

Bounding the Climate Viability of Natural Gas as a Bridge Fuel

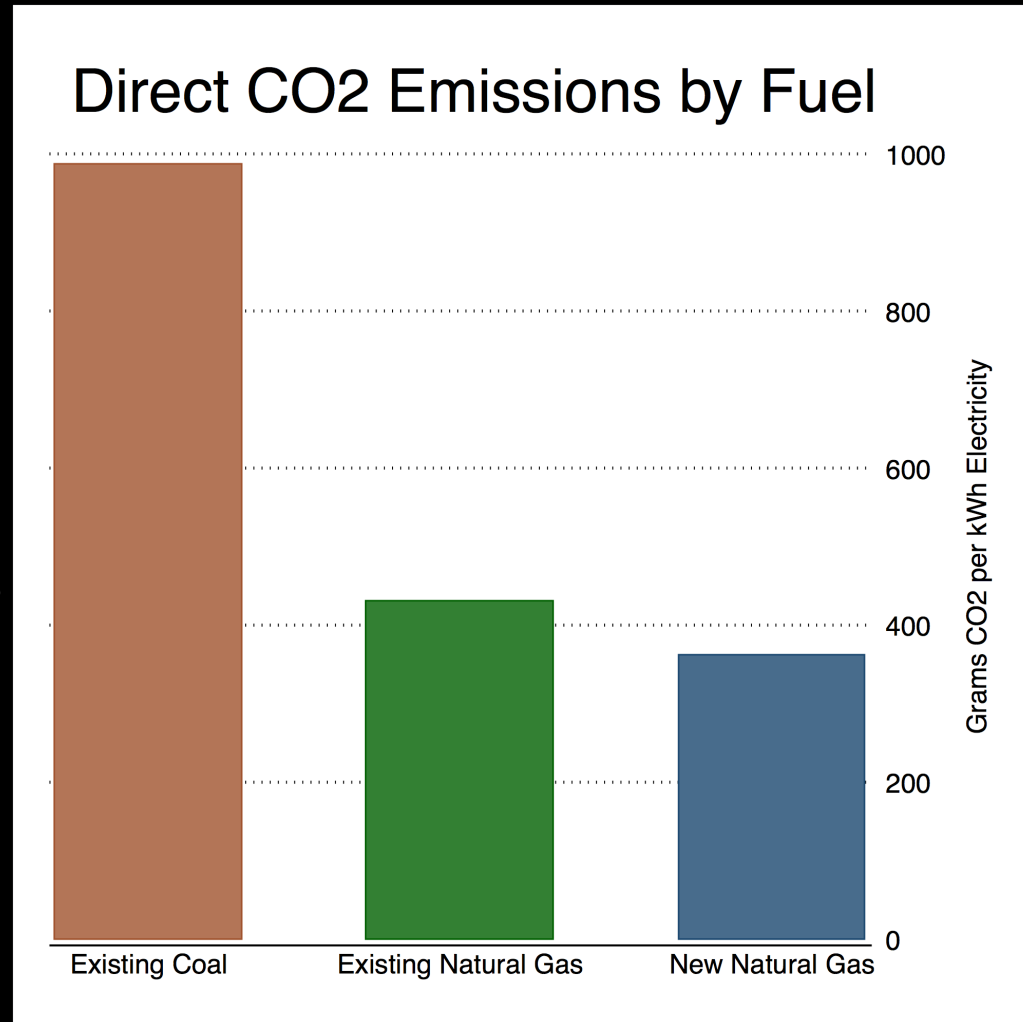
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Special thanks to Ken Caldeira, Xiaochun Zhang, and Nathan Myhrvold

Direct Emissions - Electricity

- Current U.S. coal efficiency is 33%
- Current U.S. gas efficiency is 42%
- New U.S. coal efficiency $\geq 43\%$
- New U.S. gas efficiency $\geq 50\%$ (HHV)
- Results are sensitive to scenarios; gas looks better when replacing existing coal (and generation efficiency impacts CH₄ leakage effects)

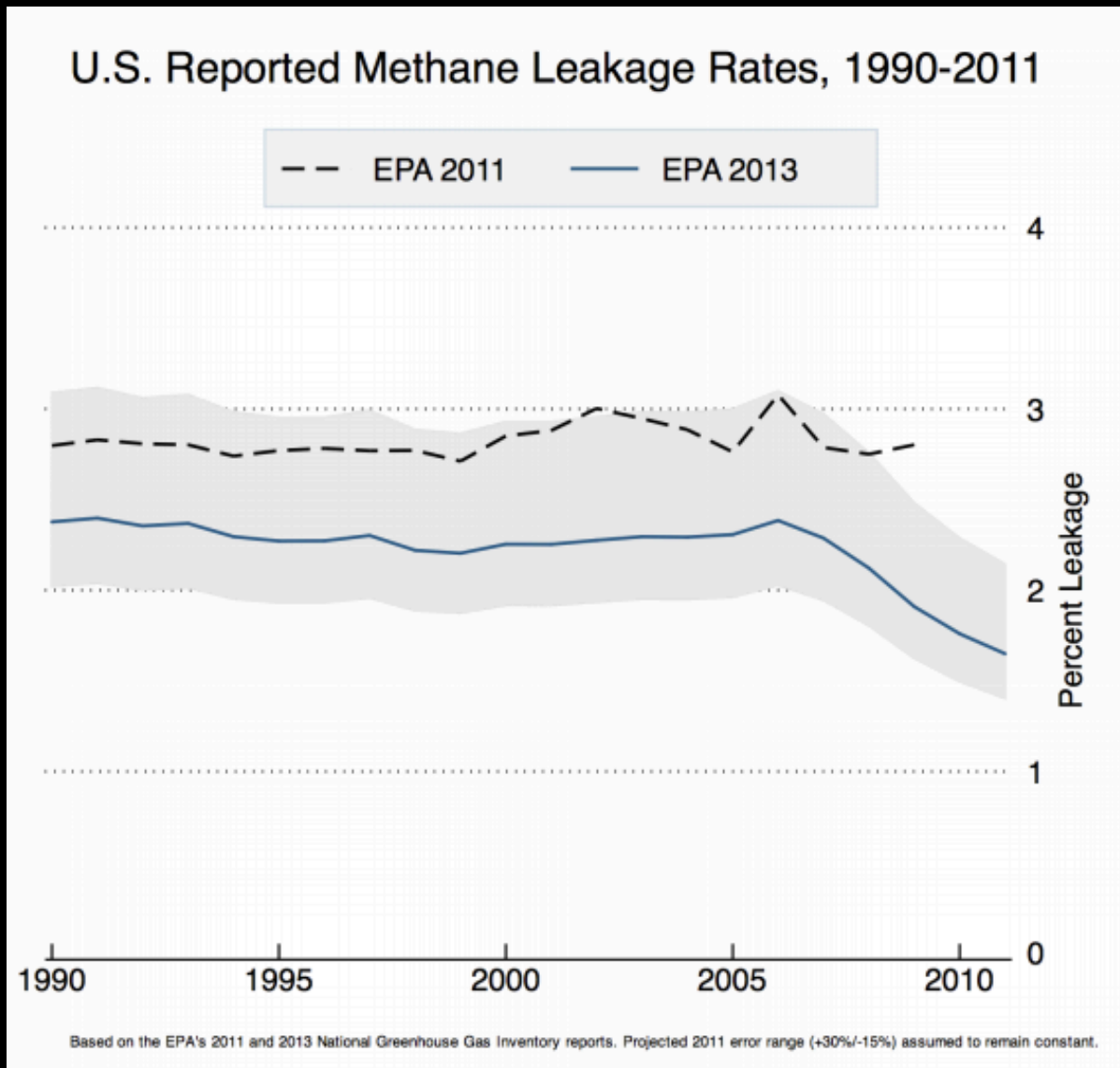


But... Methane

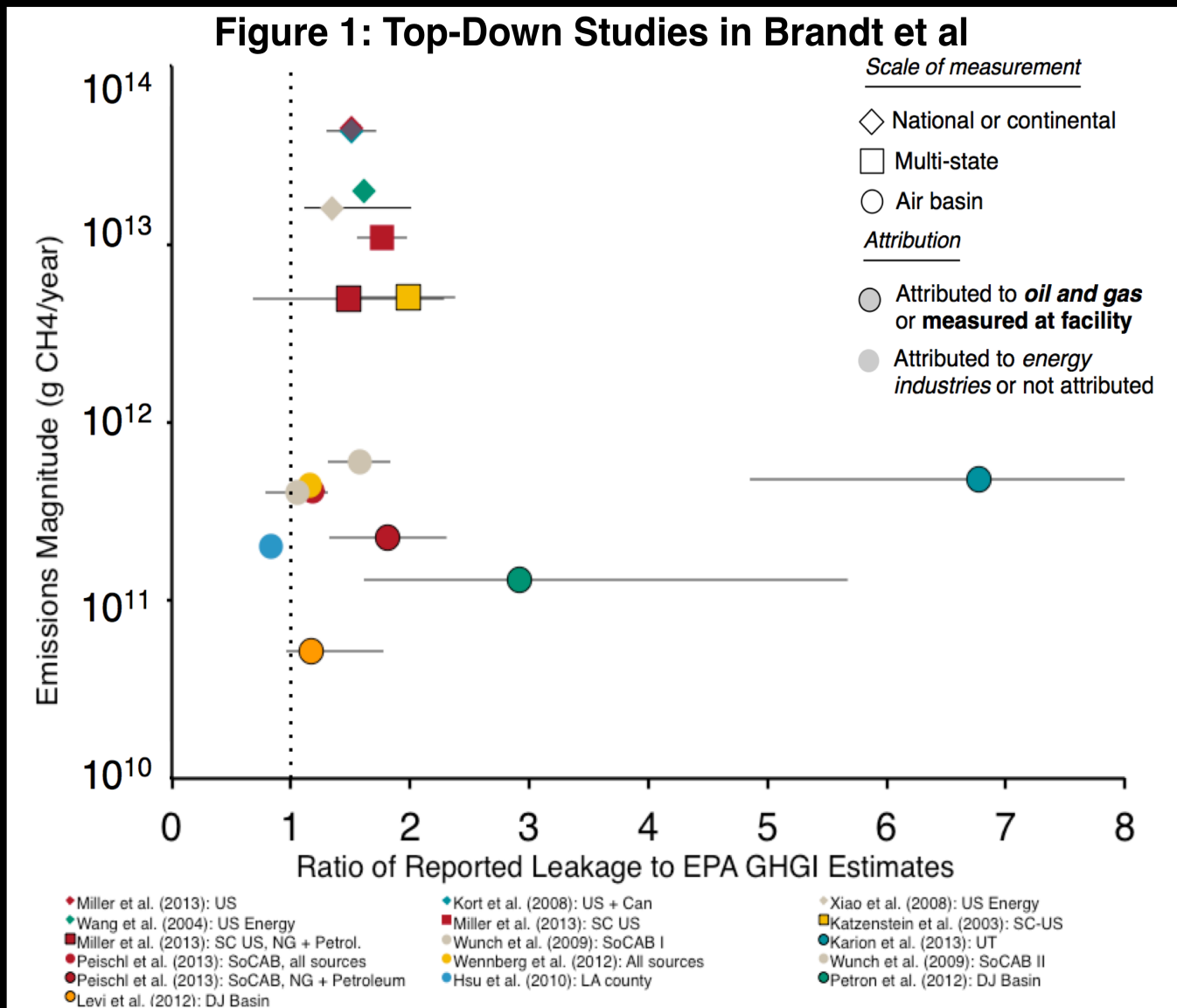
- CH₄ is a powerful greenhouse gas, with a global warming potential 21 to 34 times larger than CO₂ (21 is only direct effects; 34 includes ozone, stratospheric H₂O and other indirect effects).
- System-wide leakage rates are highly uncertain, with estimates ranging from 1% to 6% or more

And Gas Infrastructure is Sticky

EPA GHGI Leakage Estimates are Low

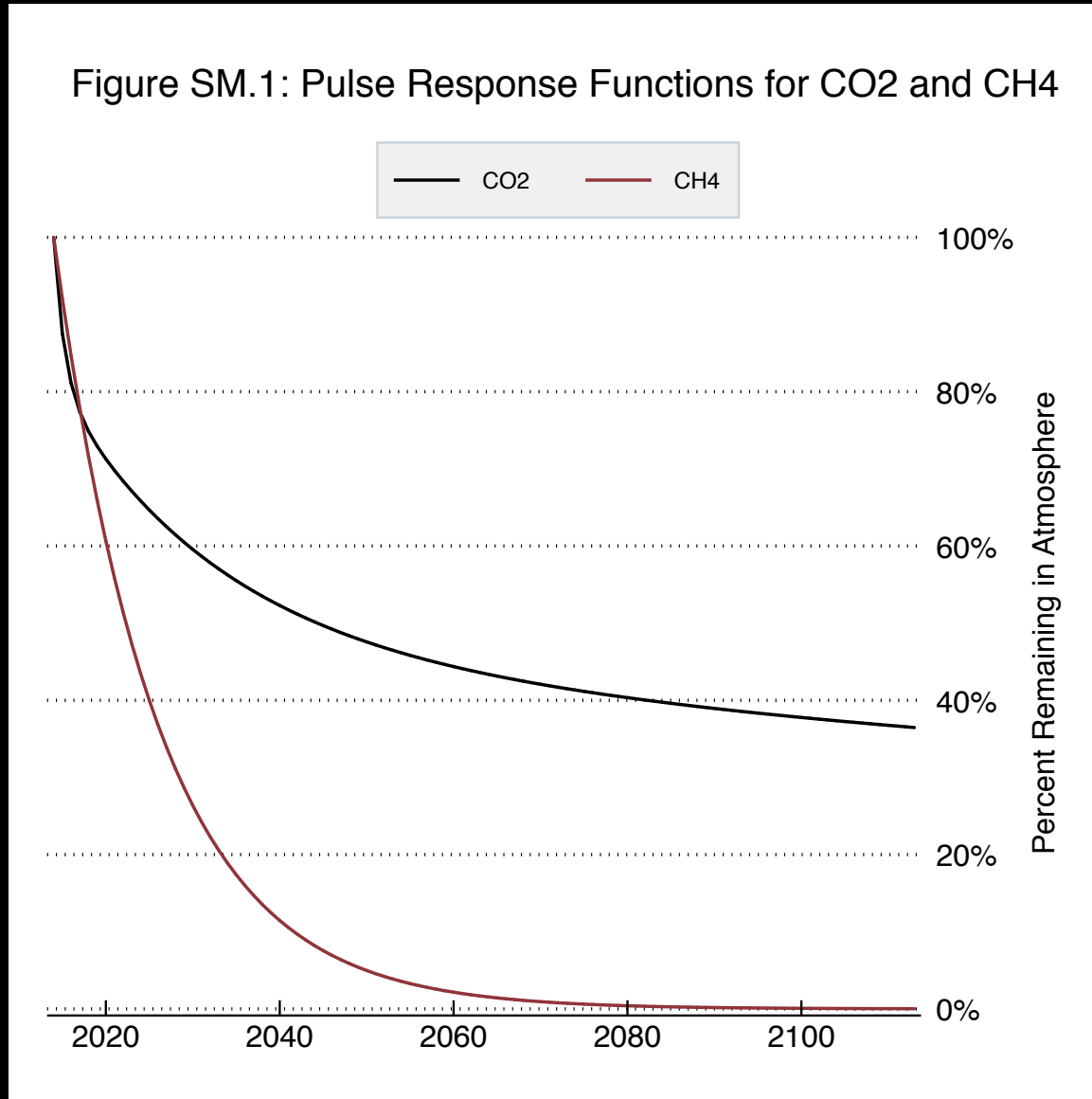


Others in the Literature are Higher



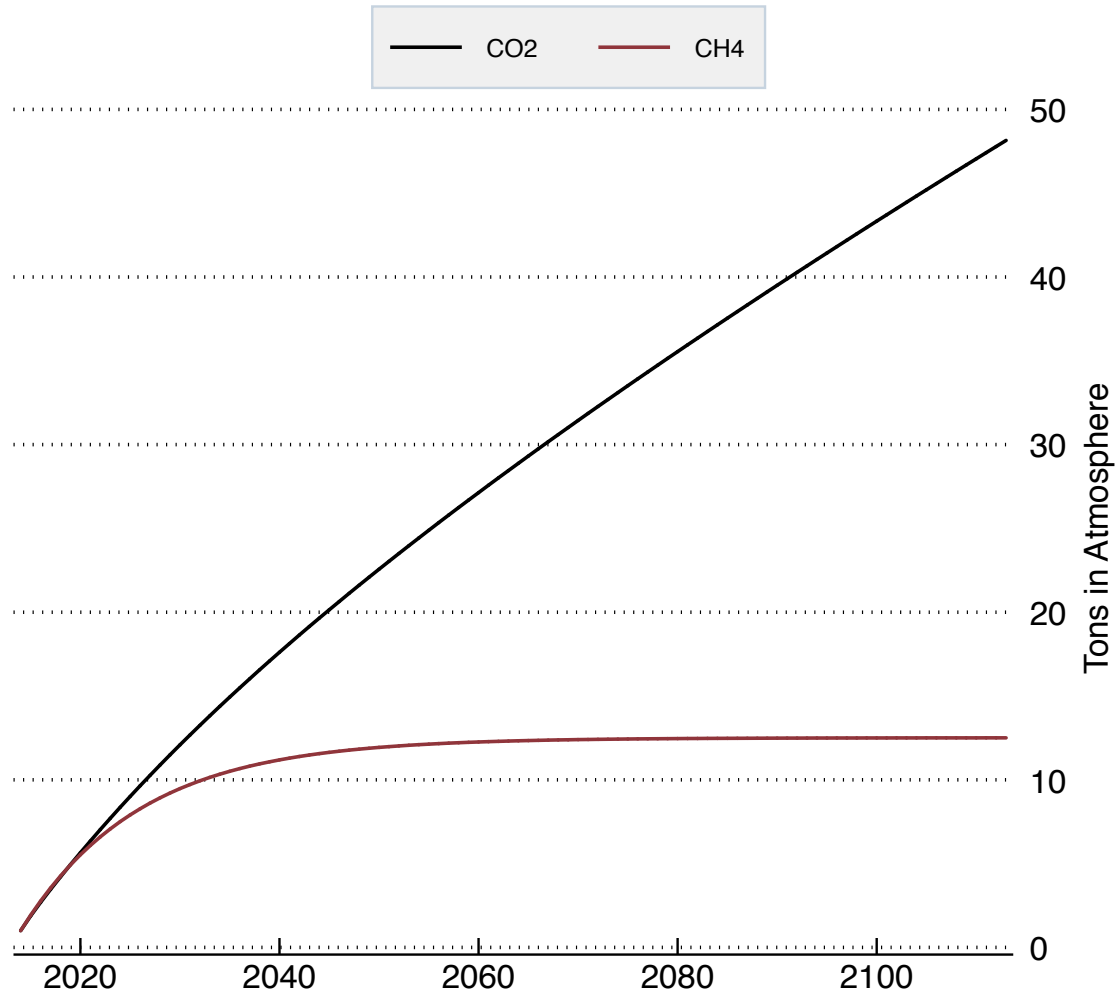
Atmospheric Dynamics of CO₂ and CH₄: Moving Beyond Global Warming Potential

Decay functions for discrete pulses

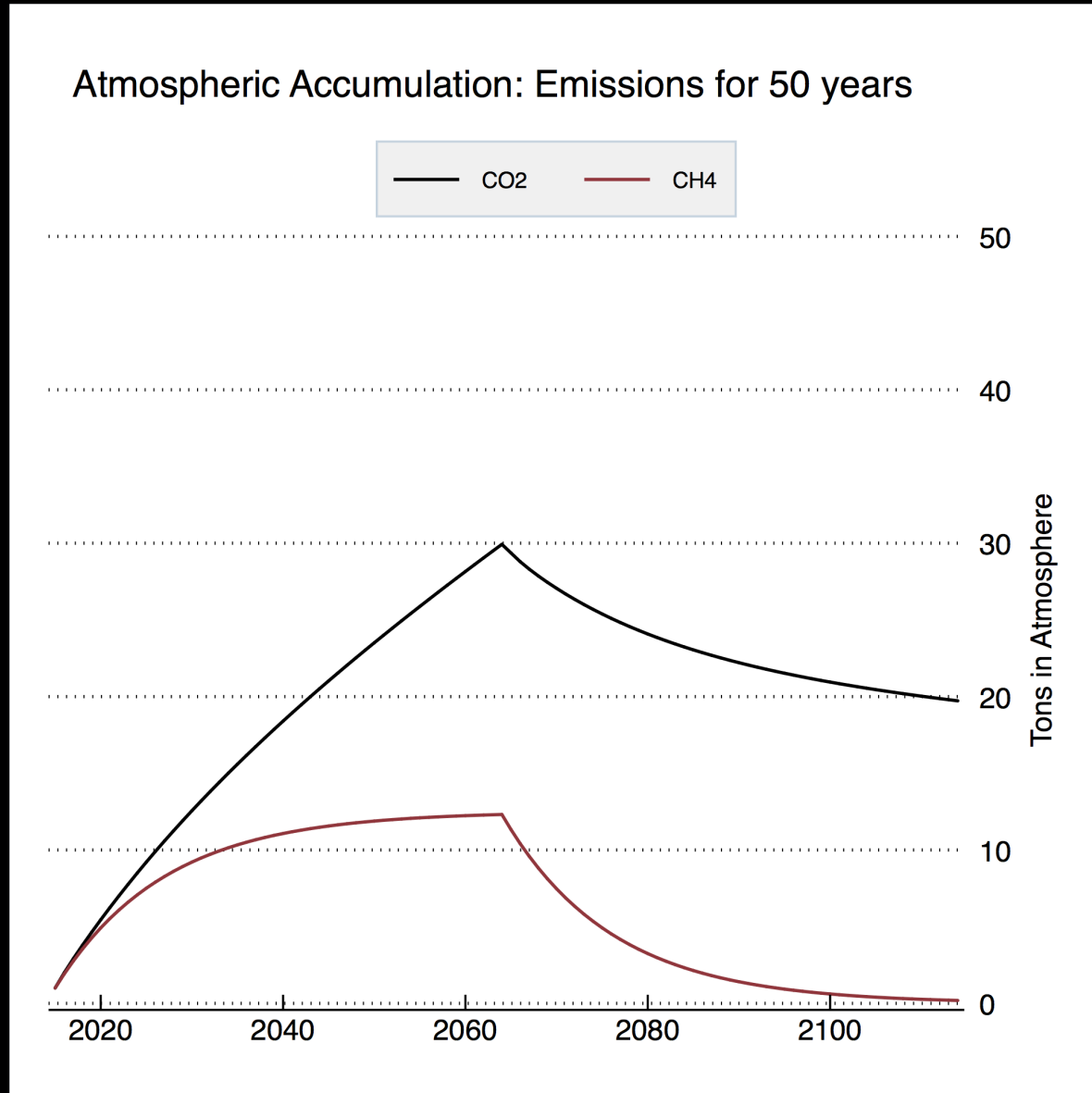


Atmospheric Accumulation under Constant Emissions

Figure SM.2: Atmospheric Accumulation of CO₂ and CH₄



What if Emissions Cease?



Translating Emissions to Radiative Forcing

Trace gas	Simplified expression Radiative forcing, ΔF (Wm^{-2})	Constants
CO ₂	$\Delta F = \alpha \ln(C/C_0)$ $\Delta F = \alpha \ln(C/C_0) + \beta(\sqrt{C} - \sqrt{C_0})$ $\Delta F = \alpha(g(C) - g(C_0))$ where $g(C) = \ln(1 + 1.2C + 0.005C^2 + 1.4 \times 10^{-6}C^3)$	$\alpha = 5.35$ $\alpha = 4.841, \beta = 0.0906$ $\alpha = 3.35$
CH ₄	$\Delta F = \alpha(\sqrt{M} - \sqrt{M_0}) - (f(M, N_0) - f(M_0, N_0))$	$\alpha = 0.036$
N ₂ O	$\Delta F = \alpha(\sqrt{N} - \sqrt{N_0}) - (f(M_0, N) - f(M_0, N_0))$	$\alpha = 0.12$
CFC-11 ^a	$\Delta F = \alpha(X - X_0)$	$\alpha = 0.25$
CFC-12	$\Delta F = \alpha(X - X_0)$	$\alpha = 0.32$

$$f(M, N) = 0.47 \ln[1 + 2.01 \times 10^{-5} (MN)^{0.75} + 5.31 \times 10^{-15} M(MN)^{1.52}]$$

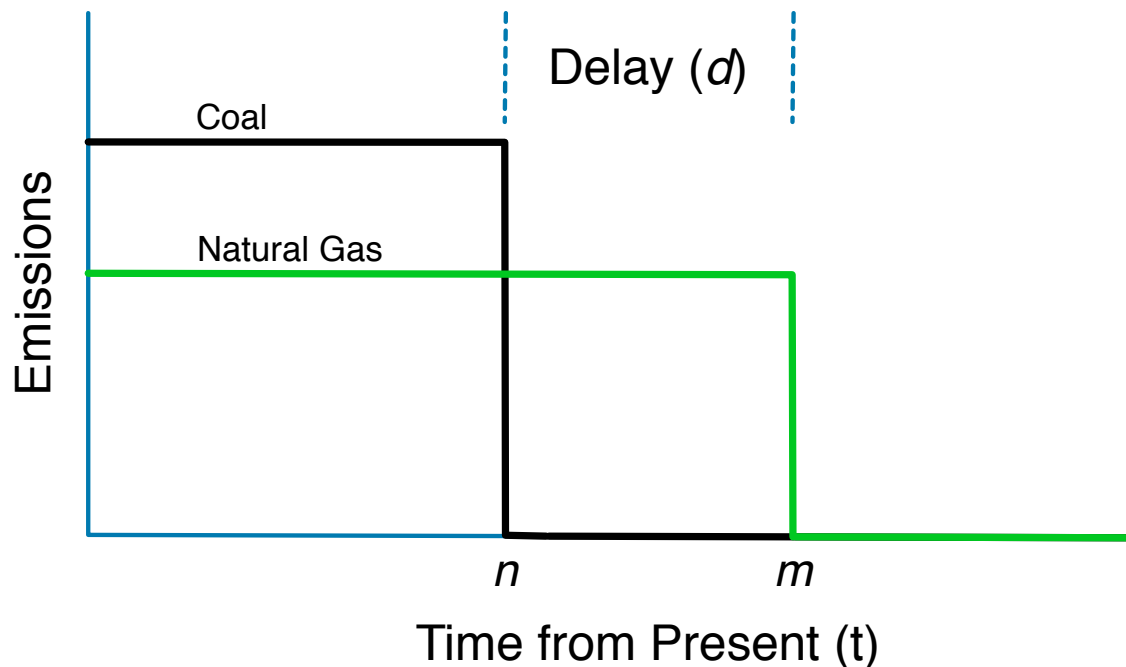
C is CO₂ in ppm

M is CH₄ in ppb

N is N₂O in ppb

X is CFC in ppb

We examine the impact of leakage rates, generation efficiencies, and delays in near-zero carbon technology adoption on the viability of immediately replacing coal with natural gas generation.



4 Efficiency Scenarios

- 1) New (50% efficient) Gas vs. Current (33% efficient) Coal
- 2) New (50% efficient) Gas vs. New (43% efficient) Coal
- 3) Current (42% efficient) Gas vs. Current (33% efficient) Coal
- 4) Current (42% efficient) Gas vs. New (43% efficient) Coal

10,000 Different Model Runs

1 to 100 years of Coal generation
1 to 100 years of Gas generation

50 Potential Leakage Rates

1 percent to 6 percent leakage,
in increments of 0.1 percent.

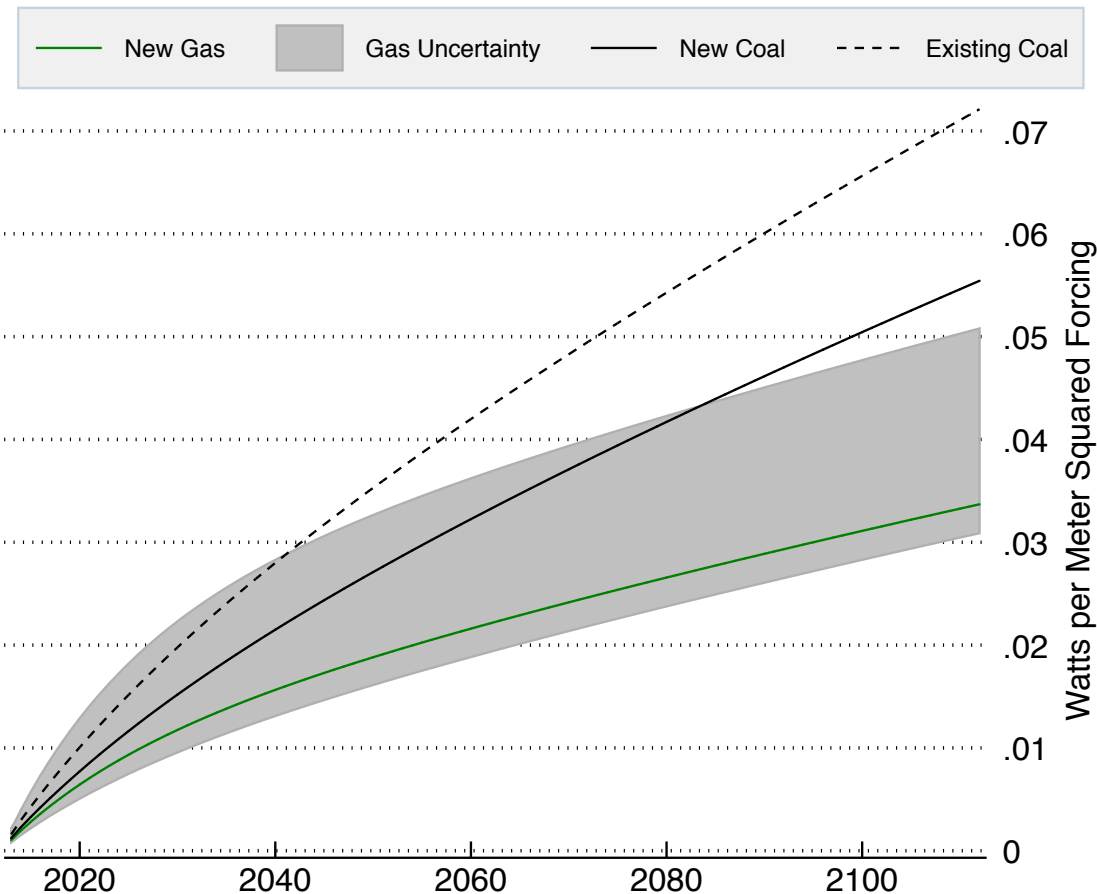
3 Forcing Time Horizons

20 years
100 years
500 years

100-year Constant Generation

Figure 2: Coal vs Gas Forcing for 100 years

Assuming Continuous Generation of 100 GW



Leakage Rates for Forcing Parity

Table 1

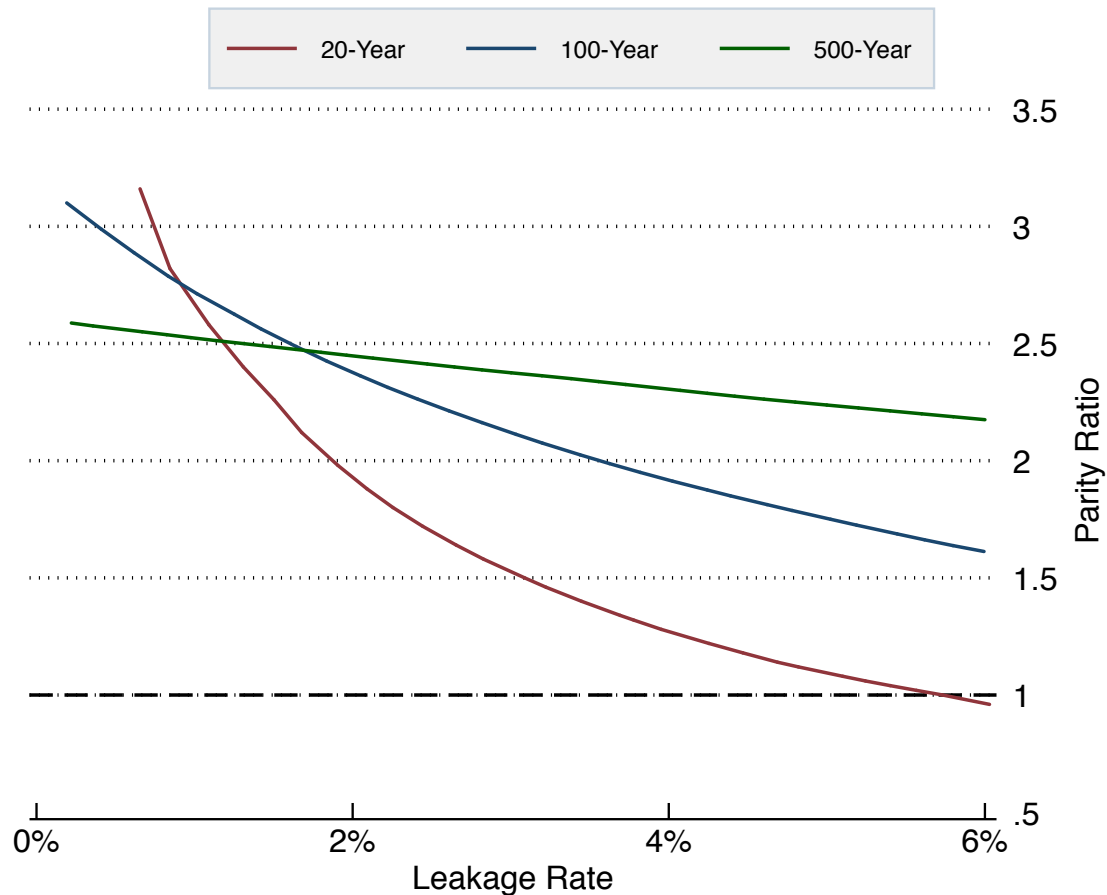
Leakage rates for forcing parity, 100 years generation.

Scenario	20-year (%)	100-year (%)	500-year (%)
New gas replacing current coal	5.1	9.9	36
New gas instead of new coal	3.2	6.4	24
Current gas replacing current coal	4.5	8.8	33
Current gas instead of new coal	2.7	5.2	20

What if we Delay Renewables?

Figure 4: Allowable Delays in Near-Zero Technology

Years of Gas-Equivalent per Year of Coal Avoided, New Gas/Existing Coal



More complex case
of $m > n$

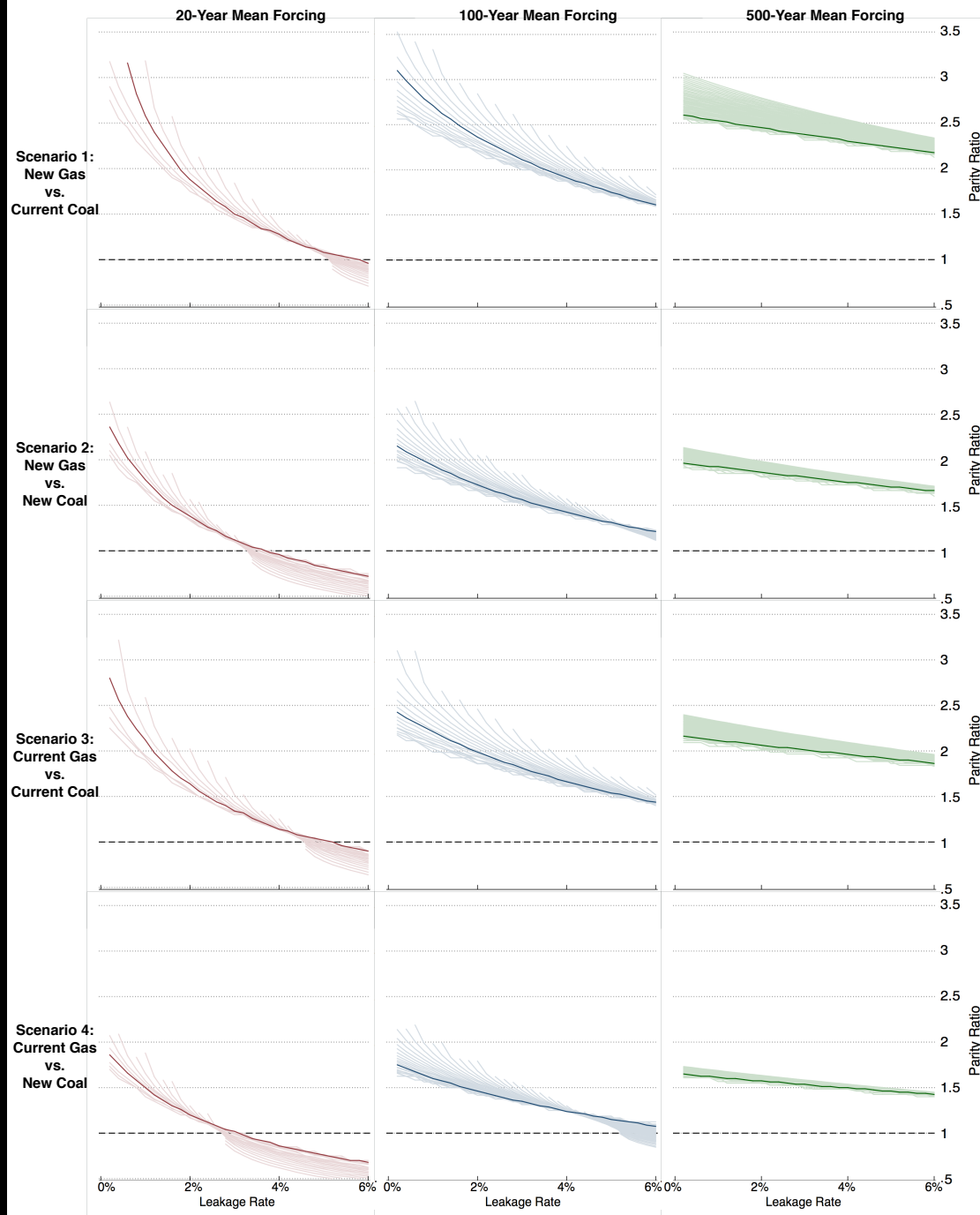
Parity Ratios for 2% Leakage

Table 2

Allowable years of gas per years of coal displaced at 2% leakage.

Scenario	20-year	100-year	500-year
New gas replacing current coal	1.8	2.4	2.5
New gas instead of new coal	1.4	1.7	1.9
Current gas replacing current coal	1.6	2.0	2.1
Current gas instead of new coal	1.2	1.5	1.6

Figure SM.4: Parity Ratios by Leakage Rate, Scenario, and Years of Coal Displaced



Parity ratio generally insensitive to time displaced: an important finding that lets us create a more generalized solution.

Takeaways

Gas can be a viable bridge even if it modestly delays near-zero carbon technologies IF leakage is low.

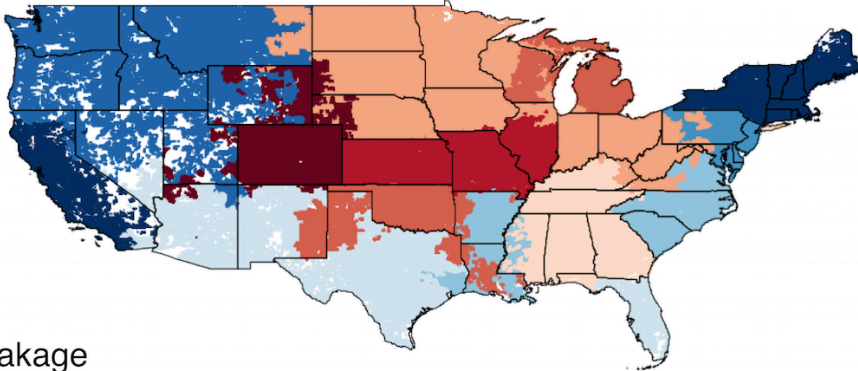
Not if large-scale replacement of coal by NZCT is expected to occur in the next ~12 years, however.

A natural gas bridge makes it much easier to avoid 3C+ warming but harder to hit ambitious 2C or below targets.

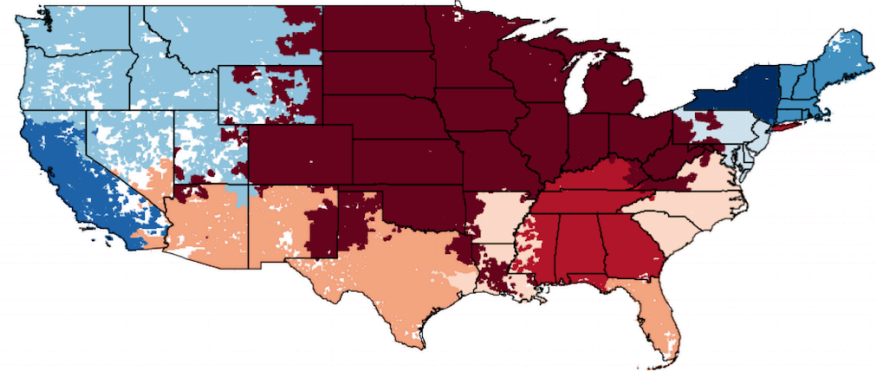
Climate Impacts of Vehicles by NERC Subregion

Electric vs. Hybrid Gasoline

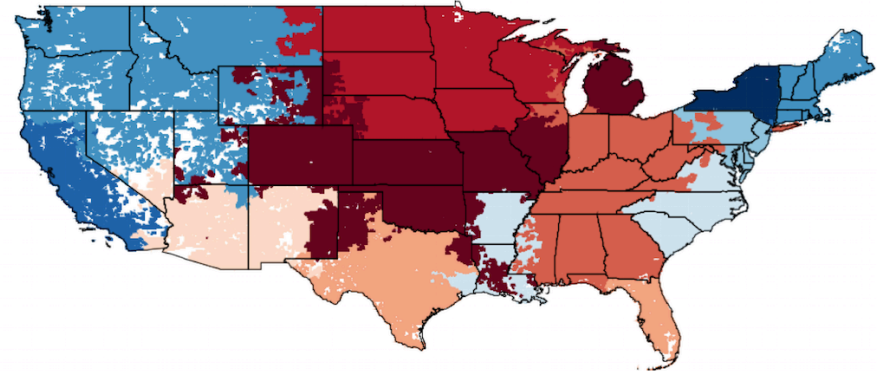
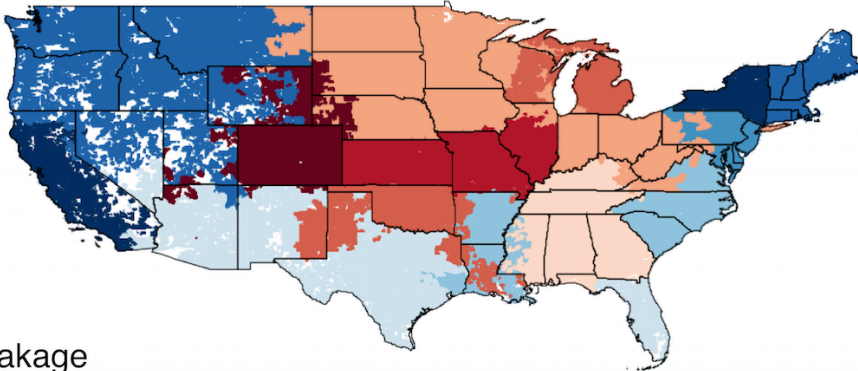
1% Leakage



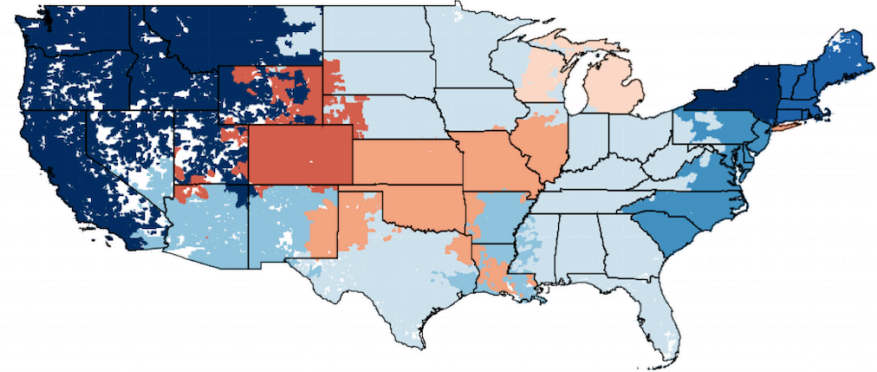
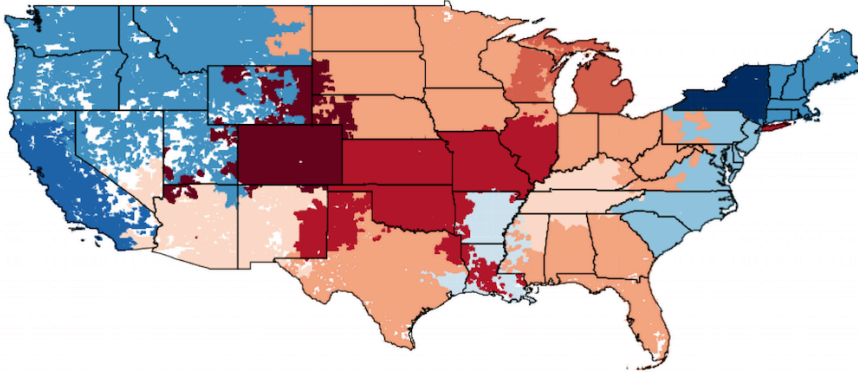
Electric vs. Hybrid Natural Gas



2% Leakage



6% Leakage

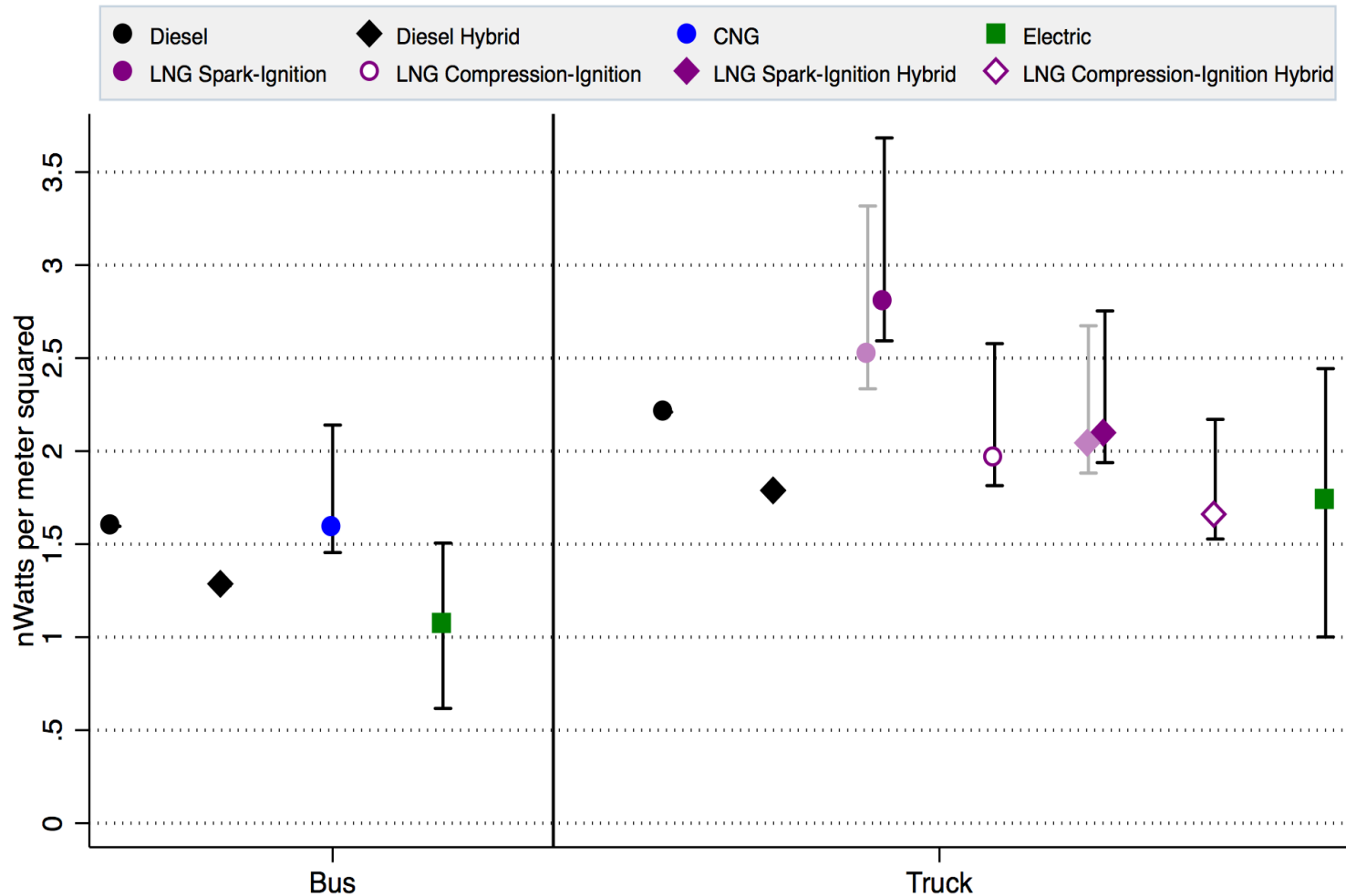


-40% or less -40% to -30% -30% to -20% -20% to -10% -10% to 0% 0% to +10% +10% to +20% +20% to +30% +30% to +40% +40% or more

Heavy Vehicles

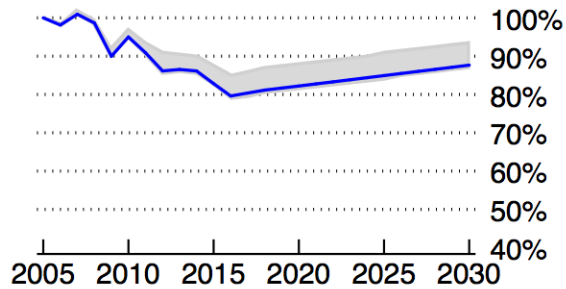
Diesel, Gas, and Electric Bus and Truck Mean Forcings

Over a 100-year time horizon for a vehicle driven 30 years

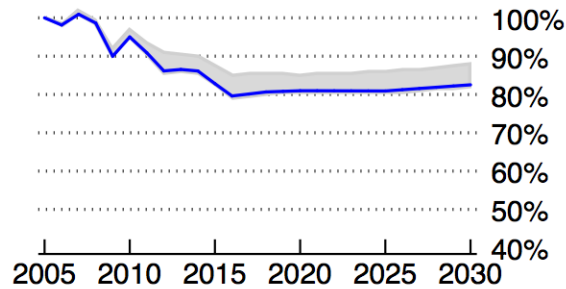


EPA IPM Clean Power Plan Scenarios

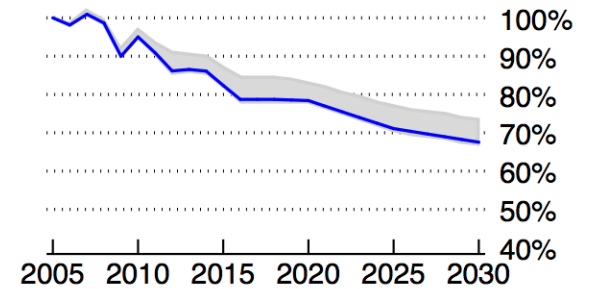
Fixed



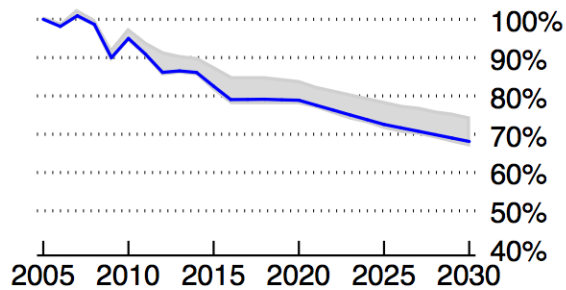
Base



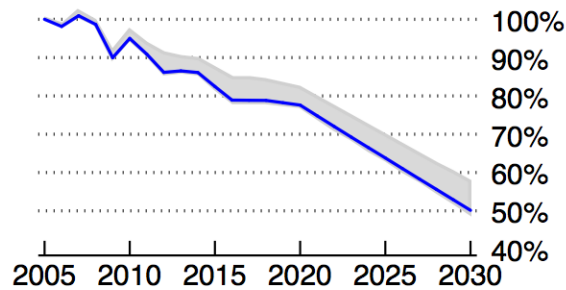
Mass



Rate



HighRenew1



HighRenew2

