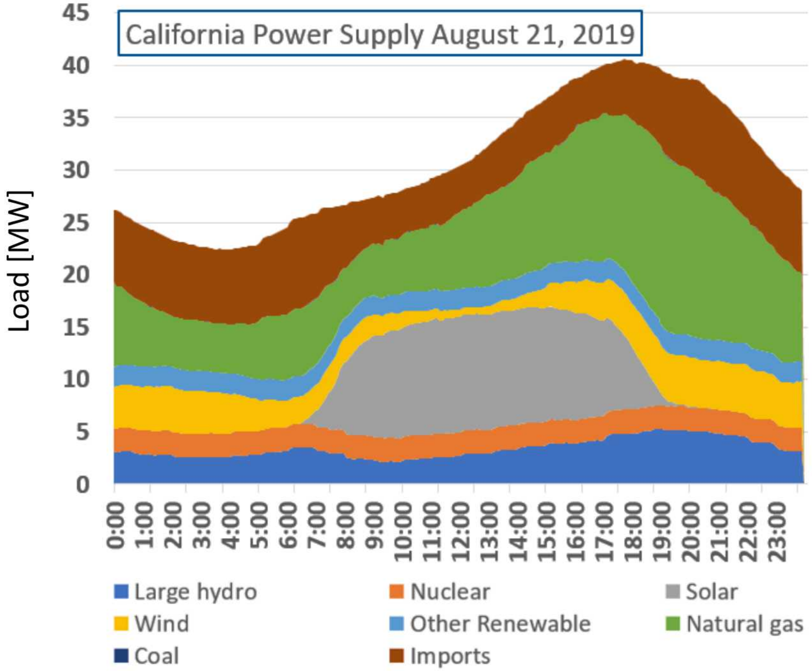
Source: Energy Policy 44: 160–173 (2012)

- In this example (UK 2009-2010) marginal CO_2 emissions are 54% higher than the average

- US EPA eGRID 2016 puts "non-baseload" emissions **50%** higher than the grid average; marginal emissions from AVERT in 2016 were **68%** higher
- Growing acknowledgement that marginal emissions are appropriate for evaluating EV GHG impacts Environ. Sci. Tech.50, 8937–8953 (2016)
- "Only when low-emission plants would have been curtailed [without] PEVs can PEV adoption result in increased use of these plants" Environ. Res. Lett. 11 024009 (2016)

Short-term and long-term marginal electricity sources can be defined

Short-term:



- Renewables are growing rapidly, but marginal gas and high-CO_2 imports are dominant during EV charging hours
- Curtailment of renewables does occur in CA, but is expected to be minor across the nation

Long-term:

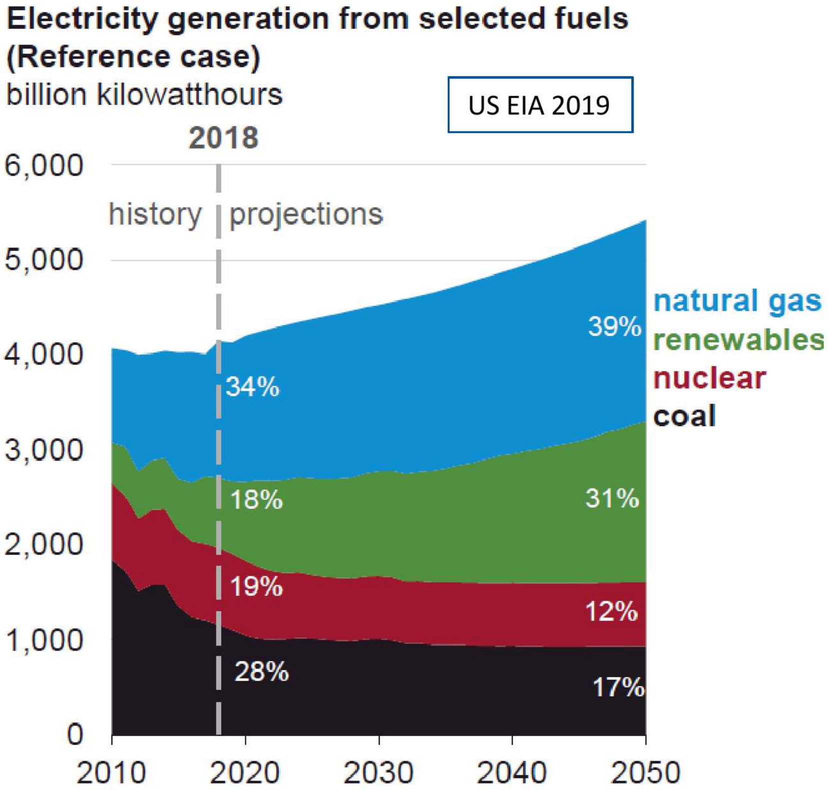
Source: Dr. K. Hatamura, private comm. 2019

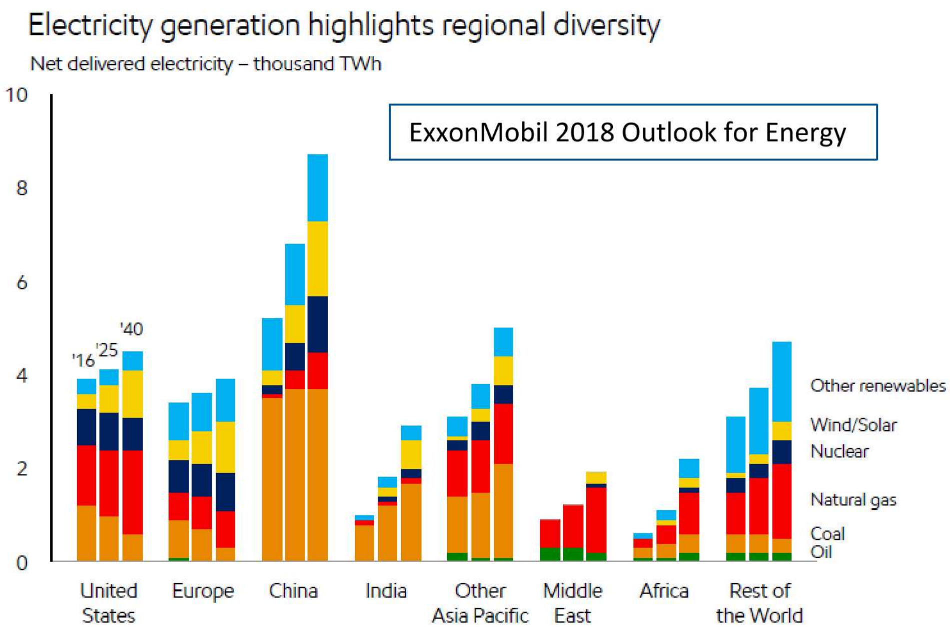
Scenario		Charge Condition	Marginal Power	Emission Factor
A	Economic Principle	night	Thermal	0.76
		daytime w/o surplus	LNG	0.54
		daytime with surplus	Solar	0.04
		night with storage	LNG	0.54
B	CO_2 Reduce First	night	Coal	0.99
		daytime with surplus	Solar	0.04
		daytime w/o surplus	Coal	0.99
		night with storage	Coal	0.99
C	Add Nuclear	all cases	Nuclear	0.02

kg-CO2/kWh

- Long-term marginal sources are due to technologies with an impact large enough to create structural changes in the power supply system
- In the absence of nuclear power or large surpluses in solar, natural gas power generation will be the marginal source (in Japan)

Marginal sources are not expected to change significantly through 2050



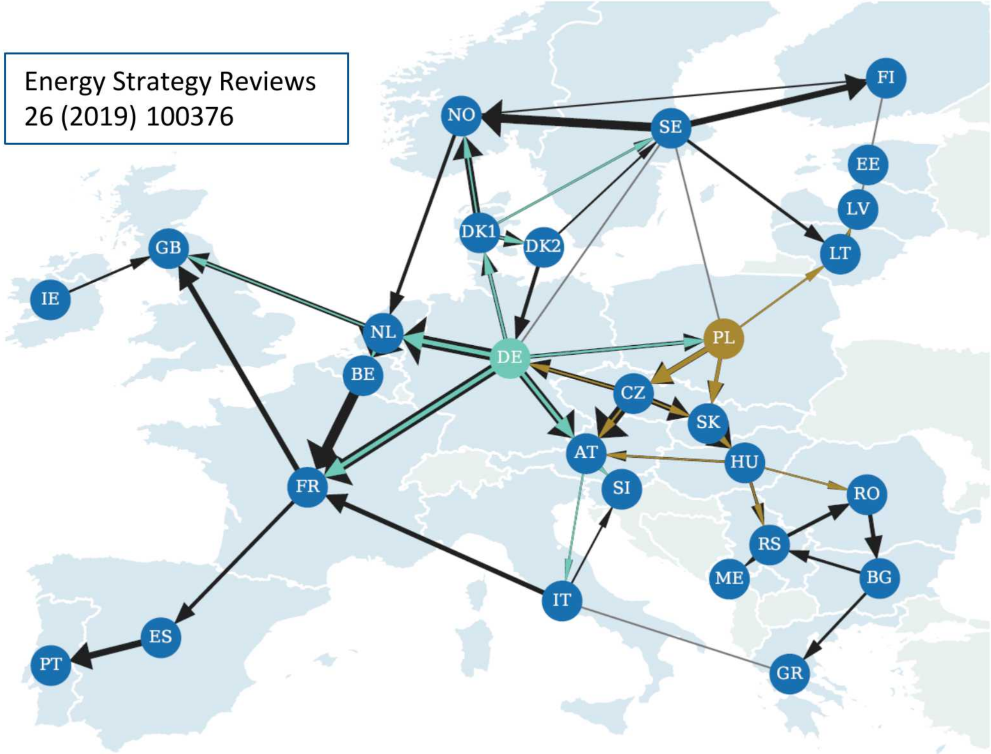


- The overall growth in electricity demand will exceed the growth in renewables

- In regions like China, India, and Asia-Pacific, coal will likely be a significant component of future marginal electricity generation

Marginal carbon sources may cross borders

Energy Strategy Reviews 26 (2019) 100376



U. Mich. Report SWT-2017-18

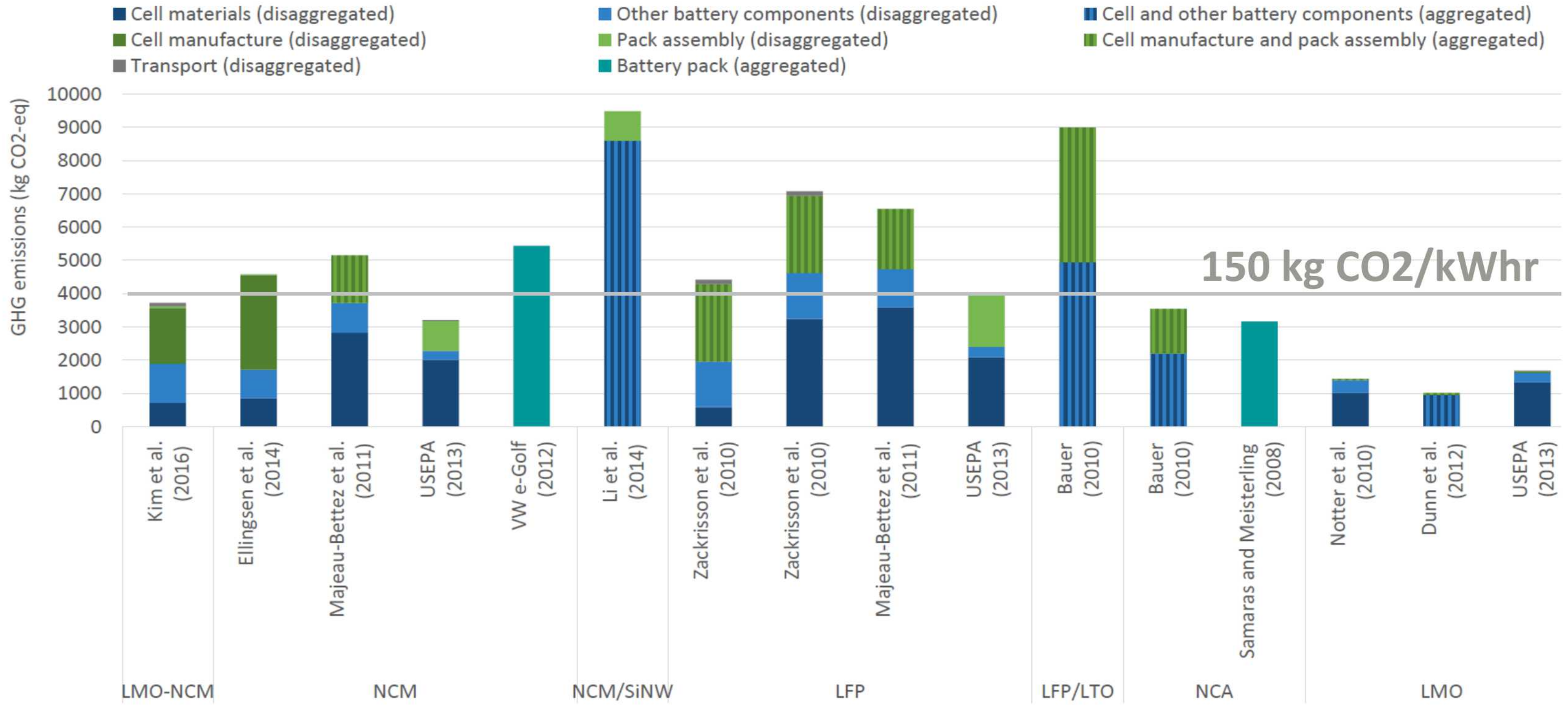
Group	Country	MPG-equivalent	L/100 km
1000 – 5100 MPG_{ghg}	Albania	5100.0	0.05
	Paraguay	5084.1	0.05
	Nepal	5071.3	0.05
	Ethiopia	4463.3	0.05
	Congo (Dem. Rep.)	4003.6	0.06
	Switzerland	1905.3	0.1
	Norway	1820.6	0.1
	Sweden	1421.6	0.2

- Increased energy demand in very clean power systems can have significant marginal CO_2 emissions
- Real-time, cross-border carbon accounting is complex but not unachievable

Carbon intensity associated with battery production

Cradle-to-gate GHG emissions of a 26.6 kWh Li-ion battery

Source: Ellingsen et al. (2017)



- In the analysis that follows we use 150 kg CO_2/kWh [Ellingsen 2018]

  [*cf.* Ricardo April 2019 ~ 170 kg CO_2/kWh]

Comparative CO_2 emissions from ICEVs & BEVs

We compare like-functionality mid-size vehicles with a similar range

Current Day BEV:

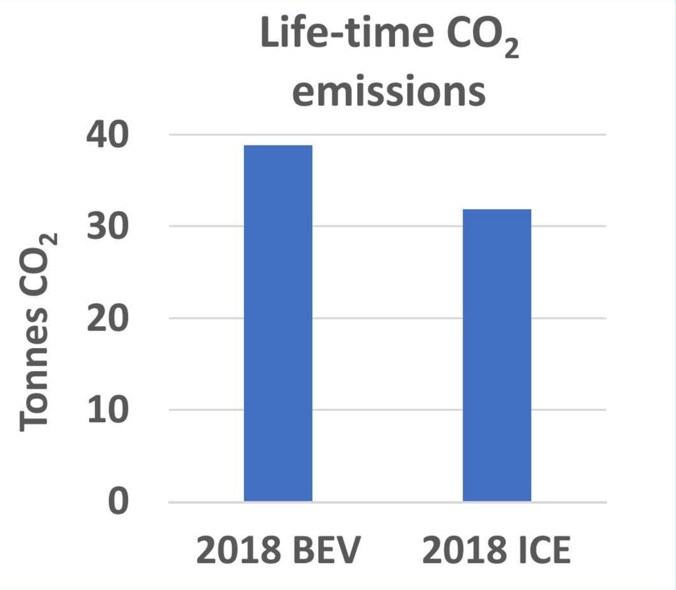
$$CO2 = 150\ \frac{kg{-}CO2}{kWhr} * 75\ kWhr + 0.708\ \frac{kg\ CO_2}{kWhr} * 26\ \frac{kWhr}{100\ mi} * 150{,}000\ \text{mi}$$

$$CO2 = 11.3 + 27.6 = \sim 39 \text{ tonnes } CO_2$$

Current Day ICEV (HEV):

$$CO2 = 11.055\ \frac{kg{-}CO2}{gal} * \frac{1}{52}\frac{gal}{mi} * 150{,}000\ \text{mi}$$

$$CO2 = \sim 32 \text{ tonnes } CO_2$$



Assumptions:
- 2018 US average marginal emissions rate = 0.708 kg CO_2/kWhr per EPA AVERT model
- Emissions associated with battery manufacture = 150 kg-CO2e/kWhr; 75 kWhr battery; no replacement battery
- Energy requirements for BEV = 26 [KW-hr/100 mi] (Tesla Model 3 2018)
- Carbon intensity of gasoline = 11.055 kg-CO2/gal (GREET 2018)
- 2018 Camry Hybrid 5-cycle fuel economy = 52 mpg
- 150,000 mi lifetime ~25-yr NHTSA survivability weighted estimate

How might this change looking forward to 2050?

Future BEV:

$$CO2 = 100\ \frac{kg{-}CO2}{kWhr} * 75\ kWhr + 0.460\ \frac{kg\ CO_2}{kWhr} * 22\ \frac{kWhr}{100\ mi} * 150{,}000\ \text{mi}$$

$$CO2 = 7.5 + 15.2 = 22.7\ \text{tonnes}\ CO_2$$

Future ICEV (HEV):

$$CO2 = 11.055\ \frac{kg{-}CO2}{gal} * \frac{1\ gal}{75\ mi} * 150{,}000\ \text{mi}$$

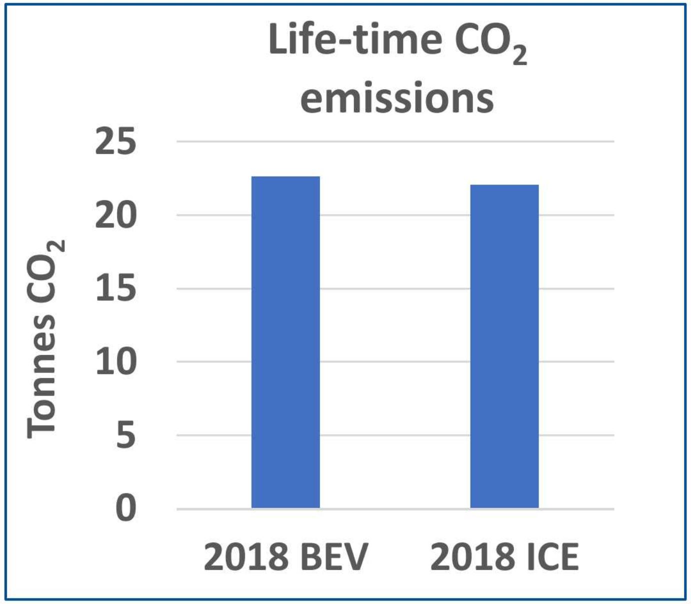
$$CO2 = 22.1\ \text{tonnes CO2}$$

Assumptions:

- Future US average marginal emissions rate = 0.460 kg CO_{2e}/kWhr
- Emissions associated with battery manufacture = 100 kg-$CO2_e$/kWhr; 75 kWhr battery; no replacement battery
- Energy requirements for BEV = 22 [KW-hr/100 mi]
- Carbon intensity of gasoline = 11.055 kg-CO2/gal (GREET 2018)
- 150,000 mi lifetime close to 25-yr NHTSA survivability weighted estimate

Conclusion

- In the short-term in the US, BEVs offer no CO_2 emission benefits over HEVs (or even 41 mpg conventional ICEs)
- Looking to the future, we can expect approximate parity between the two technologies as the electric grid improves



A comparative analysis needs to consider fleet-wide impacts

Autoevolution.com

- The US vehicle fleet is made up of a wide variety of vehicles
- Consumer preferences can vary widely

- A wide variety of vehicles in the market responds to a wide variety of consumer needs

Hat tip: Carla Bailo, CAR, 2019

The US DOE Energy Information Agency publishes detailed projections out to 2050

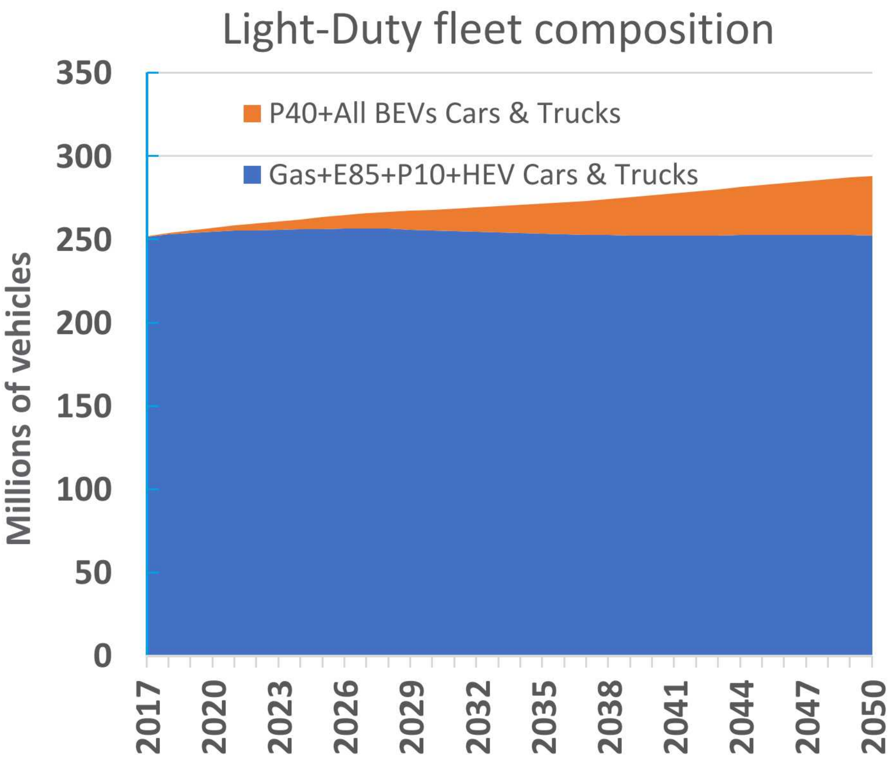
Projections include:

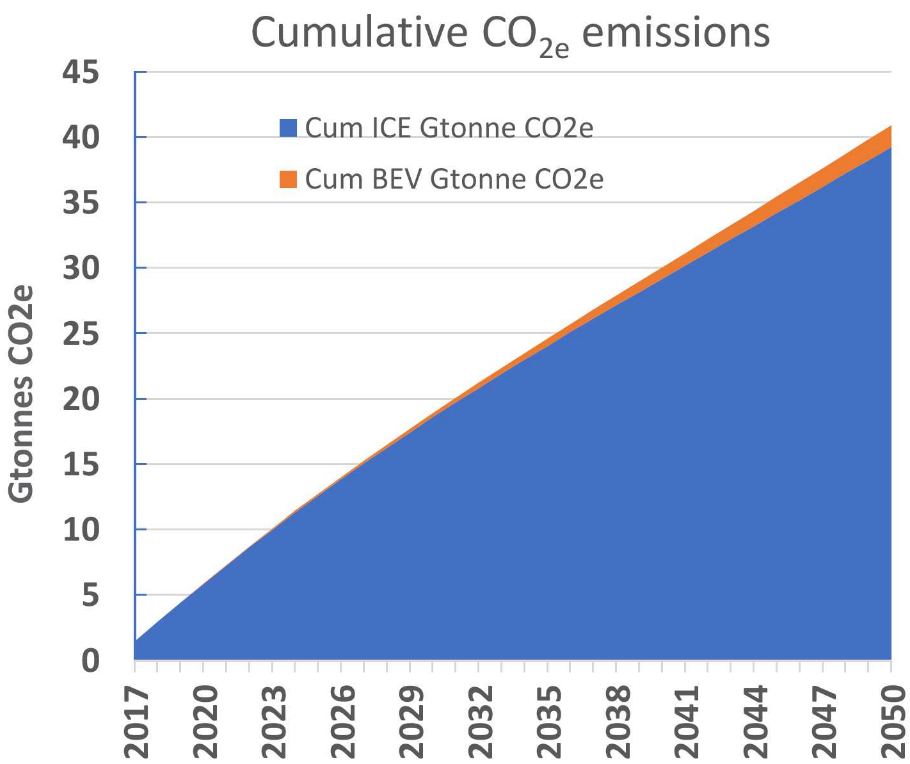
- Market share of various vehicles
- Transportation energy use by sector (light-duty electricity, gasoline, …)
- Allows fleet average energy use by technology type
  - ICEVs: Gasoline, Flex, HEVs, PHEV10s
  - BEVs: PHEV40s, BEV100, BEV200, BEV300

Carbon Intensity:

- Gasoline – GREET 2018
- Electricity – Marginal CO_2 from natural gas, in proportion to shares of combined-cycle and open-cycle gas turbines installed
  Generation component of GREET 2018 carbon intensity extrapolated to 65% CC efficiency in 2050 and GT efficiency to 42%

EIA projections of BEV market penetration in 2050 are modest

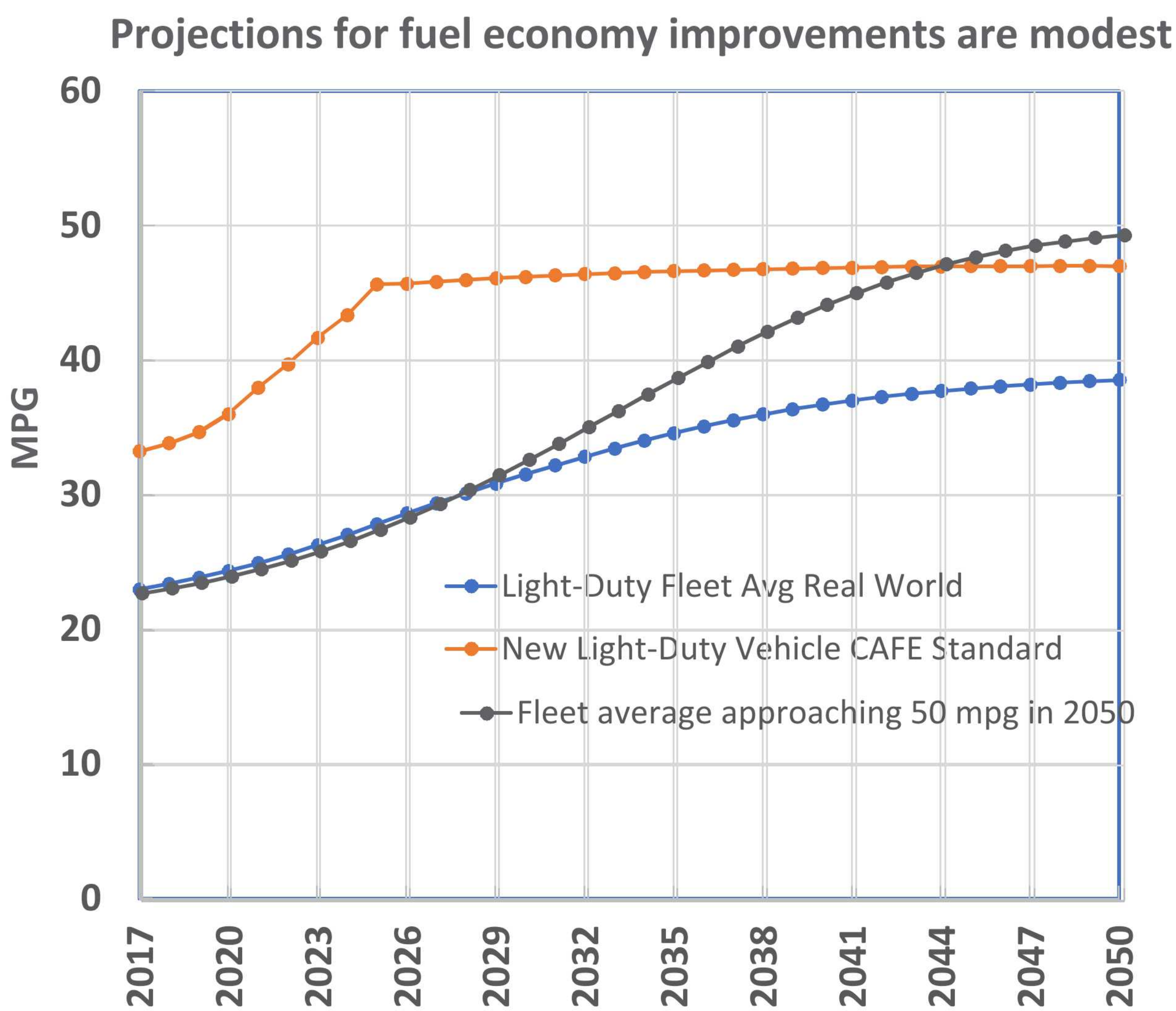




- In 2050, the US EIA estimates a US BEV fleet size of 36 million vehicles – ~12%
- This will account for 5% of the LD transportation energy use, and 8% of the annual CO_{2e} emissions (larger value due mainly to battery production)

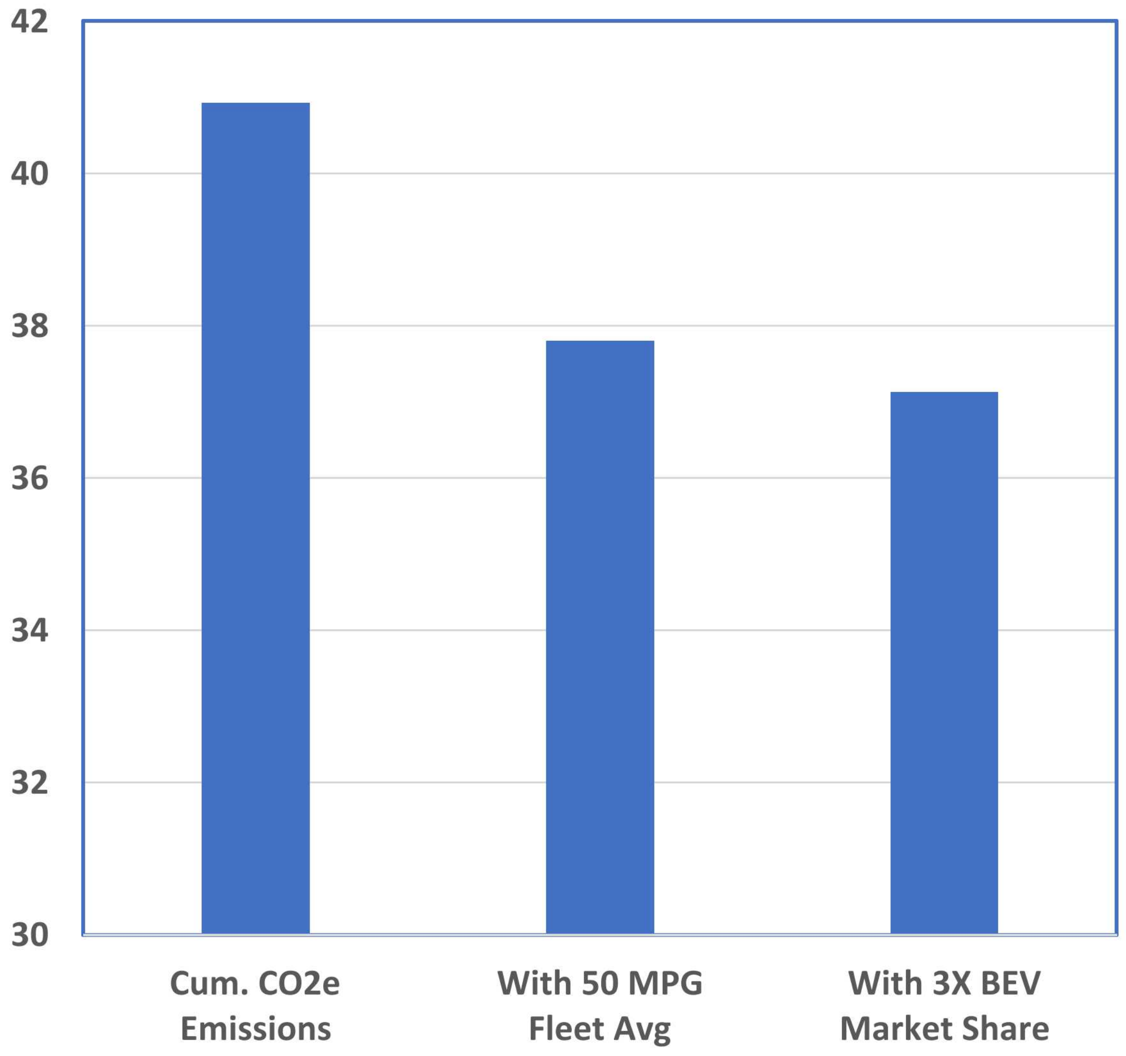
A closer look at EIA projections for fleet fuel efficiency

- The fleet average CAFE fuel economy rises to ~47 MPG in 2025
- Current standards require no additional LD efficiency increases beyond 2025
- Our ICE potential efficiency estimates indicate that approaching a fleet average of 50 MPG is readily achievable

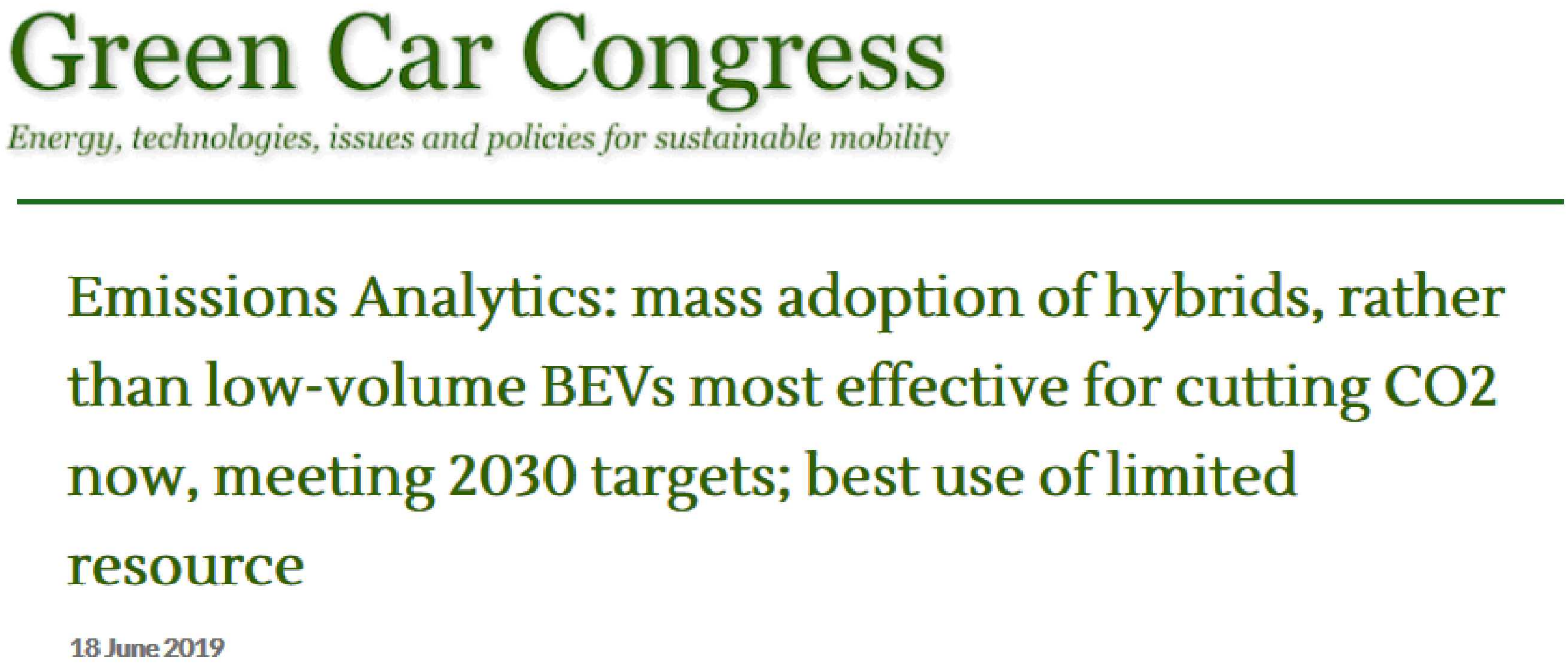


The relative impact of increased ICE efficiency and increased BEV market share is similar

- A balanced policy portfolio would try to achieve fleet CO_2 reductions through both paths



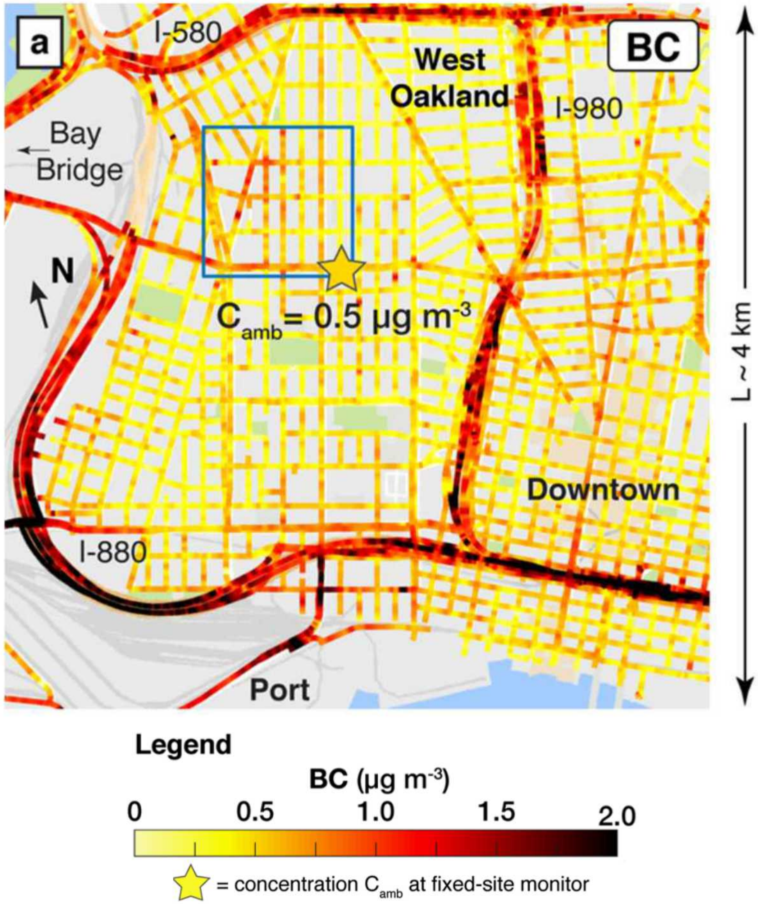
Others have reached similar conclusions



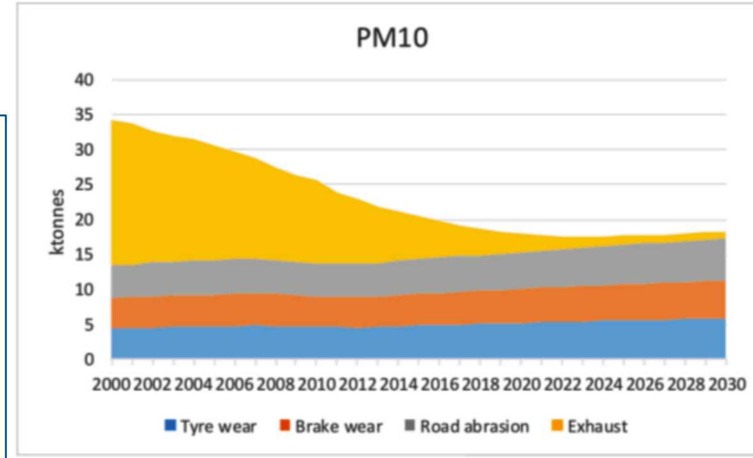
"Improving the air quality in cities is another popular reason for those championing BEVs. It is, however, a false assertion that they are needed to fulfil this purpose. Existing technology is more than capable…"

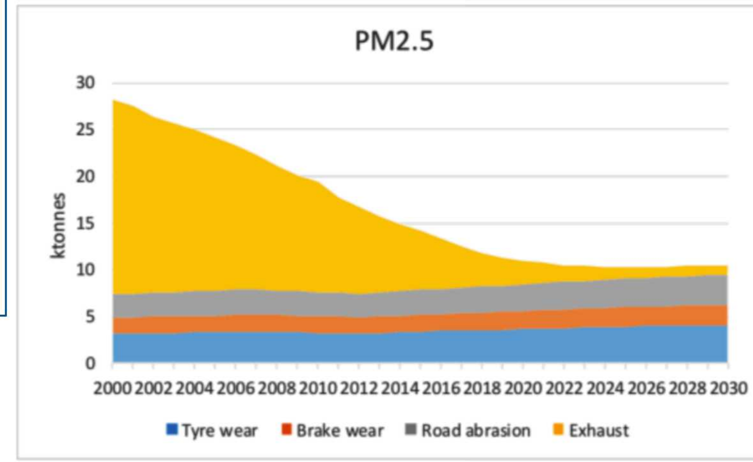
Current ICE PM emissions are reasonably low…
…and are less than tire, brake, and road wear PM

Source: Env. Sci. Tech. 51, 6999, 2017



https://www.greencarcongress.com/2019/07/20190714-nee.html



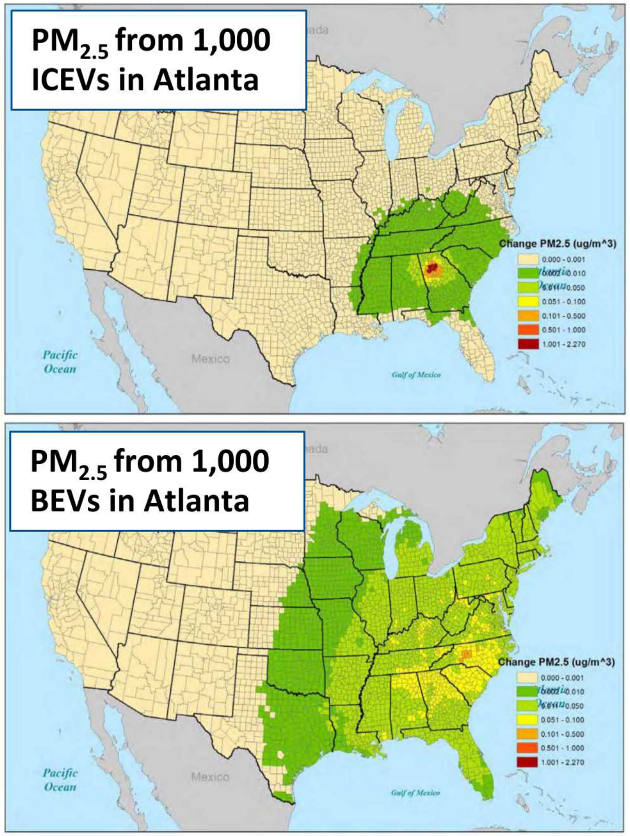


- Current EPA PM2.5 standard is 12 mg/m^3

- Continued PM reduction is desirable, as exhaust PM toxicity may be greater

Vehicle PM emissions are nonetheless expected to have significant health impacts

Source: Holland et al., Am. Econ. Rev 2016

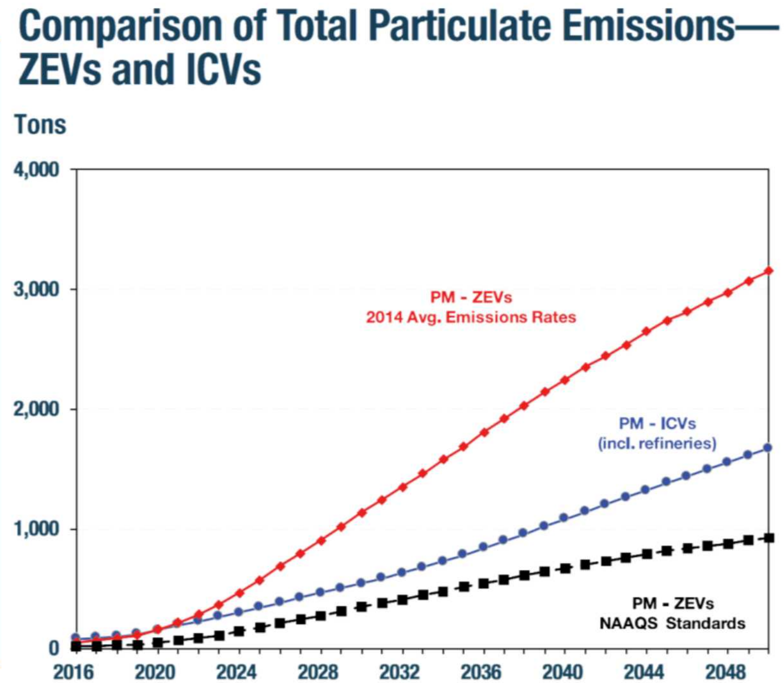


- ICEV damage per mile: 2.38¢
- BEV damage per mile: 2.73¢

Appropriate BEV purchase subsidy: **-$535**

* Holland et al. estimated marginal PM2.5 emissions

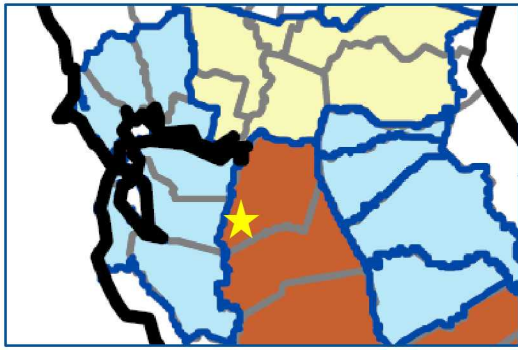
Source: www.ourenergypolicy.org/wp-content/uploads/2018/05/R-JA-0518.pdf

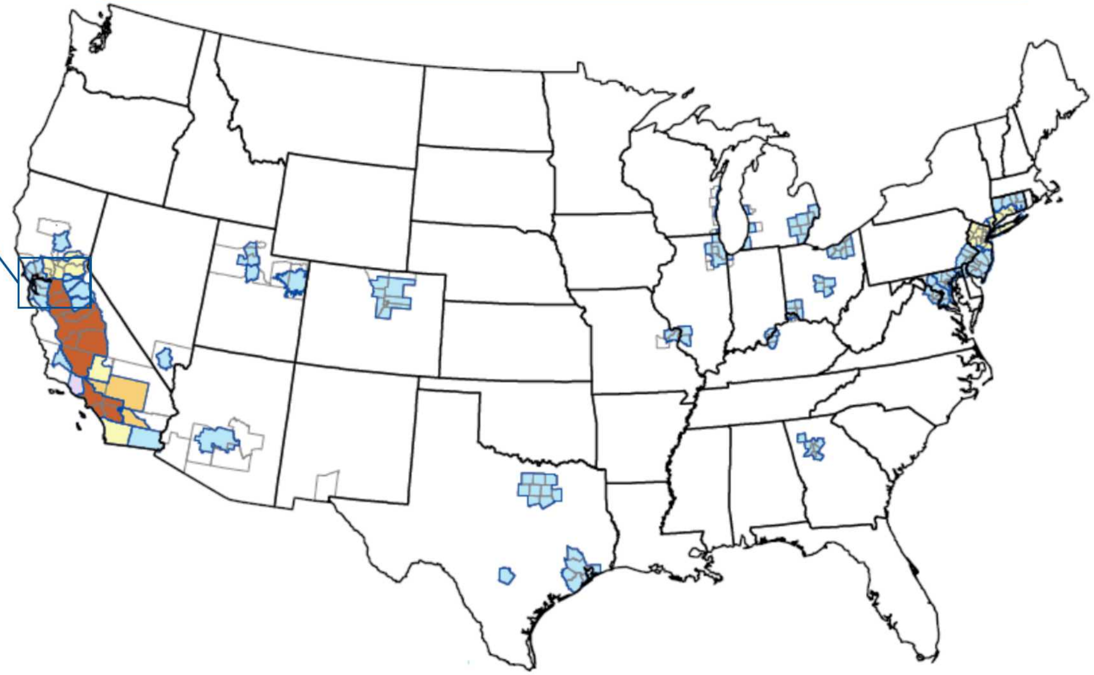


- Analyses using grid-averaged emissions also indicate that PM emissions from BEVs will exceed those from ICEVs
- BEV PM emissions could be significantly reduced if all plants were to meet current standards

What about NOx/HC/SO_2 emissions?

Ozone non-attainment areas — July 31, 2019





- NO_x reacts with volatile organic compounds (VOCs) and sunlight in the atmosphere to form O_3
- NO_x (and SO_2) also lead to secondary particulates
- SO_2 is also harmful

(1) $R\cdot + O_2 + M \longrightarrow RO_2\cdot + M$

(2) $RO_2\cdot + NO \longrightarrow NO_2 + RO\cdot$

(3) $HO_2\cdot + NO \longrightarrow NO_2 + OH\cdot$

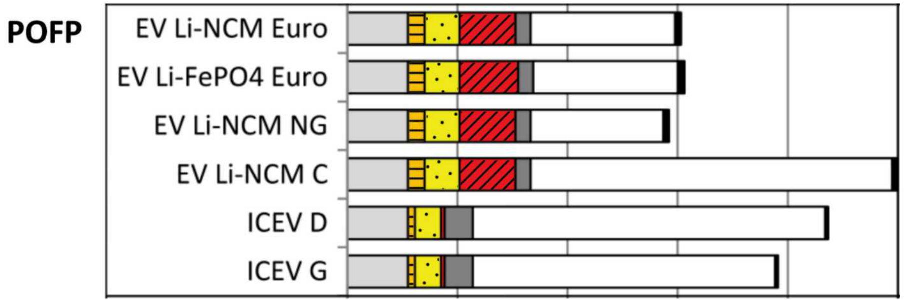
(4) $NO_2 + hv \longrightarrow O(^3P) + NO, \lambda < 400nm$

(5) $O(^3P) + O_2 + M \longrightarrow O_3 + M(heat)$

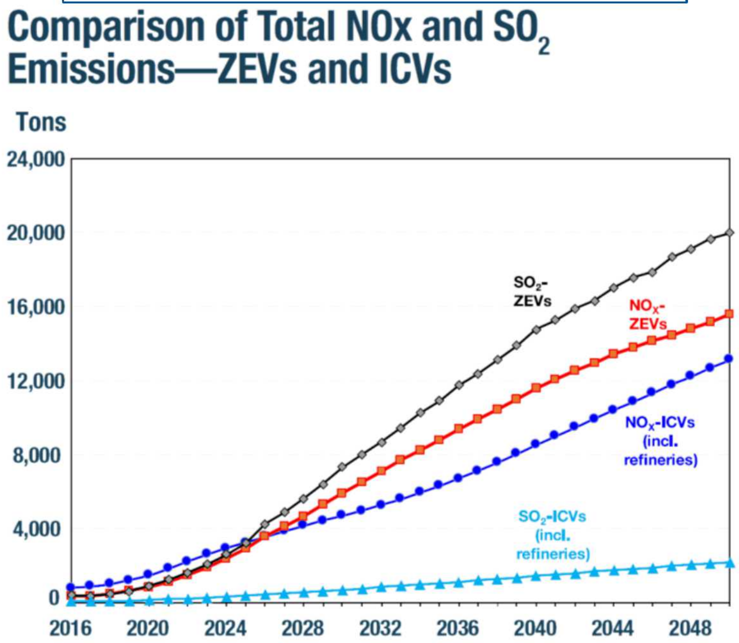
(6) $O_3 + NO \longrightarrow NO_2 + O_2$

A variety of sources indicates that NO_x emissions are comparable between BEVs and ICEVs

Source: J. Ind. Eco. 17: 53-64 (2012)



Source: www.ourenergypolicy.org/wp-content/uploads/2018/05/R-JA-0518.pdf



- Displacement of emissions can result in a disproportional impact on communities near generating plants

Key messages

- The future will hold a wide variety of transportation solutions – some will make more sense than others in different situations
- It's not all about CO_2. Pollutants, cost, consumer preferences matter
- An accurate assessment of CO_2 and local pollutant impact benefits from a fleet-wide approach
- Premature policy implementation based on overly simple analysis can produce negative unforeseen consequences
- A clean, sustainable energy future requires government and media to promote STEM education in a broad range of disciplines