# Evolution of the United States Energy System and Related Emissions under Varying Social and Technological Development Paradigms: Plausible Scenarios for Use in Robust Decision Making

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Supporting Information: 10 pages, 7 figures, 2 tables

Additional supporting information is available as an excel workbook

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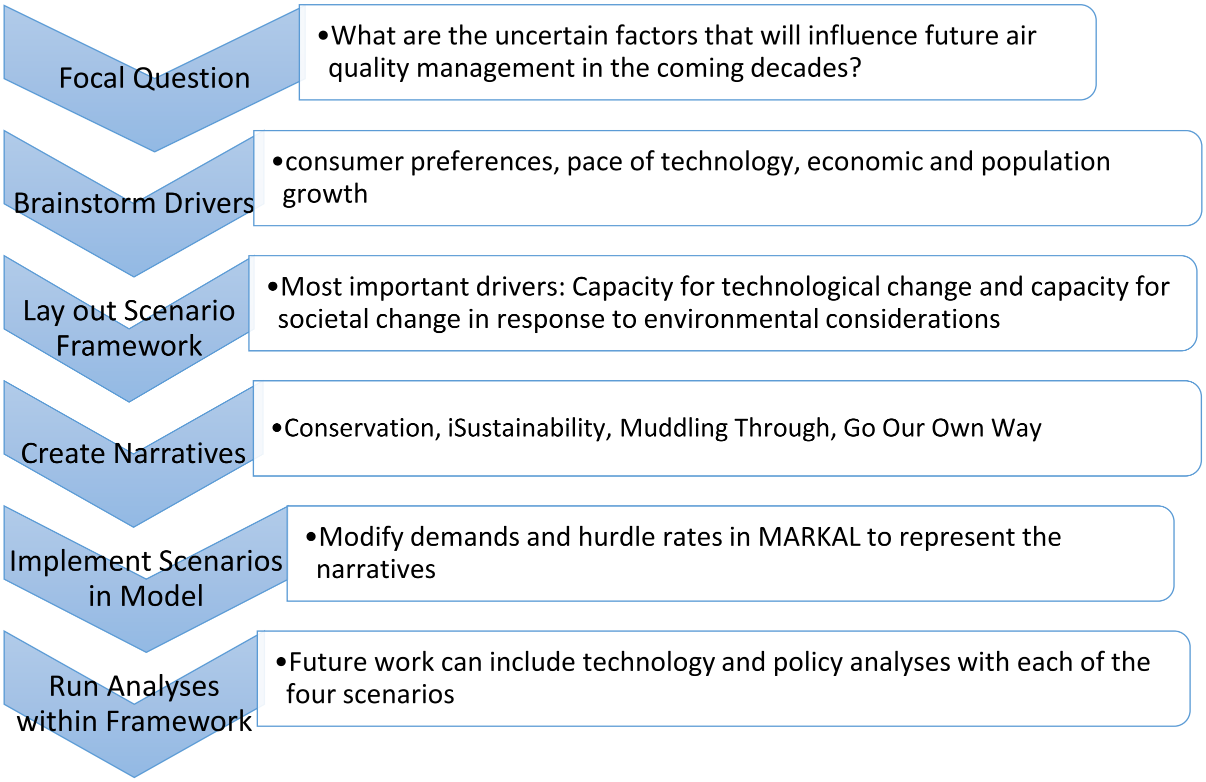
# S1. Process Flowchart



- What are the uncertain factors that will influence future air quality management in the coming decades?
- consumer preferences, pace of technology, economic and population growth
- Most important drivers: Capacity for technological change and capacity for societal change in response to environmental considerations
- Conservation, iSustainability, Muddling Through, Go Our Own Way
- Modify demands and hurdle rates in MARKAL to represent the narratives
- Future work can include technology and policy analyses with each of the four scenarios

**Figure S1. A flowchart depicting the process of scenario analysis.**

## S2. Hurdle Rate Description

Technology-specific hurdle rates allow each scenario's societal preferences for one technology or another to be reflected in the model's optimization process. In MARKAL, the present value (V) of a technology is calculated using standard engineering economics cash flow. MARKAL optimizes on the value of the entire energy system, so it determines the minimum present value where the annual costs include negative revenue terms. For example, the present value calculation associated with a technology is reflected in Figure S1 and in Equations S1 and S2, below.

*Abbreviations*

| | |
|---|---|
| A | Other annual costs |
| Ac | Amortized annual capital cost |
| C | Capital cost of the technology |
| d | System-wide discount rate |
| h | Technology specific hurdle rate |
| n | Lifetime of the technology |
| V | Present value |
| t | Number of years in the future at which the purchase is made |

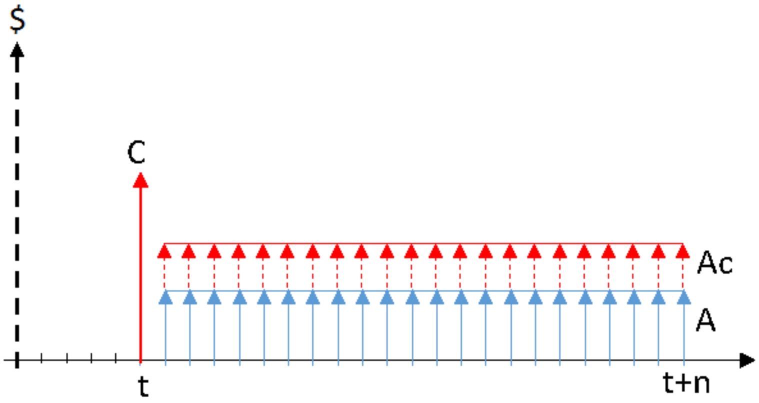


**Figure S2. Cash flow diagram illustrating the present value calculation and the role of the hurdle rate, h.**

The amortized annual capital cost, Ac, of the technology is calculated using the technology-specific hurdle rate, h:

$$Ac = C * [h * (1 + h)^n]/[(1 + h)^n - 1] \tag{Eq. S1}$$

where C is the capital cost of the technology, and n is the lifetime of the technology.

The present value, V, that is considered by MARKAL when optimizing is then calculated by bringing Ac and other annual costs, A, back to the present using the system-wide discount rate, d:

$$V = (Ac + A) * [(1 + d)^n - 1]/[d * (1 + d)^n] * 1/(1 + d)^t \tag{Eq. S2}$$

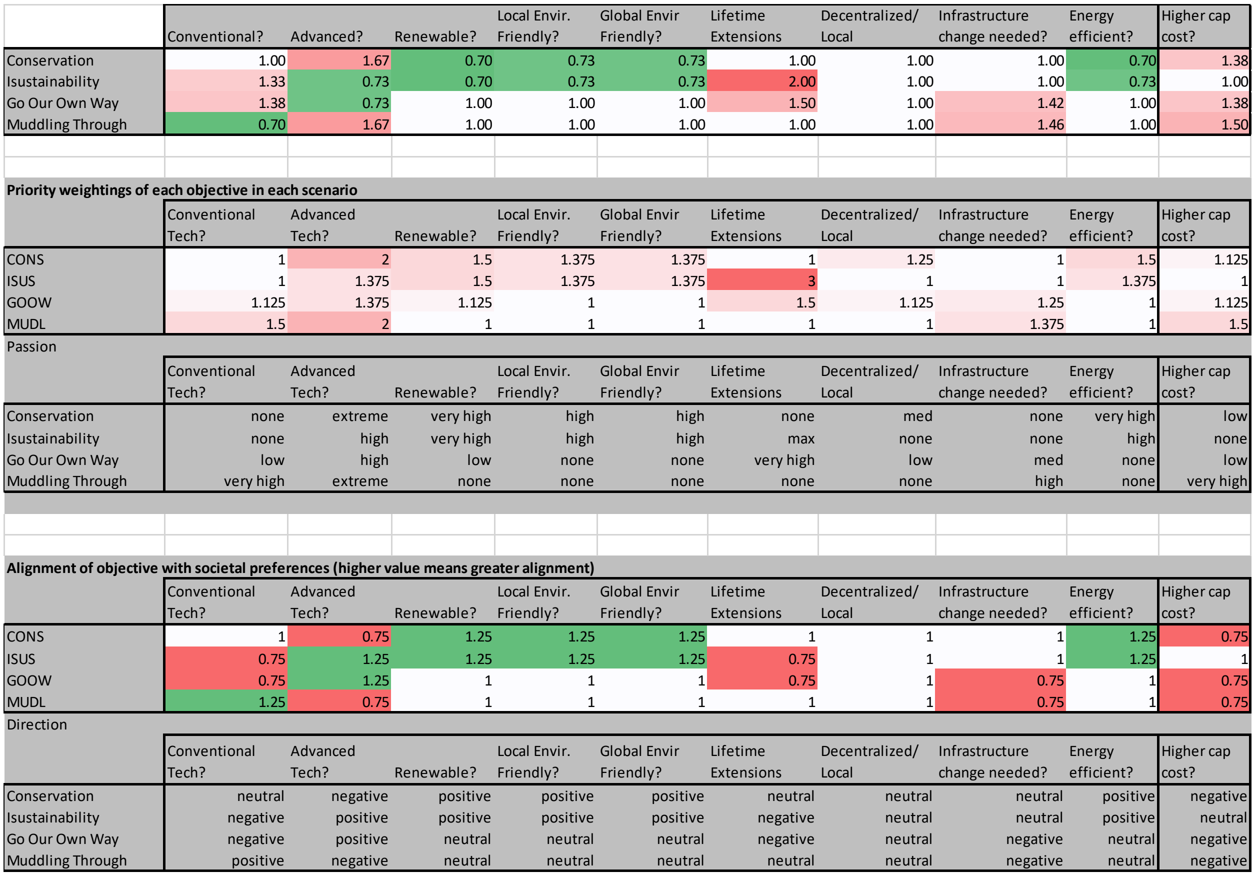
where t is the number of years in the future at which the purchase is made.

For the scenario implementations, a value of 0.05 is used for d. A typical value for h is 0.15, reflecting factors such as internal rate of return and hesitancy to make large capital expenditures. The effect of changing the hurdle rate is easily calculated. For example, if we assume C is $30,000, A is $5,000, n is 20 years, t is 5 years, and h and d are 0.15 and 0.05, respectively, the present value of the technology as seen by the objective function is $96,000. If h is reduced to 0.1, potentially reflecting a preference for the technology, the present value becomes $83,000.

## S3. Hurdle Rate Calculation

The tables below provide additional information on the calculation of hurdle rates for the scenarios. For each technology and attribute, a score of 1 or 0 was assigned, where 1 represents that attribute applies to that technology. As the calculation is additive and the impact of the attribute is multiplicative, an attribute with a score of 0 will not impact the overall score of the technology.

**Table S1. Calculation of technology and scenario-specific hurdle rates. The colors help visualize the relative magnitude of the values in each table and grey shaded cells denote descriptive information.**



| | Conventional? | Advanced? | Renewable? | Local Envir. Friendly? | Global Envir Friendly? | Lifetime Extensions | Decentralized/ Local | Infrastructure change needed? | Energy efficient? | Higher cap cost? |
|---|---|---|---|---|---|---|---|---|---|---|
| Conservation | 1.00 | 1.67 | 0.70 | 0.73 | 0.73 | 1.00 | 1.00 | 1.00 | 0.70 | 1.38 |
| Isustainability | 1.33 | 0.73 | 0.70 | 0.73 | 0.73 | 2.00 | 1.00 | 1.00 | 0.73 | 1.00 |
| Go Our Own Way | 1.38 | 0.73 | 1.00 | 1.00 | 1.00 | 1.50 | 1.00 | 1.42 | 1.00 | 1.38 |
| Muddling Through | 0.70 | 1.67 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.46 | 1.00 | 1.50 |

**Priority weightings of each objective in each scenario**

| | Conventional Tech? | Advanced Tech? | Renewable? | Local Envir. Friendly? | Global Envir Friendly? | Lifetime Extensions | Decentralized/ Local | Infrastructure change needed? | Energy efficient? | Higher cap cost? |
|---|---|---|---|---|---|---|---|---|---|---|
| CONS | 1 | 2 | 1.5 | 1.375 | 1.375 | 1 | 1.25 | 1 | 1.5 | 1.125 |
| ISUS | 1 | 1.375 | 1.5 | 1.375 | 1.375 | 3 | 1 | 1 | 1.375 | 1 |
| GOOW | 1.125 | 1.375 | 1.125 | 1 | 1 | 1.5 | 1.125 | 1.25 | 1 | 1.125 |
| MUDL | 1.5 | 2 | 1 | 1 | 1 | 1 | 1 | 1.375 | 1 | 1.5 |

Passion

| | Conventional Tech? | Advanced Tech? | Renewable? | Local Envir. Friendly? | Global Envir Friendly? | Lifetime Extensions | Decentralized/ Local | Infrastructure change needed? | Energy efficient? | Higher cap cost? |
|---|---|---|---|---|---|---|---|---|---|---|
| Conservation | none | extreme | very high | high | high | none | med | none | very high | low |
| Isustainability | none | high | very high | high | high | max | none | none | high | none |
| Go Our Own Way | low | high | low | none | none | very high | low | med | none | low |
| Muddling Through | very high | extreme | none | none | none | none | none | high | none | very high |

**Alignment of objective with societal preferences (higher value means greater alignment)**

| | Conventional Tech? | Advanced Tech? | Renewable? | Local Envir. Friendly? | Global Envir Friendly? | Lifetime Extensions | Decentralized/ Local | Infrastructure change needed? | Energy efficient? | Higher cap cost? |
|---|---|---|---|---|---|---|---|---|---|---|
| CONS | 1 | 0.75 | 1.25 | 1.25 | 1.25 | 1 | 1 | 1 | 1.25 | 0.75 |
| ISUS | 0.75 | 1.25 | 1.25 | 1.25 | 1.25 | 0.75 | 1 | 1 | 1.25 | 1 |
| GOOW | 0.75 | 1.25 | 1 | 1 | 1 | 0.75 | 1 | 0.75 | 1 | 0.75 |
| MUDL | 1.25 | 0.75 | 1 | 1 | 1 | 1 | 1 | 0.75 | 1 | 0.75 |

Direction

| | Conventional Tech? | Advanced Tech? | Renewable? | Local Envir. Friendly? | Global Envir Friendly? | Lifetime Extensions | Decentralized/ Local | Infrastructure change needed? | Energy efficient? | Higher cap cost? |
|---|---|---|---|---|---|---|---|---|---|---|
| Conservation | neutral | negative | positive | positive | positive | neutral | neutral | neutral | positive | negative |
| Isustainability | negative | positive | positive | positive | positive | negative | neutral | neutral | positive | neutral |
| Go Our Own Way | negative | positive | neutral | neutral | neutral | negative | neutral | negative | neutral | negative |
| Muddling Through | positive | negative | neutral | neutral | neutral | neutral | neutral | negative | neutral | negative |

The final hurdle rates for electricity generation technologies are provided in the main text, Table 1. A similar table for light duty vehicles is provided in Table S2. The secondary Supplemental Information consists of an Excel worksheet with hurdle rates for all remaining technologies in the MARKAL model.

**Table S2. Hurdle rates for light duty vehicles in four scenarios. Shading in cells helps visualize relative hurdle rates within each scenario. Dark red technologies are unlikely to be used and dark green technologies are more likely to be used in that scenario.**

| | CONS | ISUS | GOOW | MUDL |
|---|---|---|---|---|
| Gasoline | 0.21 | 0.2 | 0.28 | 0.16 |
| E85 Flex Fuel | 0.10 | 0.10 | 0.40 | 0.23 |
| Diesel | 0.21 | 0.15 | 0.21 | 0.23 |
| LPG | 0.21 | 0.15 | 0.29 | 0.33 |
| CNG | 0.34 | 0.11 | 0.21 | 0.55 |
| $H_2$ Fuel Cell | 0.17 | 0.06 | 0.21 | 0.55 |
| Gasoline Hybrid | 0.21 | 0.15 | 0.21 | 0.23 |
| Diesel Hybrid | 0.14 | 0.11 | 0.21 | 0.23 |
| Flex Fuel Hybrid | 0.10 | 0.08 | 0.29 | 0.33 |
| Gasoline Plug-in | 0.24 | 0.08 | 0.21 | 0.55 |
| E85 Plug-in | 0.12 | 0.04 | 0.21 | 0.55 |
| Electric | 0.17 | 0.06 | 0.21 | 0.55 |

## S4. Additional Results

The total primary energy used in each case, shown in Figure S2, by energy or fuel type is interesting. The Conservation and iSustainability cases have more use of renewable resources than the other cases while the Muddling Through case has incredibly high total use and large quantities of natural gas. It is also interesting to examine the electricity use by sector. Figure S3 provides a graphical representation of how much electricity is used by each sector in 2050. An interesting point to note is that transportation electricity is a small fraction of total electricity use, even in iSustainability in which there was significant demand for electric vehicles. The residential and commercial solar in this figure show generation from PV (solar photovoltaic) occurring in end use demand locations, not electricity consumption. In Conservation, end-use energy demands are defined to be low in all sectors, but these demands are not satisfied as efficiently as in iSustainability and Go Our Own Way, leading to higher electricity use per unit of end-use demand. In Muddling Through, the very high electricity use comes not only from increased demands but also from lower efficiency in residential and commercial end use technologies, so that a 15% increase in end-use energy demand leads to more than a 15% increase in electricity generation. In iSustainability, electricity increases more moderately than demand because efficiency is improved. This scenario has the lowest electricity use per unit of demand by sector, except for the larger electricity use in the light duty transportation sector. Even though many plug-in hybrid and electric vehicles are used in this case, the vehicles are very efficient and consume only 2.6% of total electricity in 2050. In Go Our Own Way, demand is satisfied more efficiently than the cases with low technological development, and only a very small amount of electricity is needed in the transportation sector.

Water consumption can be another important metric of the environmental suitability of different energy futures. Figure S4 presents the water consumption in 2050 in each case, which shows that the cases where the environment is prioritized use less water in the energy sector. Figure S5 presents the ratio of marginal damages to useful energy in each scenario as a way to compare the utility of the energy system against its damages. The sectoral damages are calculated for each year in the Excel document that is part of the SI. Total damages are reported in the main text.

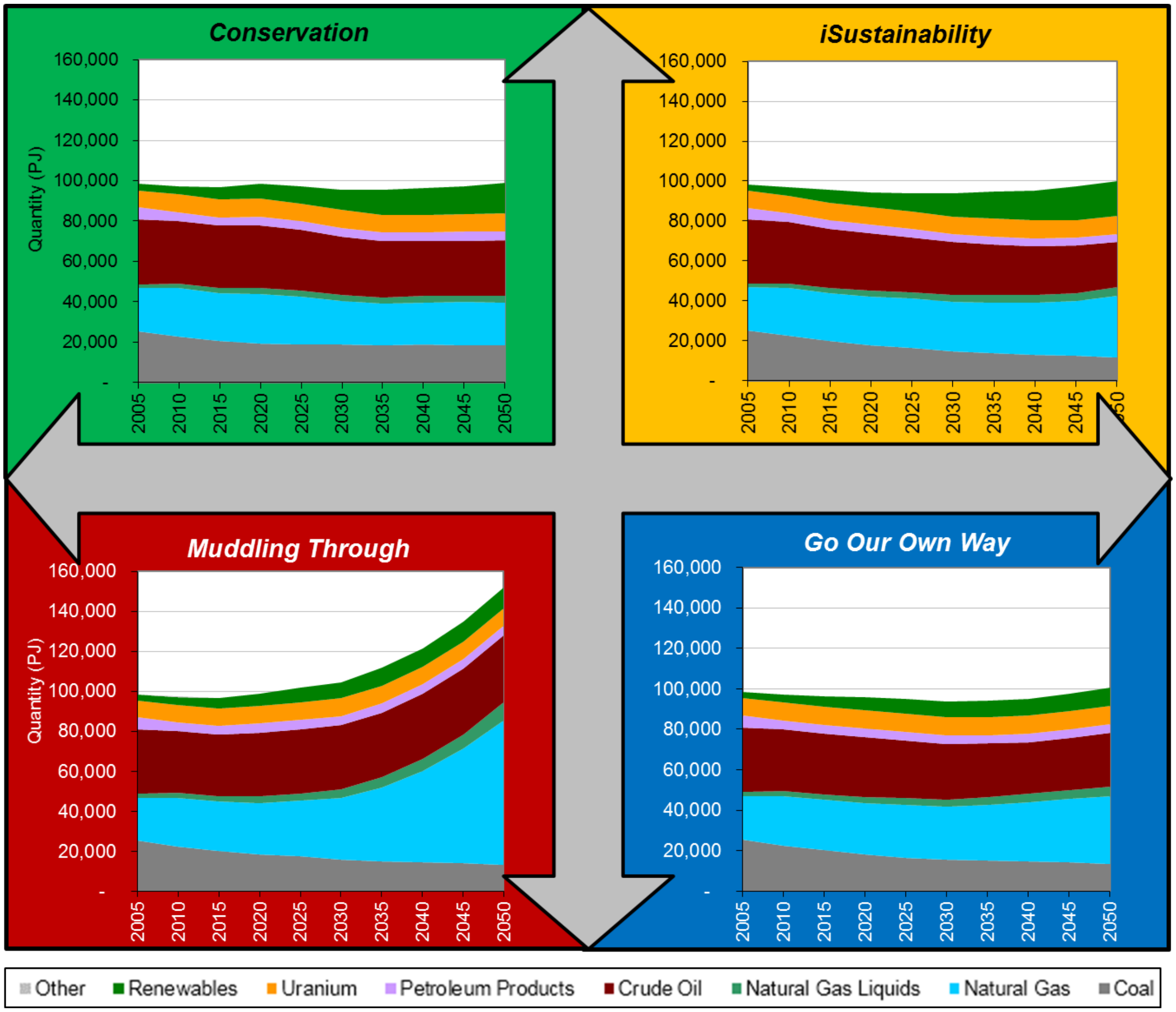


**Figure S3. Total primary energy consumption by fuel and case. The y axis units are in petajoules.**

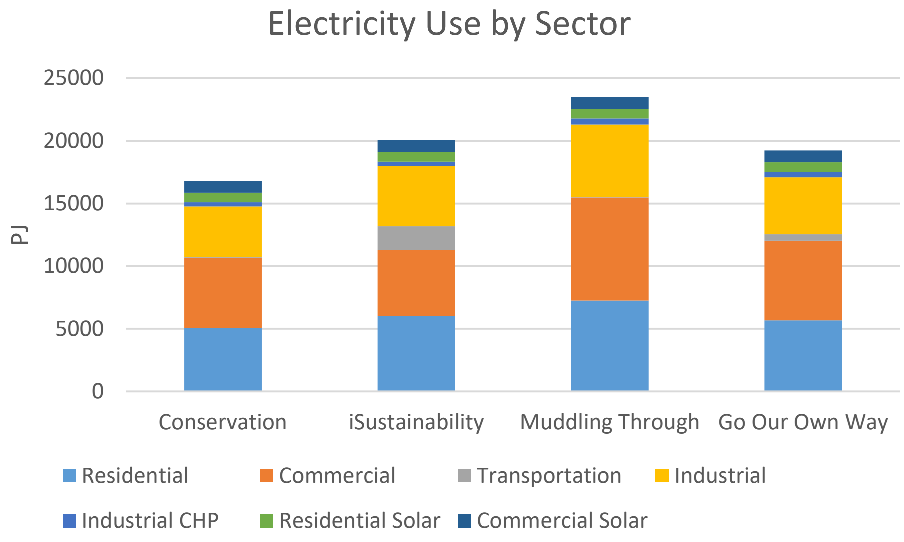


**Figure S4. Electricity use by Sector in 2050 for each scenario. Residential and commercial solar represent non-utility generation, not consumption.**

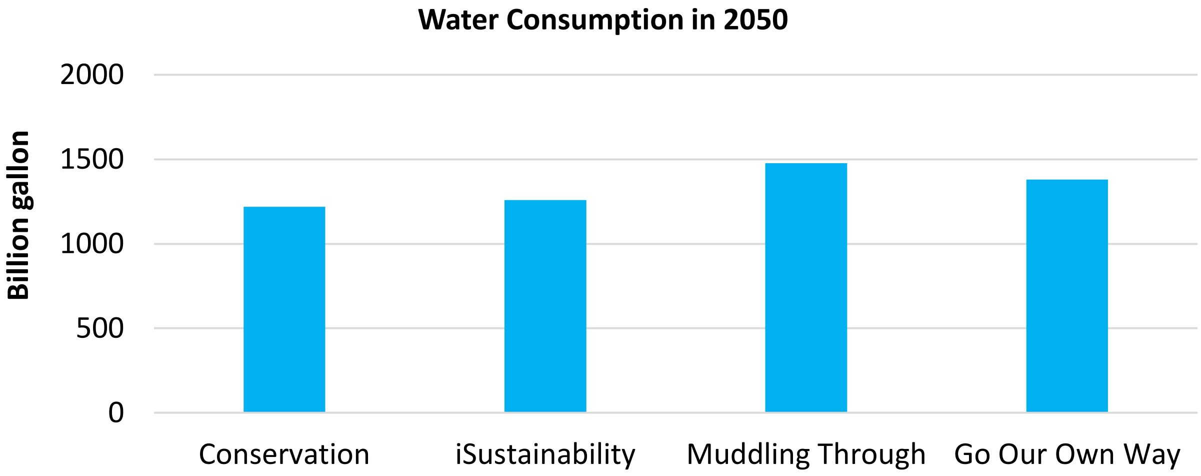


**Figure S5. Water consumption in 2050 for each scenario.**

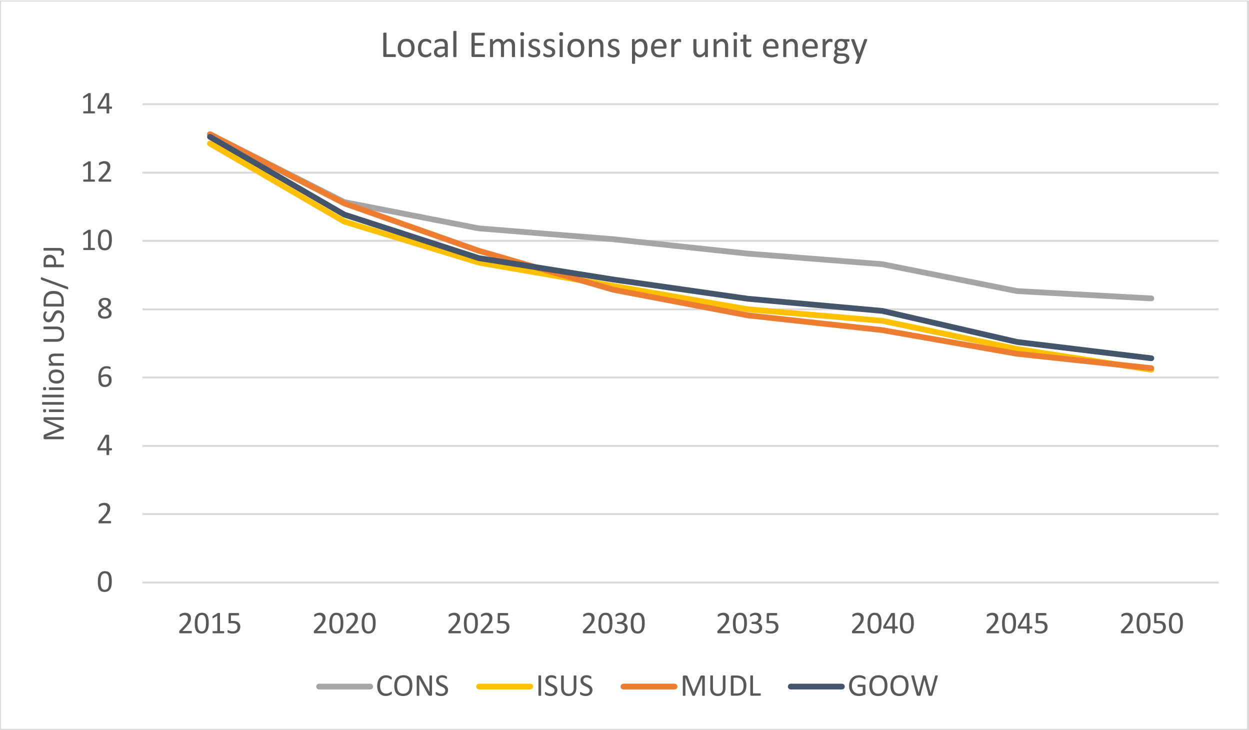


**Figure S6. Normalized criteria air pollutant emissions (damages) per unit of useful energy.**

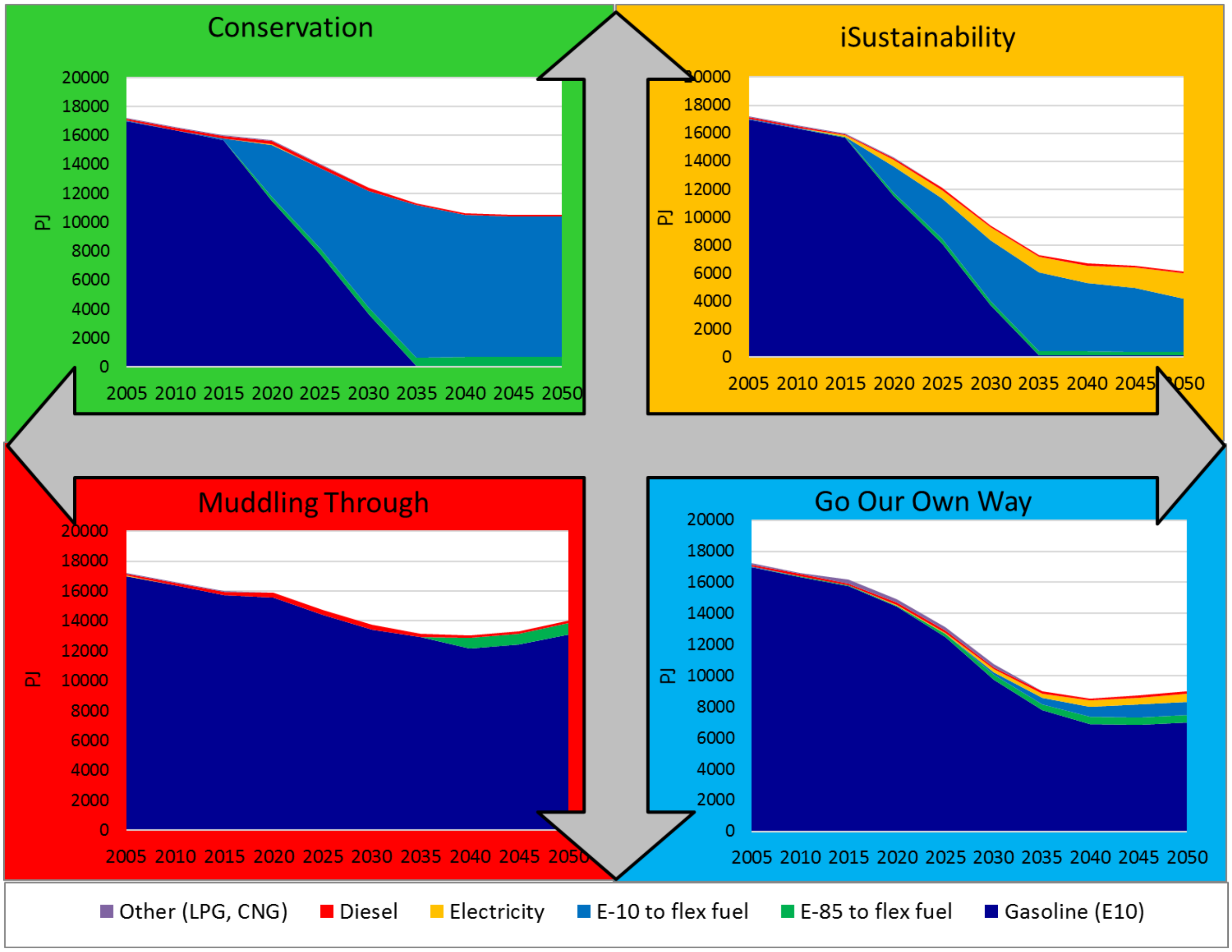


**Figure S7. Fuel used in light duty vehicles.**

Figure 2 in the text presents the miles traveled by different vehicle technologies. Figure S7 shows the fuel use by light duty vehicles. Because some scenarios have heavy use of flex fuel and hybrid vehicles, and the efficiency of the vehicles improves over time, the two figures present different information. The two shades of blue in Figure S6 show that the largest portion of the fuel consumption comes from gasoline (or E10, which is gasoline with 10% ethanol blend that is found at most gas stations today as standard fuel). Electric vehicles are more efficient, so cases with high levels of electric vehicles have lower fuel consumption, but the percentage of fuel from gasoline remains relatively high. Both plug in and hybrid vehicles can also reduce the total quantity of fuel required, while keeping gasoline dominant compared to other fuels. Another interesting result from the scenarios is that E85 is often a small fraction of the fuel supplied to flex fuel vehicles. This is displayed in Figure S7 with the green and lighter blue, and in Figure 2 by using dashed lines. In Conservation, there is a high impetus to purchase E85 vehicles, but the production of the fuel at a reasonable price is unable to keep pace in this scenario with stagnant technology, so consumers continue to purchase mostly gasoline for these vehicles. In the Muddling Through scenario, flex fuel vehicles are entirely fueled by E85 because demand has driven the cost of gasoline so high that consumers are searching for alternative fuel options. In iSustainability, there is again a high demand for purchasing vehicles with many fueling options, including hybrid flex fuel vehicles, that have three energy options. As with Conservation, the choice of fuel in operation remains mostly gasoline, as very little E85 is used, and even less electricity goes to the plug-in hybrids. Go Our Own Way is the scenario in which the capability of plug in hybrid flex fuel vehicles is most thoroughly utilized. In this scenario roughly a third of the operation occurs using each of electricity, gasoline, and E85. In this scenario, consumers appreciate the convenience of having multiple options produced through technological advancement. As a result of the scenario specific hurdle rates, we saw different combinations of technology choice, but also the choice of fuels in the cases where multiple fueling options were possible. In addition, the technology and fuel choice combination that results was quite consistent with the original scenario narratives.