Analysis of costs and timeframe for reducing CO_2 emissions by 70% in the U.S. auto and energy sectors by 2050

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U.S. GREENHOUSE GAS INVENTORY

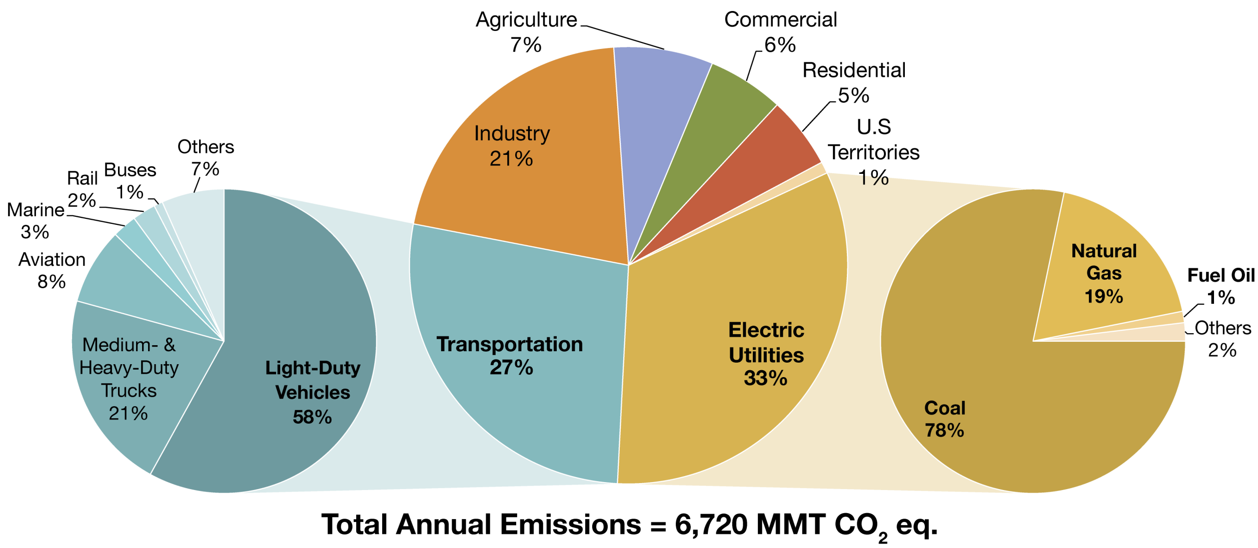

Fig. S1. Breakdown of U.S. greenhouse gas emissions by sector based on U.S. EPA data.[1] Bolded sectors, which contribute to just over 47% of all GHG emissions, are the subject of this study.

MATHEMATICAL FORMULATION OF THE MODEL

Sets

N_v	Set of vehicle technologies $\{ICEV, HEV, BEV, PHEV\}$ or Conventional Vehicle, Hybrid Electric Vehicle, Battery Electric Vehicle, Plug-in Hybrid Electric Vehicle.
N_e	Set of electric generation technologies $\{PC, NGGT, NGCC, P, B, N, H, W, SPV, STH, G\}$ or Pulverized Coal, Natural Gas (Gas Turbine), Natural Gas (Combined Cycle) Petroleum, Biomass, Nuclear, Hydroelectric, Wind, Solar Photovoltaic, Solar Thermal, and Geothermal.
T	Set of ages for technologies. 0 implies a new technology unit.
Y	Set of years in the model are indexed from $0,\ldots,\lvert Y \rvert$. Year 0 is 2014.
$N = N_v \cup N_e$	Set of all technologies.

Inputs

$DEPLOYMENT\_COST(i,k)$ — Unit cost of purchasing or constructing one new unit of technology $i \in N$ in year $k \in Y$.

$MAINTENANCE\_COST(i,j,k)$ — Annual unit maintenance cost of technology $i \in N$ that is of age $j \in T$ in year $k \in Y$.

$FUEL\_COST(i,k)$ — Cost per kg of fuel for technology $i \in N$ in year $k \in Y$.

$SCRAPPAGE\_VALUE(i,j,k)$ — Market value that owners of technology $i \in N$ stand to receive when scrapping or decommissioning a unit of age $j \in T$ in year $k \in Y$ at the end of its life.

$TAKE\_BACK\_VALUE(i,j,k)$ — Additional amount that owners of technology $i \in N$ stand to receive when scrapping or decommissioning a unit of age $j \in T$ in year $k \in Y$ before the end of its typical maximum service life.

$D_v(k)$ — Annual demand for vehicles miles traveled (VMT) in year $k \in Y$.

$D_e(k)$ — Annual demand for MWh in year $k \in Y$. This excludes the demand for electricity generated each year by *BEV* and *PHEV* vehicles which is determined endogenously and added separately.

$EN(i,j,k)$ — Annual electricity demand per vehicle of technology $i \in N$ of age $j \in T$ in year $k \in Y$. For technologies *ICEV* and *HEV* these will be 0 in all years and for all age vehicles.

$GEN_v(i,j,k)$ — Annual usage (miles traveled) for vehicle technology $i \in N_v$ for units of age $j \in T$ in year $k \in Y$. Miles travelled per vehicle is assumed to be constant for all technologies of all ages, and thus the variation in VMT is only due to changes in number of vehicles with time.

$GEN_e(i,j,k)$ — Annual electricity generation rate of unit of electric technology $i \in N_e$ for units of age $j \in T$ in year $k \in Y$ measured in MWh.

$CARBON\_INTENSITY(i)$ — Carbon intensity of fuel used in technology $i \in N$ (kg CO_2/kg fuel)

$FUEL\_EFFICIENCY_s(i,j,k)$ Quantity of fuel needed per mile (for $i \in N_v$) or per MWh (for $i \in N_e$) for a unit of age $j \in T$ in year $k \in Y$. Note that *s* refers to the vehicle sector (*v*) or the electric sector (*e*).

$c_{new_v}(i,k)$ Unit purchase and operating cost of a vehicle of technology $i \in N_v$ in year $k \in Y$, defined as:

$$DEPLOYMENT\_COST(i,k) + MAINTENANCE\_COST(i,k) + FUEL\_EFFICIENCY_v(i,k) \bullet GEN_v(i,k) \bullet FUEL\_COST(i,k)$$

$c_{old_v}(i,j,k)$ Unit operating cost of an old (existing in the stock) technology $i \in N_v$ of age $j \in T$ in year $k \in Y$, defined as:

$$MAINTENANCE\_COST(i,j,k) + FUEL\_EFFICIENCY_v(i,j,k) \bullet GEN_v(i,j,k) \bullet FUEL\_COST(i,k)$$

$c_{new_e}(i,k)$ Unit construction and operating cost of a new unit of electric generation capacity of technology $i \in N_e$ in year $k \in Y$, defined as:

$$DEPLOYMENT\_COST(i,k) + MAINTENANCE\_COST(i,k) + FUEL\_EFFICIENCY_e(i,k) \bullet GEN_e(i,k) \bullet FUEL\_COST(i,k)$$

$c_{old_e}(i,j,k)$ Unit operating cost of an old technology $i \in N_e$ of age $j \in T$ in year $k \in Y$, defined as:

$$MAINTENANCE\_COST(i,j,k) + FUEL\_EFFICIENCY_e(i,j,k) \bullet GEN_e(i,j,k) \bullet FUEL\_COST(i,k)$$

$c_{ret_s}(i,j,k)$ Unit retirement cost of technology for sector *s* (vehicle (*v*) or energy (*e*)) where $i \in N_s$ of age $j \in T$ in year $k \in Y$, defined as:

$$SCRAPPAGE\_VALUE(i,j,k) + TAKE\_BACK\_VALUE(i,j,k)$$

r Discount rate for net present value calculations, assumed as 7%.

$INITFLEET(i,j)$ Initial number of units of technology $i \in N$ of age $j \in T$.

$INITPROD_s$ Initial production capacity in sector *s* (vehicle (*v*) or electric (*e*)).

$P(i,j)$ Cumulative probability that a unit of technology $i \in N$ of age $j \in T$ will survive to the following year.

$Z_{low}(i,k), Z_{hi}(i,k)$ — Low and high allowable changes in the percent composition of technology $i \in N$ in year $k \in Y$.

$G_{low}(i,k), G_{hi}(i,k)$ — Low and high allowable changes in the percent composition of the new deployment (new sales or new capacity addition) for technology $i \in N$ in year $k \in Y$.

$MARKET\_SHARE(i,k)$ — Upper bound on the total market share of technology $i \in N$ in year $k \in Y$.

$e(i,j,k)$ — Emission factor per unit of technology (new or old) $i \in N$ of age $j \in T$ in year $k \in Y$, defined as

$$FUEL\_EFFICIENCY_s(i,j,k) \bullet GEN_s(i,j,k) \bullet CARBON\_INTENSITY(i)$$

where *s* refers to either the vehicle (*v*) or energy (*e*) sectors

$E_s(k)$ — Emission target for sector *s* in year $k \in Y$ in kg CO_2/year.

$PROD\_GROWTH_s(k)$ — Production capacity growth rate in sector *s* (vehicle (*v*) or energy (*e*)). This is the rate at which production capacity grows from year 0 to year *k*.

Decision Variables

$new(i,k)$ — Number of new units of technology $i \in N$ deployed in year $k \in Y$.

$old(i,j,k)$ — Number of old or existing units of technology $i \in N$ of age $j \in T$ in existence in year $k \in Y$.

$ret(i,j,k)$ — Number of units of technology $i \in N$ of age $j \in T$ retired in year $k \in Y$.

Objective Function

Based on the unit cost inputs and decision variables defined earlier, the net present value (*NPV*) objective function of the minimization problem for both sectors can then be written as shown in Eq. (S1).

$$\min_{\substack{new\\old\\ret}} NPV = \sum_{k=1}^{|Y|} \frac{\left(\left(\sum_{i \in N} new(i,k) \cdot c_{new}(i,k) \right) + \left(\sum_{i \in N} \sum_{j=1}^{|T|} \left(old(i,j,k) \cdot c_{old}(i,j,k) \right) + \left(ret(i,j,k) \cdot c_{ret}(i,j,k) \right) \right) \right)}{(1+r)^{k-1}} \tag{S1}$$

This essentially translates to "minimize the net present value of all costs over the analysis time horizon by changing the number of new units sold, number of old units retired, and number of old units present in the fleet." Note that the *FUEL_EFFICIENCY* term in the definition of c includes any increase in fuel efficiency of a unit of a given technology type over time due to technological improvements, as well as the decrease in fuel efficiency with age of that unit. Also, c_{new} captures any trends in the deployment costs such as reduction in Lithium ion battery costs, and solar farm commissioning costs.

Constraints

Fleet Constraints

$\forall k \in Y$

$$\left\{ \sum new_v(i,k) \bullet GEN_v(i,k) \right\} + \left\{ \sum_{i \in N} \sum_{j=1}^{|T|} old_v(i,j,k) \bullet GEN_v(i,j,k) \right\} \geq D_v(k) \tag{S2}$$

The total demand constraint in the auto sector can be expressed as shown in Eq. (S2), and it essentially represents the total number of vehicle miles traveled as a function of time. The demand for electricity, expressed in MWh of generation, includes the demand from charging of electric vehicles. The demand from EV charging is endogenously calculated by running the electric and auto sector models iteratively, with EV charging emissions factors from one iteration (calculated as the generation-weighted average emissions per MWh in the electric sector) used in the subsequent iteration until the root mean square error of emission factors for all years over the analysis time horizon (2015 – 2050) converges to less than 1% with respect to the previous iteration.

$$\forall k \in Y$$
$$GEN_e(k) = \left\{ \sum_{i \in N_e} \sum_{j=1}^{|T|} old_e(i,j,k) \right\} + \left\{ \sum_{i \in N_e} new_e(i,k) \right\}$$
$$\geq D_e(k) + \left\{ \sum_{i \in N_v} \sum_{j=1}^{|T|} old_v(i,j,k) \bullet EN(i,j,k) \right\} + \left\{ \sum_{i \in N_e} new_v(i,k) \bullet EN(i,k) \right\} \quad \text{(S3)}$$

In this study, the total population of the LDV sector fleet is assumed to grow at 1% annually, with the miles traveled per year by a vehicle of any technology type and age remaining constant. As such, the annual increase in VMT is assumed to be due to increase in number of vehicles alone. The non-EV related demand in the electric sector is assumed to grow as projected in the AEO 2015 report.[2]

The total market share of a given technology can be expressed as the ratio of the sum of old and new units of that technology to the total number of units in the fleet. The model allows the total market share of technologies to be constrained to restrict the manner in which new technologies are introduced into the market or old technologies are phased out of the market. These constraints are implemented by requiring that the *change* in total market shares of a certain technology from the previous year be within the exogenously defined bounds of $-Z_{low}$ and $+Z_{hi}$. The total market share constraints can be written as shown in Eq. (S4). Rollout of new technologies and phasing out of old technologies can also be controlled by restricting the change in new units deployed over the previous year to exogenously defined bounds of $-G_{low}$ and $+G_{hi}$ (Eq. (S5)). Together, these two approaches constitute the deployment smoothing constraints.

$$\forall i \in N, k \in Y$$
$$\left\{1 - Z_{low}(i,k)\right\} \bullet \left\{new(i,k-1) + \sum_{j=1}^{|T|} old(i,j,k-1)\right\} \le new(i,k) + \sum_{j=1}^{|T|} old(i,j,k) \le \left\{1 + Z_{hi}(i,k)\right\} \bullet \left\{new(i,k-1) + \sum_{j=1}^{|T|} old(i,j,k-1)\right\} \qquad \text{(S4)}$$

$$\forall i \in N, k \in Y$$
$$\left\{1 - G_{low}(i,k)\right\} \bullet new(i,k-1) \le new(i,k) \le \left\{1 + G_{hi}(i,k)\right\} \bullet new(i,k-1) \qquad \text{(S5)}$$

Additionally, the total market share (and not change in total market share) of a given technology in a year can also be constrained as follows.

$$\forall i \in N_v, k \in Y$$
$$new_v(i,k) + \sum_{j=1}^{|T|} old_v(i,j,k) \le MARKET\_SHARE(i,k) \bullet D_v(k)$$
$$\forall i \in N_e, k \in Y$$
$$new_e(i,k) + \sum_{j=1}^{|T|} old_e(i,j,k) \le MARKET\_SHARE(i,k) \bullet \left\{ \begin{array}{l} D_e(k) + \left[\sum_{i \in N_v} \sum_{j=1}^{|T|} old_v(i,j,k) \bullet EN(i,j,k) \right] \\ + \left[\sum_{i \in N_v} new_v(i,k) \bullet EN(i,k) \right] \end{array} \right\} \qquad \text{(S6)}$$

In addition to these fleet constraints, the total new unit production capacity (for all technologies combined) in any given sector can also be restricted to simulate a gradual ramp up in capacity of new vehicles or electricity generation. For instance, this constraint can prevent the sales of 50% more vehicles (25 million) in year 1 of the analysis, which is unlikely to happen since the additional vehicle manufacturing facilities needed to meet this production increase cannot realistically be built in a year. It should be noted that the same effect can be achieved using the new unit deployment smoothing constraint, and restricting the total new unit production capacity is just another way of restricting increase in deployment of new units. As such, the production constraint can be written as shown in Eq. (S7). We note here that in this paper, none of the market share, production, or deployment smoothing constraints have been applied in any scenario.

$$\forall k \in Y$$
$$\sum_{i \in N_v} new_v(i,k) \le INITPROD_v \bullet PROD\_GROWTH_v(k)$$
$$\sum_{i \in N_e} new_e(i,k) \le INITPROD_e \bullet PROD\_GROWTH_e(k) \tag{S7}$$

Emission Constraints

Sector-wide emissions can be expressed as the sum of emissions from old units that have survived scrappage or forced retirement and the emission from new units. The emission constraints can then be expressed as an annual target for each year of the analysis horizon (Eq. (S8)), or as an aggregate constraint over the entire analysis horizon such that the total allowable emissions over a given period equal the sum of the annual emission targets over that same period (Eq. (S9)).

$$\forall k \in Y$$
$$\sum_{i \in N_s} new_s(i,k) \bullet e_{new}(i,k) + \sum_{i \in N_s} \sum_{j=1}^{|T|} old_v(i,j,k) \bullet e_{old}(i,j,k) \le E_s(k) \tag{S8}$$

$$\sum_{k=1}^{|Y|} \left\{ \sum_{i \in N_s} new_s(i,k) \bullet E_{new}(i,k) + \sum_{i \in N_s} \sum_{j=1}^{|T|} old_s(i,j,k) \bullet e_{old}(i,j,k) \right\} \le \sum_{k=1}^{|Y|} E_s(k) \tag{S9}$$

This model assumes a uniform rate of emission reduction from 2011 through 2050 to achieve a set reduction in GHGs relative to 1990 emission values. The time period of interest to us is until 2050. However, as discussed earlier, the analysis time horizon for both sectors goes well beyond

2050 to account for operating costs beyond 2050. The value of elements in the vector E for years beyond 2050 is held at the constant value of the 2050 target. Thus, elements of the E vector fall on a straight line with a slope of $\left(E(2050)-E(2014)\right)/\left(2050-2014\right)$ until 2050, followed by a straight line with slope 0 beyond 2050.

The climate action scenario assumes that regulatory measures such as sector-wide emission targets, emission permits and trading schemes, or carbon tax will be put in place starting from the year in the climate action is initiated, and continuing through the year 2050 and beyond so as to reduce and maintain annual emission levels in 2050 and beyond to 71% of the 2010 values. The 71% CO_2 reduction value is chosen as the mean value of the 70% – 72% range for CO_2 reduction provided by the IPCC (IPCC, 2014). This emission "constraint" is implemented in two ways in this study depending on the analysis. The first approach treats 2010 as the baseline climate action year based on the IPCC AR5[3] report, and assumes a linear annual reduction in emissions through 2050 such that the annual sector-specific emission in 2050, E_{2050}, is 1 – 0.71 = 0.29 times the 2010 emission value, E_{2010}. The sum of the annual "ideal" emissions E_{ideal} (that is if climate action had initiated in 2010) from 2010 till the end of the analysis time horizon (2010 + $|Y|$), minus the sum of the annual emission deficit accrued between 2010 and the climate action year y_{CA} (due deviation of actual emissions E_{actual} from the ideal emissions E_{ideal}) is then treated as the emission budget B for the years between the climate action year y_{CA} and 2050. This can be expressed mathematically as follows.

$$B = \sum_{y=2010}^{2010+|Y|} E_{ideal}(y) - \sum_{y=2015}^{y_{CA}} \left\{ E_{actual}(y) - E_{ideal}(y) \right\} \quad \text{(S10)}$$

where,

$$\forall y \in [2010, 2050]$$

$$E_{ideal}(y) = (y - 2010) \bullet \left\{ \frac{0.29 \bullet E_{2010} - E_{2010}}{2050 - 2010} \right\} + E_{2010}$$

and

$$\forall y \in [2051, 2010 + |Y|]$$

$$E_{ideal}(y) = (2050 - 2010) \bullet \left\{ \frac{0.29 \bullet E_{2010} - E_{2010}}{2050 - 2010} \right\} + E_{2010} \tag{S11}$$

Based on Eqs. (S10) and (S11), the emission budget constraint can be rewritten as shown in Eq. (S12).

$$\sum_{k=1}^{|Y|} \left\{ \sum_{i \in N_s} new_s(i,k) \bullet e_{new}(i,k) + \sum_{i \in N_s} \sum_{j=1}^{|T|} old_s(i,j,k) \bullet e_{old}(i,j,k) \right\} \leq B \tag{S12}$$

The second approach of implementing an emission constraint is by including the emissions in the objective function as a cost. This approach requires emissions to be ascribed a certain cost penalty, which is implemented in this analysis using estimates of social cost of carbon (SCC). Expressing emissions as costs eliminates the need to impose an emission budget constraint, and therefore, this approach is used when setting a specified *p%* reduction in annual emissions by 2050 leads to infeasibility in the optimization process. Further, the second approach can also be used to estimate the SCC required for achieving a certain emission reduction. Assuming that the SCC is imposed as a function of time, the objective function under the second approach can be written based on Eq. (S1) and Eq. (S12) as shown in Eq. (S13).

$$\min_{\substack{new\\old\\ret}} \sum_{k=1}^{|Y|} \left\{ \frac{\left\{ \sum_{i \in N} new(i,k) \bullet \left(c_{new}(i,k) + SCC(k) \bullet e_{new}(i,k) \right) \right\} + \left\{ \sum_{i \in N} \sum_{j=1}^{|T|} \left[old(i,j,k) \bullet \left(c_{old}(i,j,k) + SCC(k) \bullet e_{old}(i,j,k) \right) \right] + \left[ret(i,j,k) \bullet c_{ret}(i,j,k) \right] \right\}}{(1+r)^{k-1}} \right\} \tag{S13}$$

Other Constraints

Corporate Average Fuel Economy (CAFE) standards for vehicle fuel economies beyond 2025 (the year until which they are presently defined) are assumed to continue to follow the linear trajectory through 2050 as set by CAFE standards in miles per gallon from 2011 – 2025, which is defined as shown in Eq. (S14). This equation has an R^2 value of 0.991 considering the 2011 – 2025 CAFE standards.

$$CAFE(k) = 1.3704(k - 2010) + 26.077 \tag{S14}$$

If the *FUEL_ECONOMY* denotes the sales-weighted fuel economy in miles per gallon of a new vehicle of technology $i \in N_v$, the CAFE constraint can be expressed as shown in Eq. (S15).

$$\sum_{i \in N_v} \left(new_v(i,k) \bullet FUEL\_ECONOMY(i,k) \right) \geq \left(\sum_{i \in N_v} new_v(i,k) \right) CAFE(k) \tag{S15}$$

Similarly, the renewable portfolio standards (RPS) constraint for the electric sector, which applied to generation from new and existing generators, can be expressed as shown in Eq. (S16). Here, *REN* is the set of renewable energy technologies, and *f* is the national average fraction of total generation that is mandated from renewables.

$$\sum_{i \in REN} \left(new_e(i,k) + old_e(i,k) \right) \geq f \bullet \sum_{i \in N_e} \left(new_e(i,k) + old_e(i,k) \right) \quad \text{(S16)}$$

Non-Negativity Bounds

Finally, the non-negativity bounds for the decision variables can be expressed as follows.

$$\begin{aligned} & \forall i \in N, k \in Y \\ & new(i,k) \geq 0 \\ & \forall i \in N, j \in T, k \in Y \\ & old(i,j,k) \geq 0 \\ & ret(i,j,k) \geq 0 \end{aligned} \quad \text{(S17)}$$

Uncertainty Analysis Scenarios

Table S1. Uncertainty analysis scenarios (27) defined by levels of different parameter groups. For each parameter group, 1 = Low, 2 = Nominal, 3 = High.

Scenario	Cost Parameters	Emission Parameters	Demand Parameters
Scenario 1	1	1	1
Scenario 2	2	1	1
Scenario 3	3	1	1
Scenario 4	1	2	1
Scenario 5	2	2	1
Scenario 6	3	2	1
Scenario 7	1	3	1
Scenario 8	2	3	1
Scenario 9	3	3	1
Scenario 10	1	1	2
Scenario 11	2	1	2
Scenario 12	3	1	2
Scenario 13	1	2	2
Scenario 14	2	2	2
Scenario 15	3	2	2
Scenario 16	1	3	2
Scenario 17	2	3	2

Scenario	Cost Parameters	Emission Parameters	Demand Parameters
Scenario 18	3	3	2
Scenario 19	1	1	3
Scenario 20	2	1	3
Scenario 21	3	1	3
Scenario 22	1	2	3
Scenario 23	2	2	3
Scenario 24	3	2	3
Scenario 25	1	3	3
Scenario 26	2	3	3
Scenario 27	3	3	3

INPUTS, ASSUMPTIONS, AND OTHER DETAILS FOR THE AUTO SECTOR

Representative Vehicle Characteristics

All vehicle segments such as compact, mid-size sedan, SUVs, and light trucks within each technology are treated as one representative vehicle that has a sales-weighted average fuel economy and price based on 2015 data from the U.S. Energy Information Administration (EIA).[2] Table S2 summarizes these fuel economy and price for the year 2015.

Table S2. Representative vehicle characteristics for the auto sector

Representative Vehicle Type	Fuel Economy (MPG or MPGe)	Purchase Price (USD)
ICEV	24.9	28,020
HEV	49.1	37,107
BEV	116.9	60,655
PHEV	66.7	40,306

Initial Condition for Stock and Flow Model

New vehicles deployed in any given year make up for the number of vehicles scrapped that year plus the projected increase in the total number of vehicles over the previous year. The vehicle scrappage function is expressed as a logistic function of age of the form given by Eq.

(S18) based on Greene and Chen,[4] where t is the age of the vehicle and $d(t)$ is the discard probability (scrappage probability) function.

$$d(t) = 1 \Big/ \left\{ A_0 + e^{-(A_1 + A_2 t)} \right\} \tag{S18}$$

The discard probability function is assumed to only be a function of vehicle age and not the year in which the vehicle was produced. Furthermore, it defines the probability that a vehicle of a certain age will be scrapped during its operation in the subsequent year. Using automotive sales values from 1990 to 2014 (see Fig. S2),[5–7] total vehicles on road in 2014,[8] and the total emissions from the auto sector in 2014.[9] The parameter coefficient A_0 is expressed in terms of parameters A_1, and A_2 as shown in Eq. (S19) using the initial condition that $d(t)$ equal zero are t = 25 years based on the assumed maximum service life of vehicles in this study as 25 years.

$$A_0 = 1 - e^{-(A_1 + 25 A_2)} \tag{S19}$$

Parameters A_1 and A_2 are then determined using the Microsoft® Excel GRG non-linear solver. The solver changes the values of A_1, and A_2, and thus of $d(t)$ such that the age distribution of the fleet so obtained minimizes the square of the error between reported and predicted number of total vehicles, and subject to the constraint that the error in reported and predicted values of total sector-wide GHG emissions is less than or equal to 1%. Due to the nonlinear nature of the objective function and constraint in A_1, and A_2, the optimization was run with 100 starting points of A_1, and A_2. The set of values of A_0, A_1, and A_2 that gave the lowest objective function value were selected as the global optimizers. The discard probability function is show in Eq. (S20). Note that $d(t)$ is the one-year survival probability, that is, conditional on having survived t years, $d(t)$ gives the probability that the unit will survive until year t + 1.

$$d(t) = \frac{1}{0.9999 + e^{-(1.4635t - 19.4639)}} \quad \text{(S20)}$$

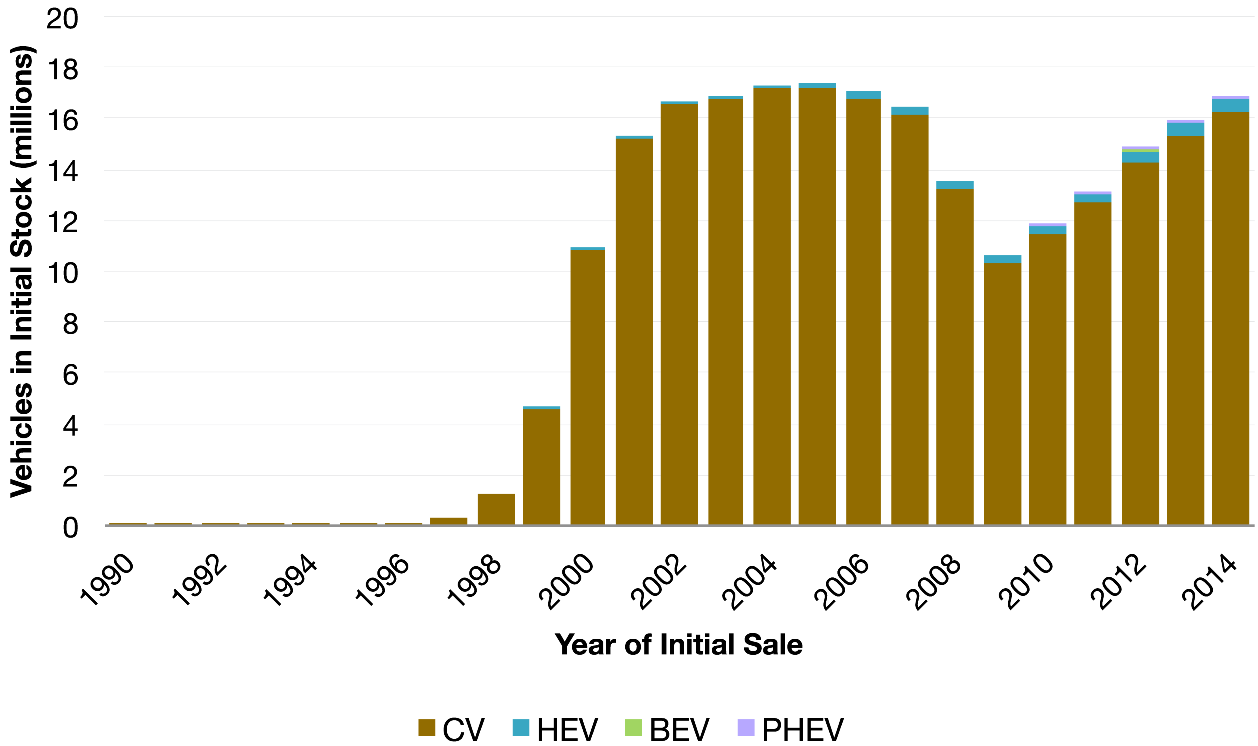

Fig. S2. Age-wise composition of initial (2014) vehicle stock for the auto sector stock and flow model based on vehicle sales data and discard probability calculated in Eq. (S20).

Details on Input Parameters, Assumptions, and Data Sources

Table S3. Auto sector model inputs, assumptions, and data sources

Parameter	**Values/Assumptions/Sources**
Gasoline vehicle fuel economy	ICEVs and PHEVs (gas driving) from 1990 to 2014 follow CAFE values; HEVs assumed to have 13% better mpg than CV; fuel economy improvement by model year based on estimates in the literature[10–12]
Electric vehicle fuel economy	MWh/miles assumed to improve at 0.5% annually after 2010[13]
Combined vehicle fuel economy	Formula for MPGe obtained from EPA rule (E_g/E_m x E_e)[14]

Parameter	Values/Assumptions/Sources
CAFE fuel economy standards	Years 1990-2025 follow CAFE standards that have been published so far; standards for 2026 and later calculated by linear extrapolation of 2008-2025 numbers[15–18]
New vehicle deployment costs	Assumption based on sales-weighted average for vehicle type excluding subsidies in 2015 (see Table S2)
Vehicle maintenance cost	Maintenance costs are assumed to be different for different vehicle technologies, and are assumed to stay constant with ageing[19,20]
Vehicle retirement costs	Retirement cost assumed to be equal to the value of vehicle calculated using average annual depreciation rate based on literature[21]
Gasoline prices	Gas prices assumed to follow EIA projections[2]
Retail consumer electricity prices	Residential electricity price assumed to follow EIA projections[2]
Vehicle miles traveled on gasoline	Average miles traveled per vehicle calculated by dividing total VMT by projected total stock of vehicles by year based on EIA projections[2]
Vehicle miles traveled on battery power	Miles on battery powered propulsion assumed to range between 50 – 70% of average miles traveled per vehicle for PHEVs
Daily EV charging amount	Calculated based on average daily miles traveled, battery capacity, and electric driving fuel economy of a vehicle as a function of time
CO2 emissions from burning fuel	Constant assuming gasoline as the fuel[22]
CO2 emissions from wall charging of EVs and EV charging demand	Low, nominal, and high values for vehicle charging emissions factor and additional load from vehicle charging calculated by iteratively running the electric and auto sector optimization models
Battery cost reduction	Rate are which batteries becomes cheaper assumed to follow non-exponential power curve based on literature data[23–25]
Technology cost reduction	Rate at which the technology becomes cheaper over the years (different from battery cost reduction which is in addition to this reduction) based on purchase price trends from EIA[2]
Relative market penetration of PHEVs and BEVs	Expressed as a ratio of PHEV:BEV sales in every year and values are 1:2, 1:1, and 2:1 for the low, nominal, and high cases of PHEV penetration
Total vehicle stock (or demand)	Obtained from EIA estimates[2]

The spreadsheet that serves as an input file for the LETSACT model for this study can be accessed using this link (https://umich.box.com/s/c1ho8bgq13gj2d68b29szudrtb7fkr0r). It contains specific values for the Low, Nom, and High cases of parameters described in Table S3.

INPUTS, ASSUMPTIONS, AND OTHER DETAILS FOR THE ELECTRIC SECTOR

Initial Condition for Stock and Flow Model

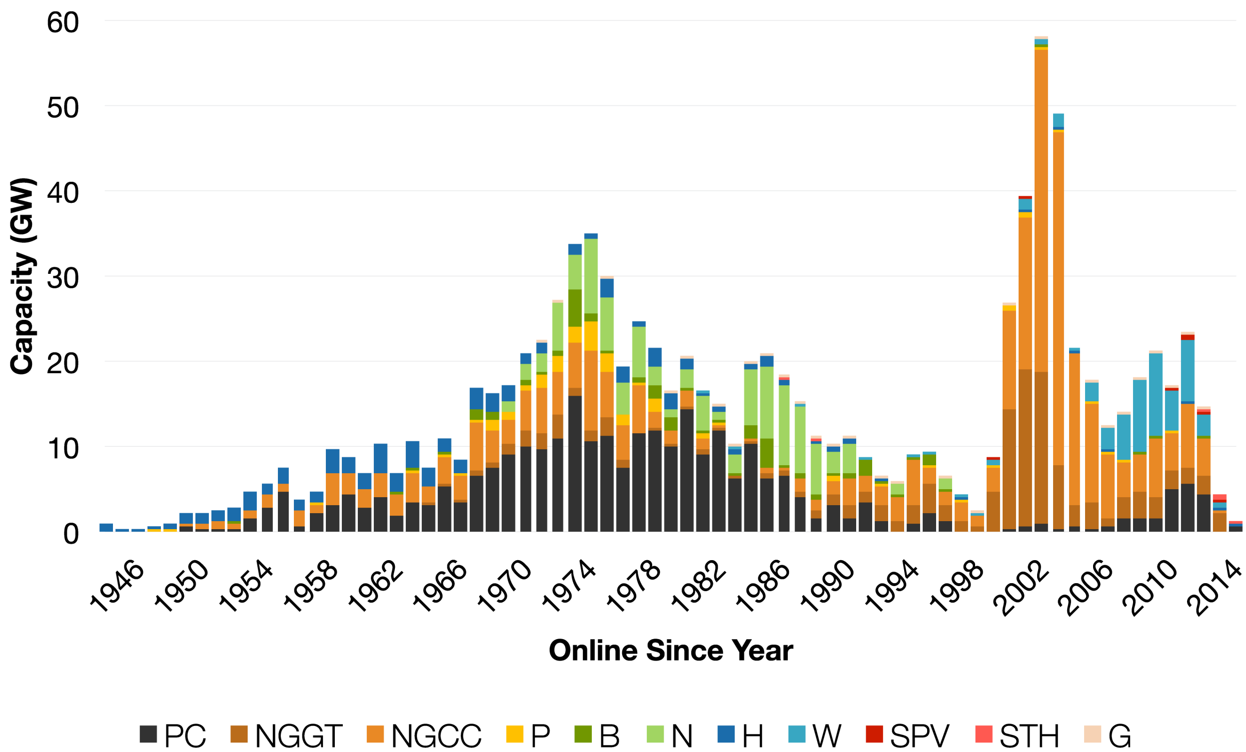

Fig. S3. Age-wise composition of initial (2014) power generation capacity for the electric sector stock and flow model based on NEEDS data.[26]

Details on Input Parameters, Assumptions, and Data Sources

Table S4. Electric sector model inputs, assumptions, and data sources

Parameter	Values/Assumptions/Sources
Age-wise distribution of 2014 initial stock	Installed capacity, generation, and generator age data obtained from eGRID and NEEDS data; Generation capacity older than 70 years, which comprised of only 3% of total capacity, is excluded from the fleet, but total generation and emission values are kept identical to actual reported values[26–29]
Capacity discard probability	Assumed to be 0 until maximum service life of the technology, and 1 after that
Maximum service life	Assumed 60 years for PC, NGCC, N, and H; 40 years for NGGT, P, and G; and 30 years for the rest
Deployment & O&M costs, heat rates, emission factors	Based on EIA, NREL, and Lazard estimates; $/kW converted to $/MWh considering 2014 capacity factors[30–32]
Capacity retirement cost	Decommissioning costs obtained for retirement of an entire plant using a certain type of fuel, and then divided by the nominal capacity of a plant using the particular fuel; forced retirement costs include decommissioning cost plus the payment for lost revenue, and any remaining debt; capital recovery factor includes ROI/interest rate (10-12%), risk (1-3%), and tax (5%), loan term for capital cost is assumed to be 20 years[33–39]
Heat rates	Heat rates of plants in the initial stock condition are based on NEEDS data, and are different from heat rates of plants deployed by the model from 2015 onwards that are based on characteristics of new plants; Heat rate is assumed to deteriorate slightly (0.05% – 0.2%) with ageing of a plant
Fuel costs	Fuel costs based on heating values of different kinds of generation units using the same fuel, and fuel prices; fuel prices obtained from EIA estimates[2]
Relative market penetration of different renewables	To incorporate some effects renewable resource availability and its distribution over the entire U.S., we deploy new capacity of W, STH, SPV, and G added in proportion to the relative available capacity for each resource based on the literature; The W:STH:SPV:G ratio is 1:0.1:0.1:0.03 in the low case, 1:0.25:0.25:0.03 in the nominal case, and 1:0.5:0.5:0.03 in the high case[40,41]

The spreadsheet that serves as an input file for the LETSACT model for this study can be accessed using this link (https://umich.box.com/s/c1ho8bgq13gj2d68b29szudrtb7fkr0r). It contains specific values for the Low, Nom, and High cases of parameters described in Table S4.

TECHNOLOGY TRAJECTORIES FOR NOMINAL SCENARIO

Technology trajectories for immediate climate action (2018) and their BAU cases for both sectors in the nominal scenario where cost, emission, and demand parameters assume their nominal value are shown in Fig. S4 and Fig. S5 respectively. Since no market share, deployment smoothing, or production constraints have been imposed in this idealized analysis of technology trajectories, we observe abrupt switches from one technology to the other. Imposition of market share and other such reality-based constraints would lead to smoother transitions that would also cause emission lock-ins, thereby further increase abatement costs and shrinking the window of tie within which climate action would still be feasible. Spreadsheets containing technology trajectories for all scenarios and for different climate action start years within each scenario can be obtained using this link (https://umich.box.com/s/8xdtv5dfew27reh98mv20qzyvjp41gnh) for the auto sector, and this link (https://umich.box.com/s/betvhqmmqf5p3s0rtn1a5gr2vbsmv3cx) for the electric sector. Differences between least-cost BAU emissions and BAU projections from the U.S. EIA are shown in Fig. S6.

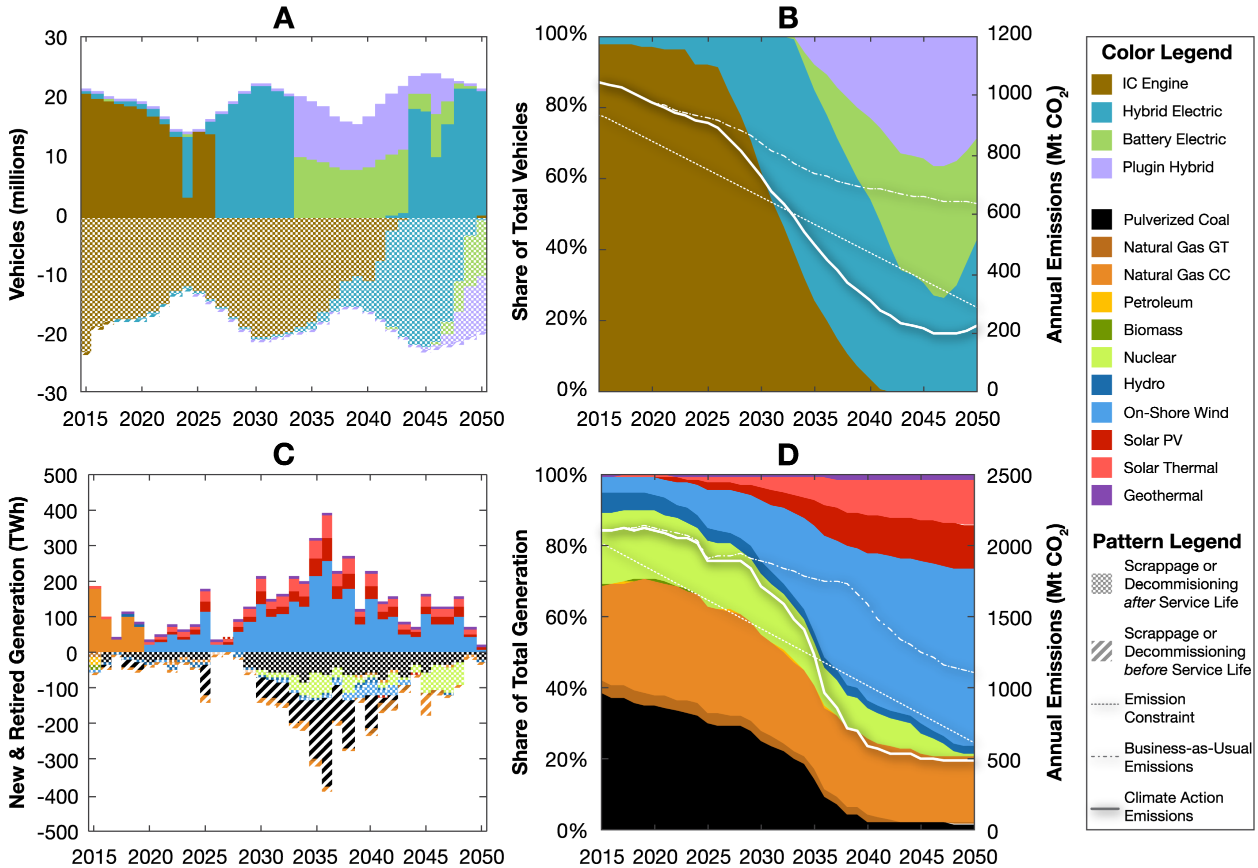

Fig. S4. Ideal least-cost trajectories under climate action starting in 2018 for the nominal cost, emissions, and demand scenario. (A) and (C) show new vehicle sales and new capacity addition respectively for the auto and electric sectors, and total stock trajectories for the two sectors are shown in (B) and (D).

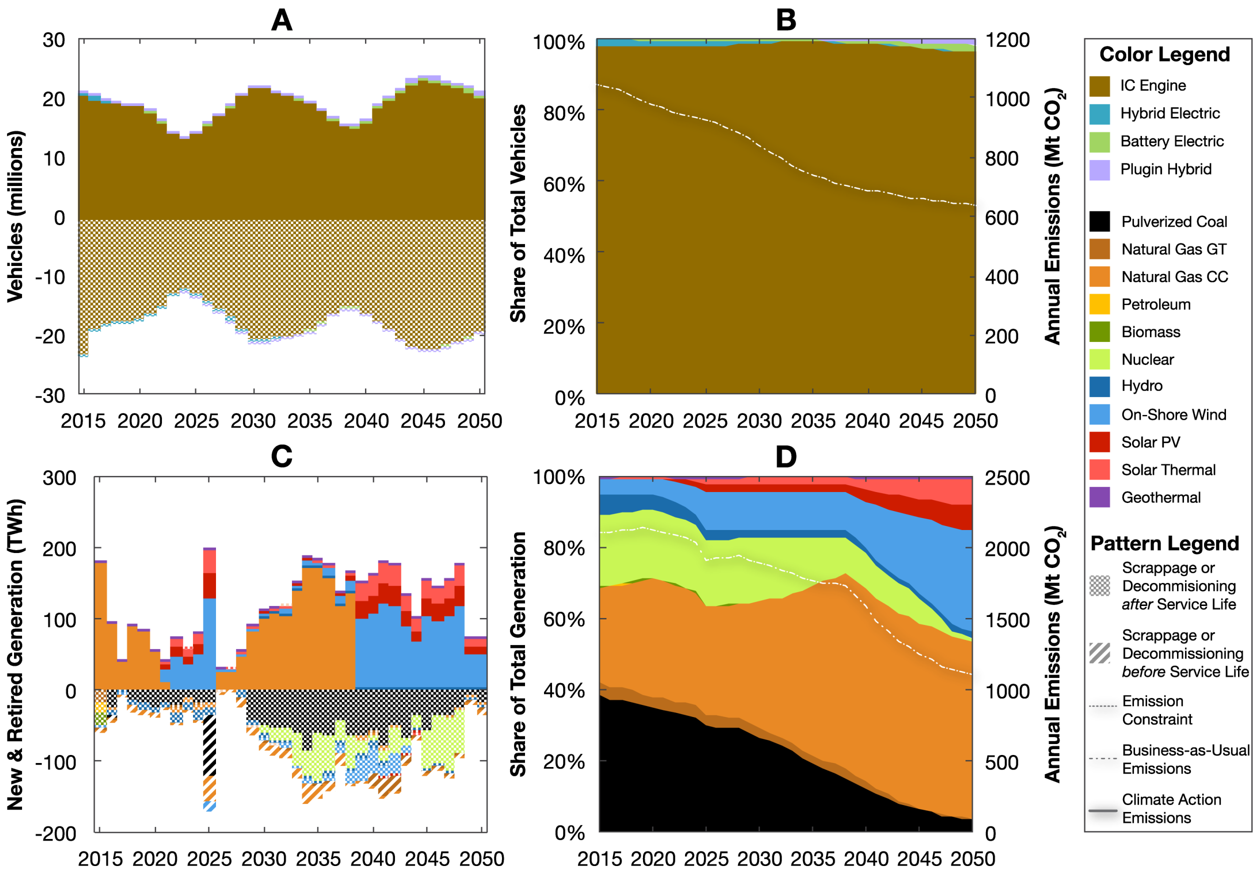

Fig. S5. Ideal least-cost trajectories under business as usual case for the nominal cost, emissions, and demand scenario. (A) and (C) show new vehicle sales and new capacity addition respectively for the auto and electric sectors, and total stock trajectories for the two sectors are shown in (B) and (D).

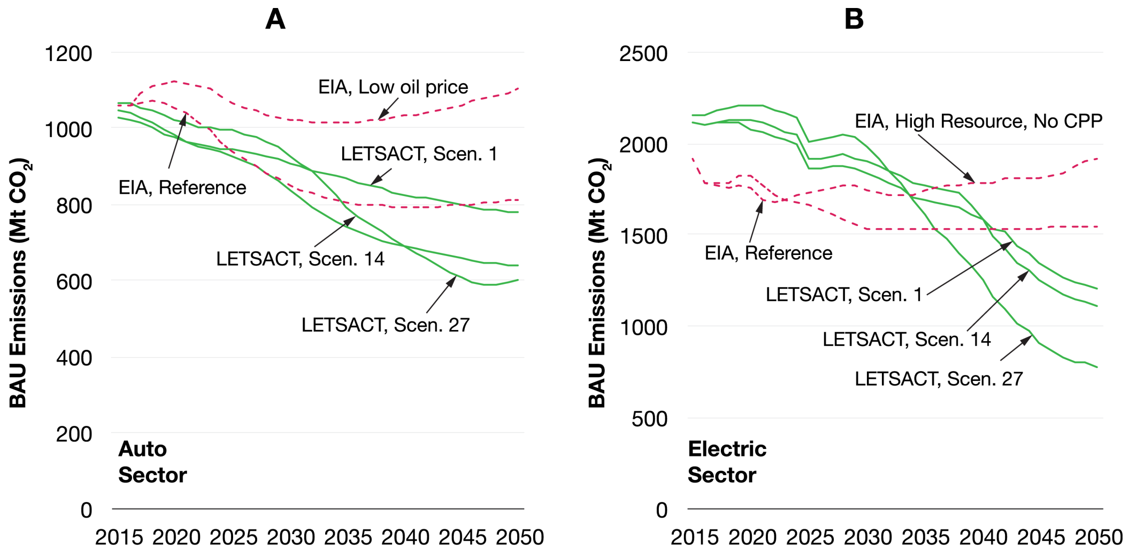

Fig. S6. Comparison of business-as-usual (BAU) emission trajectories obtained using the LETSACT model (solid green) with BAU emission trajectories projected in EIA's 2017 Annual Energy Outlook[42] (dashed red). Note that the initial difference of about 300 – 350 Mt CO_2 in the utility sector emissions between LETSACT results and the EIA reported values is because the LETSACT model includes emissions from combined heat and power plants as well.

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